Short Medium Frequency AM Antennas

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***Abstract*—Lately short antennas have again attracted broadcaster attention. These kinds of antennas have been used since the 1920s. At that time it was the logical antenna as a new application of this service after more than twenty years of telegraphic transmissions. Telegraphic transmissions were the most important radio communication service at that time, and because of the long range needed the lowest frequencies as possible were employed. For this reason very short antennas were used even if their size was enormous. Top loaded monopoles were very popular and this technique was employed for broadcast use before the vertical transmitting mast exhaustive study was carried on in the thirties.**

Nowadays a short antenna would be useful for low power applications and specially to be mounted on building tops. Of course this kind of antennas is not intended to replace the optimum monopoles or vertical dipole where maximum efficiency, maximum gain and antifading properties were achieved after exhaustive studies and after long experience theoretically and practically achieved.

CFAs, short monopoles, short dipoles and short folded monopoles have been analyzed from the theoretical and practical point of view in order to choose the simplest and most efficient model to fulfill downtown stringent requirements.

***Index Terms*—MF AM folded monopole, MF AM transmitting antenna, MF broadcast transmitting antennas.**

I. Introduction

SINCE long ago the vertically polarized antenna for medium frequencies amplitude modulation broadcasting systems has been studied exhaustively specially for antennas higher than one eight wavelength. These studies were carried out in order to improve the broadcast coverage by increasing antenna efficiency or an increase in the surface field strength. At the same time efforts were concentrated toward an increasing in the nocturnal service area, optimizing the antenna vertical radiation pattern, reducing the fading caused by the ionospheric or sky wave.

Vertical antennas with height lower than one eight wavelength for broadcast service are still not really well studied because of poor interest in low efficient radiators. Some investigations have been carried out in order to improve the radiation efficiency of the low and very low frequency antennas based practically on top loaded vertical monopole and to understand the working mechanism of these short antennas [1]. At the lower part of the spectrum frequencies only short antennas are used due to mechanical and economical restriction in the antenna size and real estate properties. At medium frequencies the possibility to get a high efficient radiator has been achieved, but at the present time, high cost real estate and height reduction due to ecological, esthetical or aeronautical problems or low power downtown installation make a short antenna or reduced size antenna a necessity. This can be studied professionally with high responsibility in order to achieve an optimum radiating system to overcome the difficult environment.

Nevertheless, if possible, this situation must be avoided and the use of a highly efficient antenna must be chosen.

Manuscript received September 17, 2001.

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Publisher Item Identifier S 0018-9316(01)10593-7.

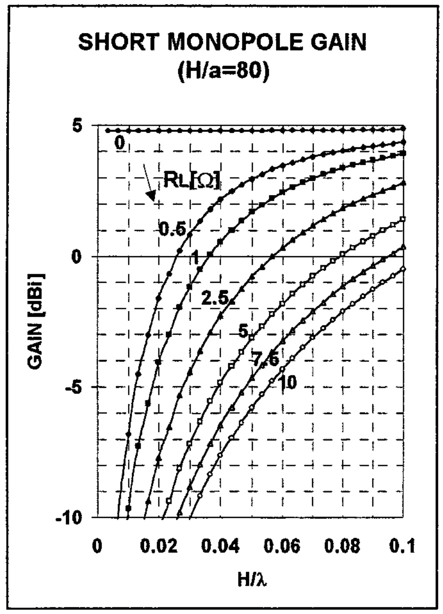


Fig. 1. Short monopole antenna directivity and gain.

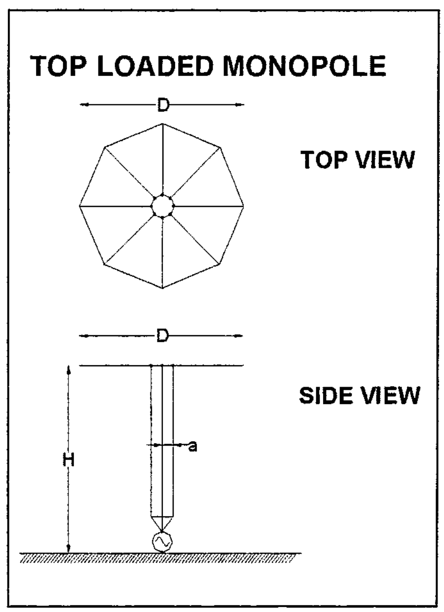
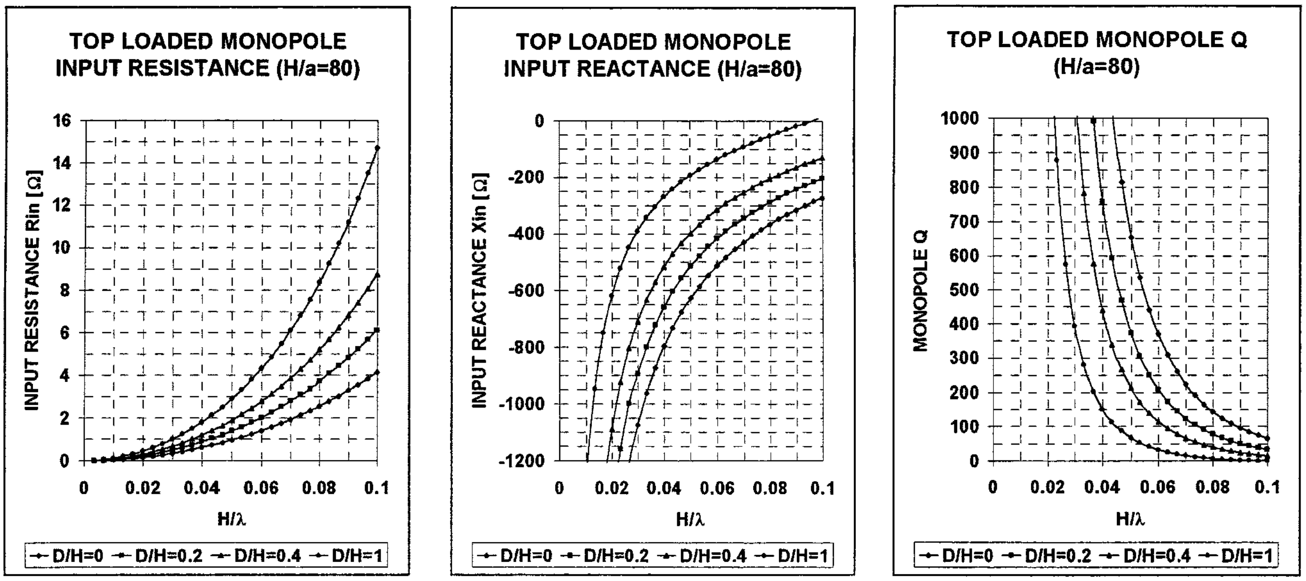
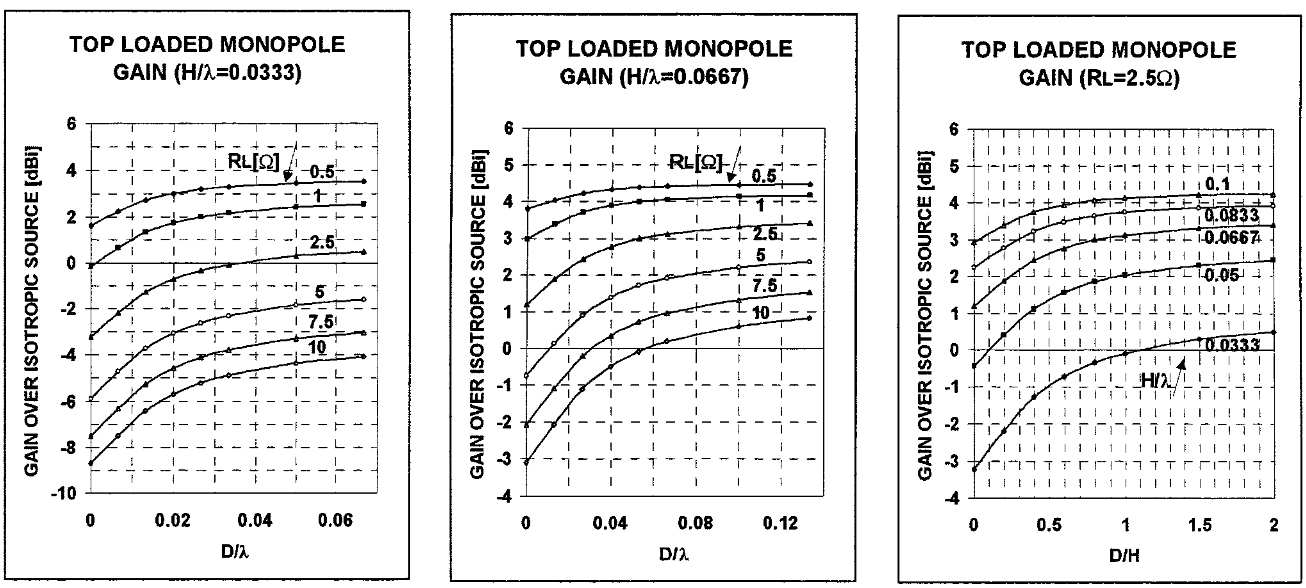


Fig. 2. Top loaded monopole sketch.



(a) (b) (c)

Fig. 3. (a) Top loaded monopole input resistance as a function of antenna height. (b) Top loaded monopole input reactance as a function of antenna height. (c) Top loaded monopole $\mathbf{Q}$.



(a) (b) (c)

Fig. 4. (a) Top loaded monopole gain for $H/\lambda = 0.0333$ as a function of D/λ. (b) Top loaded monopole gain for $H/\lambda = 0.0667$ as a function of D/λ. (c) Top loaded monopole gain for $R_L = 2.5\ \Omega$ as a function of H/λ and D/H.

The equivalent loss resistance of a short radiating systems due to ground plane, conductors and isolator losses is generally higher than the radiation resistance and for this reason high radiation efficiency is difficult to achieve. Efficiency of an antenna as other systems, is the relation between the radiated power or useful power to the total power injected into the system or the dissipated and radiated power sum. It is well known that the monopole antenna radiation resistance is a function of its height–wavelength relationship and when this relationship is low, low radiation resistance is the result.

Antenna directivity is an antenna property, it increases the radiated power in some space regions and in the short monopole antenna case, the maximum radiated power or maximum field strength is obtained along the earth and uniform in azimuth when the ground plane is perfect (infinite in extend and with infinite conductivity).

The reference antenna universally accepted nowadays is a unitary directivity radiator (1 or 0 dBi) or the isotropic source and its radiation is completely uniform into any space direction (173.2 mV/m at 1 km for 1 kW radiated).

The short vertical monopole radiation pattern depends on the cosine of the elevation angle and this property is achieved for any vertical antenna lower than one eight wavelength height over a perfect ground plane. Because of this property the di-

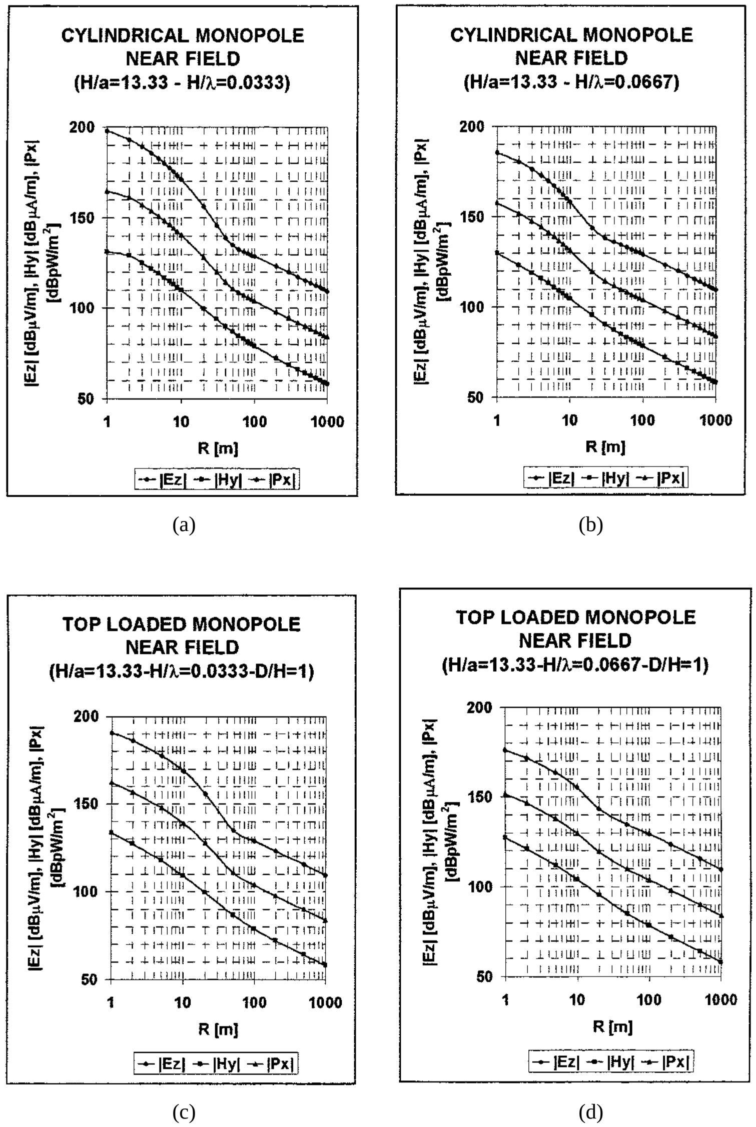


Fig. 5. (a) Cylindrical monopole near field ($H/\lambda = 0.0333$, $H/a = 13.33$). (b) Cylindrical monopole near field ($H/\lambda = 0.0667$, $H/a = 13.33$). (c) Top loaded monopole near field ($H/\lambda = 0.0333$, $H/a = 13.33$, $D/H = 1$). (d) Top loaded monopole near field ($H/\lambda = 0.0667$, $H/a = 13.33$, $D/H = 1$).

rectivity is almost the same for a very short monopole (3.0 or 4.77 dBi) and a quarter wave vertical monopole (3.27 or 5.15 dBi). Very short monopole with no losses has a field strength of 300 mV/m at 1 km for a kW radiated (109.54 dB μV/m) and a quarter wave monopole produces 313.2 mV/m at the same distance and radiated power (109.92 dB μV/m). This means an increase of 4.4% in field strength, or a very small increase taking into account the huge increase in height.

Directivity as a function of a vertical antenna height can be seen in Fig. 1 top, as the first quasi horizontal line. Clearly almost constant directivity as a function of antenna height can be seen.

Very small increase in directivity is achieved increasing the antenna height from practically nothing to a quarter wavelength. For this reason nothing can be done to improve the antenna radiation characteristics because the radiation pattern is almost constant for short antennas (height lower than one eight wavelength). It is a physical antenna condition.

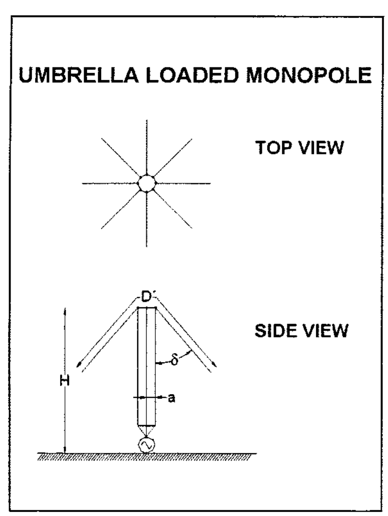


Fig. 6. Umbrella loaded monopole sketch.

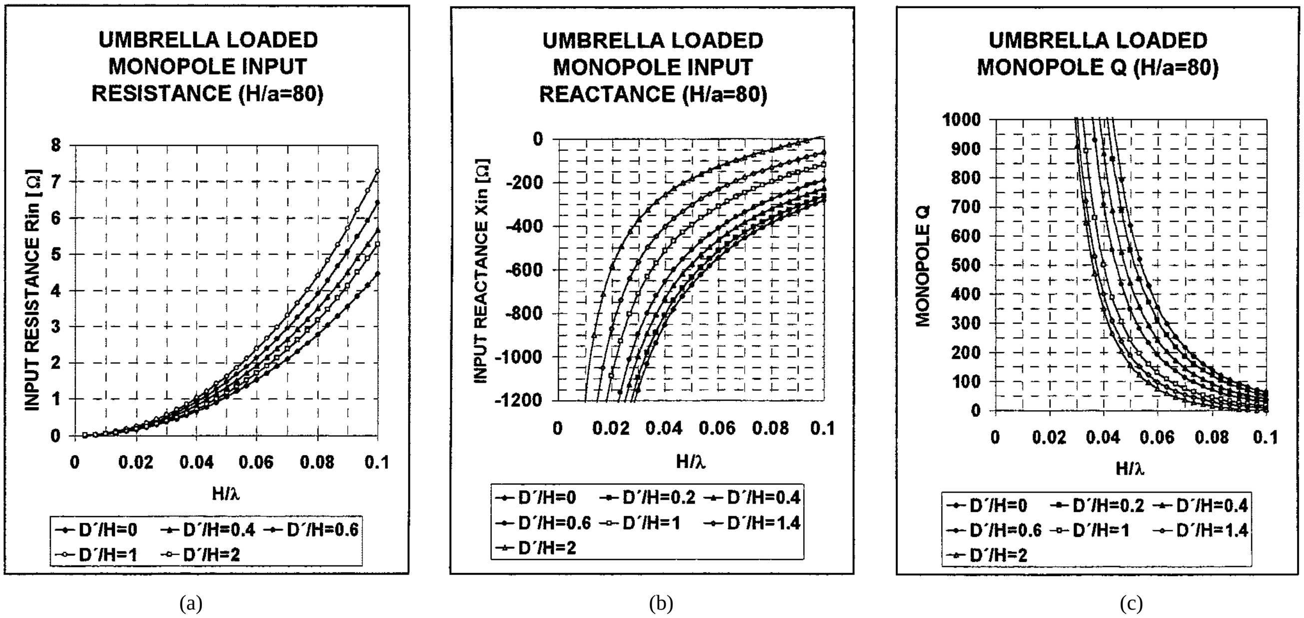


Fig. 7. (a) Umbrella loaded monopole input resistance as a function of H/λ and D'/H. (b) Umbrella loaded monopole input reactance as a function of H/λ and D'/H. (c) Umbrella loaded monopole $\mathbf{Q}$.

Attention must be concentrated on radiation efficiency because radiation resistance value depends on the square of the antenna height.

$$\textbf{Efficiency } \boldsymbol{\eta} = \frac{\mathbf{R_a}}{\mathbf{R_a} + \mathbf{R_L}}$$
$$\boldsymbol{\eta}\,(\mathbf{dB}) = \mathbf{10}\log\boldsymbol{\eta}$$

where $\mathbf{R_a}$ is the input antenna resistance and $\mathbf{R_L}$ is the equivalent total loss resistance of the antenna environment where the tuning system is included.

In this particular case, maximum efficiency means maximum antenna gain for the same directivity.

Is it well known that gain is directivity times efficiency and as efficiency reaches unity, gain equals directivity and an antenna with theoretical behavior is achieved.

$$\textbf{Gain: } \mathbf{G} = \boldsymbol{\eta}\mathbf{D} \textbf{ or}$$
$$\mathbf{G}\,(\mathbf{dBi}) = \boldsymbol{\eta}\,(\mathbf{dB}) + \mathbf{D}\,(\mathbf{dBi})$$

In order to increase this efficiency any effort increasing the radiation resistance is welcome. This statement can be seen in Fig. 1 where monopole antenna gain is plotted as a function of the equivalent total loss resistance.

It can be seen clearly, that gain is lower for the shortest antennas for the same total loss. It can be seen clearly from Fig. 1, a sharp gain decrease for monopole antennas lower than 0.05λ, even for lower total loss resistances. At the same time a decrease in antenna reactance can be useful because it reduces the antenna $\mathbf{Q}$ and an increase in antenna bandwidth is obtained.

$\mathbf{Q}$ is defined as the quotient between the input antenna reactance module to the input antenna resistance.

Unfortunately a reactance or $\mathbf{Q}$ decrease is only obtained here with an antenna height increase.

In broadcast applications this property is paramount in order to get a transmission as free as possible of distortions due to the transmitter loading variations into the pass band [1], [2].

Concentration in an efficiency increase for antennas lower than one tenth of wavelength is the task here and for this reason calculations and measurements are carried out on reduce size models. Achievements, possibly could be applied on real scale antennas in the near future. Real scale model investigations are very time consuming and generally very expensive and generally too, no supporting funds are available for this kind of research.

Calculation and measurement results indicate a substantial increase in gain for monopoles where kind of modifications or loading are implemented in order not to increase the antenna height. Monopole antenna shape has been studied in order to analyze the theoretical input impedance trying to obtain an optimum model.

Cross Field Antenna (CFA) has been analyze from the theoretical and practical point of view, making model measurement and trying to solve its behavior due to lack of information and measurements. It is pointed out that no mystery is involved in this radiating systems and the assumption on its work seems completely wrong. Measurements indicated a better radiation when used as a short cylindrical monopole and at the same time a more simple tuning system involved, permits reducing losses. It is well known that a radiating structure produces a magnetic as well an electric field around it. In the CFA case no exceptions, so each part of it can be intended as separated radiating structures with their own magnetic and electric fields. In the case of two separated excitations with a 90 degrees phase difference between them, the total produced field into space is the result of the combined fields produced from each antenna part. It seems the inventors of this antenna are claiming that the upperpart (monopole) known as E plate, produces the E field and the isolated plate (D plate) under it produces the H field and the combination of both produces the real radiated power density. This is wrong as it was pointed out, because each metallic structure produces their own E and H field. This systems is just a kind of array where both radiating structures are working to-

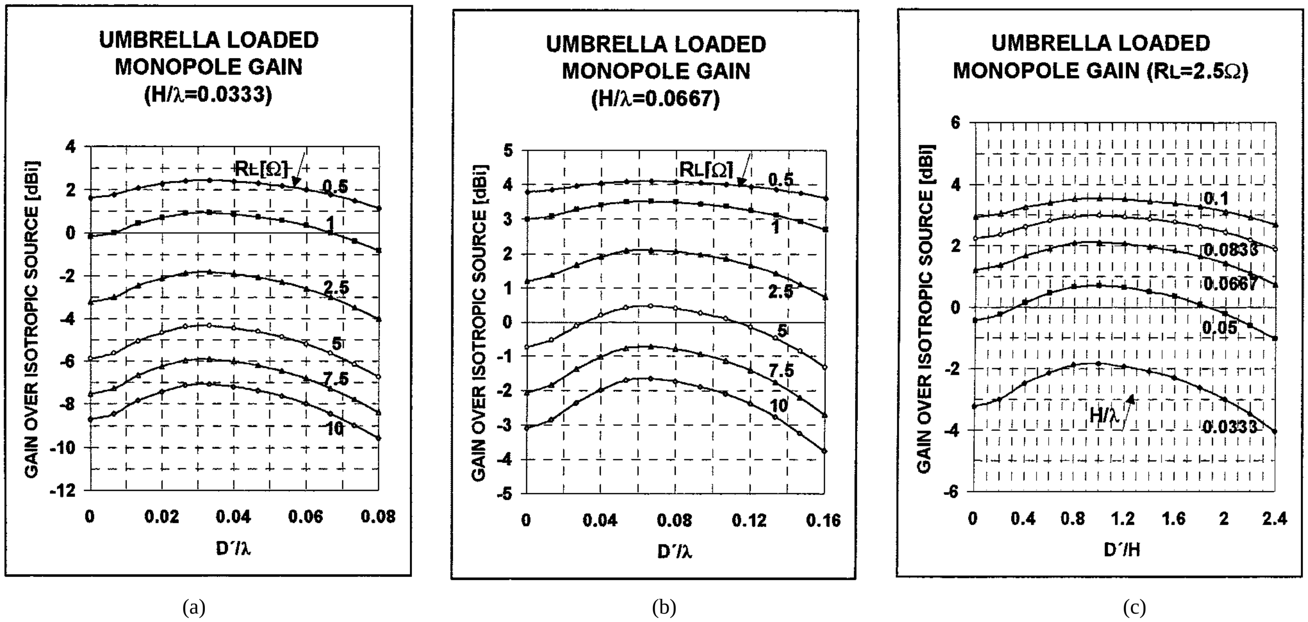


Fig. 8. (a) Umbrella loaded monopole gain for $H/\lambda = 0.0333$. (b) Umbrella loaded monopole gain for $H/\lambda = 0.0667$. (c) Umbrella loaded monopole gain as a function of D'/H and H/λ.

gether with a strong coupling between them. The power density into space is the result of the product of total E and H field produced by both structures in space surrounding the antenna. E and H field values depend of course on the feeding voltages but the radiated field strength at unit distance depends on the antenna gain over isotropic source and this gain depends on the antenna directivity and efficiency. Directivity depends on the antenna size and for heights lower than 0.1λ, directivity is similar to a short monopole or around 4.8 dBi. Fields close to the antenna can be in phase or out of phase but the radiated far fields at several wavelengths are always in phase and power density is completely real. Space impedance can be complex or almost real close to the antenna depending on the E and H relative phase but as distance reaches several wavelengths the space impedance is real and close to 377 ohms. Paragraphs 8 and 9 show calculations and measurements on CFAs.

II. Top Loaded Monopoles

One of the oldest technical method used to increase the radiation resistance of a short monopole is using a hat or a metallic structure on the monopole top. This top load can be implemented by means of a solid metal plate but generally due to mechanical and size problems at lower frequencies, it can be done by means of a wire structure.

According to its size it can be placed directly on the monopole top where the vertical monopole part can be at the same time the supporting tower. When this top load is quite big it can be supported by four or more towers. These top loading supporting towers can be metallic but it would be better if they are made up of kind of dielectric material in order not to disturb or distort the radiated field. In this case the vertical antenna part can be made up of a cage of wires or if the installation is really big by means by another tower. In the standard MF AM broadcast band (535–1705 kHz) the size is really not very big considering vertical parts lower than 0.1λ.

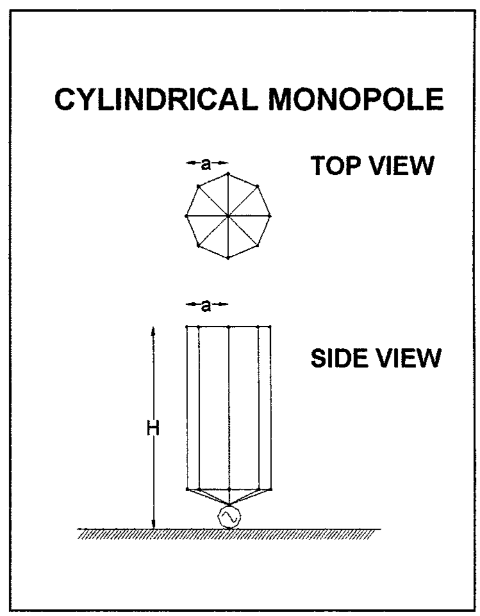
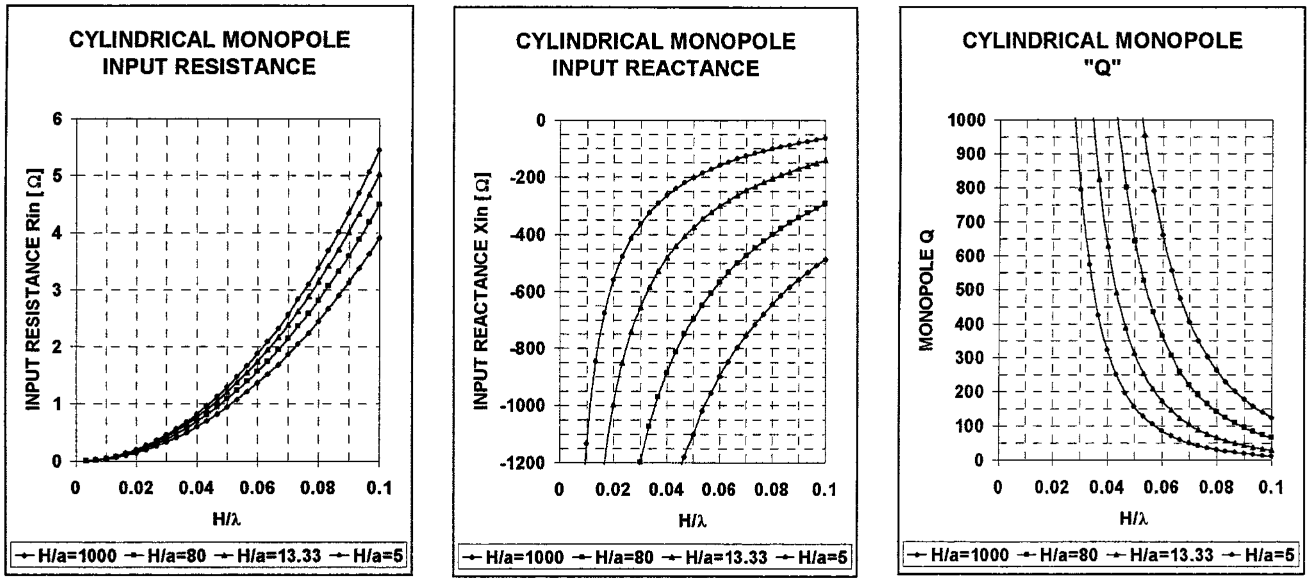


Fig. 9. Cylindrical monopole sketch.

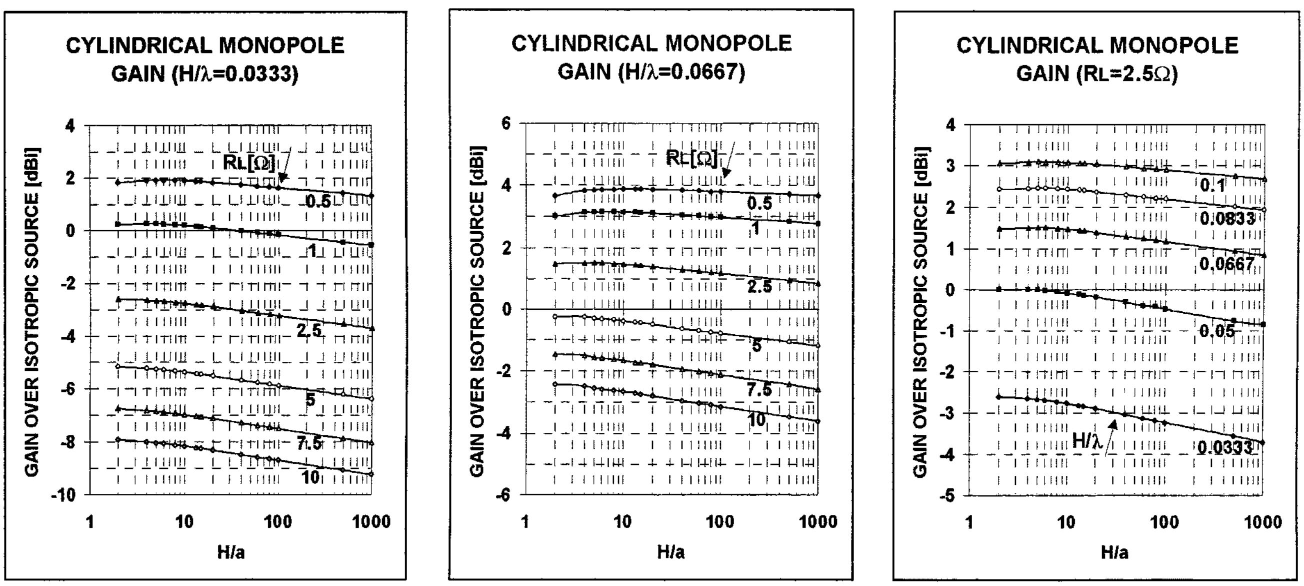
If the frequency is higher than 1 MHz this height is lower than 30 meters and generally between 10 and 20 meters. For this case the vertical antenna part is a metallic tower working as a mechanical support as well as a radiating system. On its top it can be installed a rigid metallic structure, made up of six or eight self supporting booms. A 10 or 12 meter diameter can be made easily without an excessive mechanical stress. In order to study this kind of top loading, reduced size models have been analyzed theoretically as well experimentally.

One meter high monopole model was constructed and measured at frequencies of 10 and 20 MHz. Monopole diameter was 25 millimeters so the H/a relationship was 80, corresponding at an average value or not very thin, not very fat monopole. This



(a) (b) (c)

Fig. 10. (a) Cylindrical monopole input resistance as a function of H/λ and H/a. (b) Cylindrical monopole input reactance as a function of H/λ and H/a. (c) Cylindrical monopole $\mathbf{Q}$ as a function of H/λ and H/a.



(a) (b) (c)

Fig. 11. (a) Cylindrical monopole gain as a function of H/a and R_{L}. (b) Cylindrical monopole gain as a function of H/a and R_{L}. (c) Cylindrical monopole gain as a function of H/a and H/λ.

height is equivalent to 0.0333 and 0.066 67 wavelengths for 10 and 20 MHz or 12 and 24 degree electrical height.

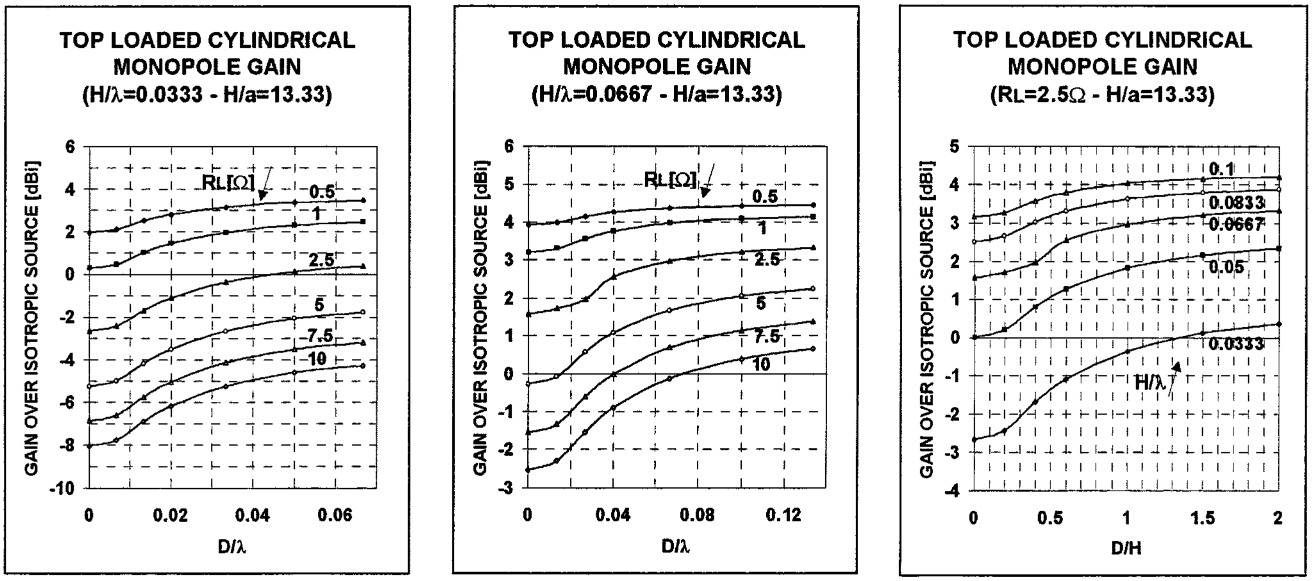
It corresponds to 10 or 20 meter for a frequency of 1 MHz or at the center of the MF AM band.

Top loaded monopole sketch can be seen in Fig. 2.

One meter high monopole input impedance and directivity calculations have been carried out for an infinite and perfect conductive ground plane. Calculations for other monopole heights give similar results maintaining the height–radius relationship and loading diameter proportions. This statement was verified by model calculations and comparing them with real scale antenna measurements.

At the same time top loading was installed on top of this model with several diameters. These real scale models can be constructed without problems and supported by only one tower. In this case the top load is made up by eight self supporting booms and connected together by means of wires in their external tips. This top load is kind of eight point star. Several diameters were used. As top load diameter is increased, an increase in input resistance is achieved but not increase of directivity. On the contrary if top load is increased in diameter more than $D/H = 1$, even if the monopole input resistance is still increasing, the directivity starts to decrease very slowly.

These calculations can be seen in the Fig. 3(a), where the input resistance is plotted as a function of antenna height or as a



(a) (b) (c)

Fig. 12. (a) Top loaded cylindrical monopole gain as a function of D/λ and $R_{\rm L}$. (b) Top loaded cylindrical monopole gain as a function of D/λ and $R_{\rm L}$. (c) Top loaded cylindrical monopole gain as a function of D/H and H/λ for $R_{\rm L} = 2.5\ \Omega$.

function of frequency. Top load diameter or D/H loading factor is taken as parameter. Increase in top load diameter is important because the input resistance increase produces a substantial gain in radiation compared to the same height non loaded monopole.

This gain increase is directly proportional to the input resistance increase. It is supposed a constant total resistance loss due to the ground plane, conductors and tuning system because this can be almost achieved in an actual installation. This resistance loss generally is not very different for different size of top loadings. Other advantage obtained with top loading is a decrease in capacitive reactance as a function of load diameter increase. Of course a decrease in antenna $\mathbf{Q}$ is obtained. This reactance decrease permits the antenna resonance with less inductive reactance and this decrease in inductive reactance decreases the inductor losses permitting a better antenna efficiency. It is pointed out that these antennas are under very stringent conditions and any small decrease in losses is always welcome. Fig. 3(b), shows the input antenna reactance as a function of antenna height or frequency with the top load diameter as parameter and Fig. 3(c), shows the corresponding monopole antenna $\mathbf{Q}$.

It is very important to repeat: an increase in top load diameter increases the input antenna resistance or an increase in radiation resistance and as result, an increase in antenna gain or an increase in the surface wave field strength is achieved. At the same time it is important to know, that no increase in directivity is achieved, or the antenna radiation pattern is practically unchanged and as consequence, the vertical beamwidth is always close to 45 degrees like in the infinitesimal monopole case, because the vertical radiation pattern is an elevation angle cosine function. This antenna unfortunately has a strong radiation at the high elevation angles and is it inconvenient for high power stations due to a very poor antifading properties during the night.

Knowing the top loaded monopole input resistance, antenna gain can be calculated as a function of the top load diameter and as a function of the total loss resistance of the radiating system

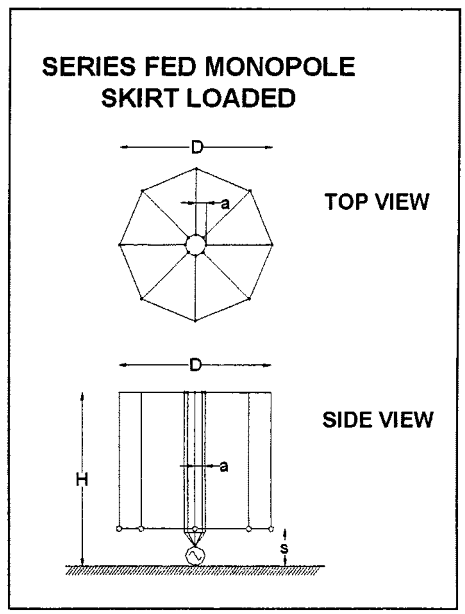


Fig. 13. Series fed monopole sketch.

for a typical antenna height. In these figures it can be seen the importance of having a very low loss system, in order to get the maximum gain. Low loss can be obtained making a very conductive and extensive ground plane as well a very low loss antenna tuner. Possibly these concepts can be kind of boring, but due to the low input antenna resistance, any small loss resistance in the imperfect ground plane or in the tuner inductors can be comparable or even higher than the antenna resistance. As an example a good inductor with 200 reactance ohms and a merit factor $\mathbf{Q}$ of 200 has a loss resistance of 1 ohm. If two of these inductors are used in the tuner the total radiating system efficiency can suffer considerably. Decreasing the ground plane loss resistance is other task and this can be achieved making an extensive

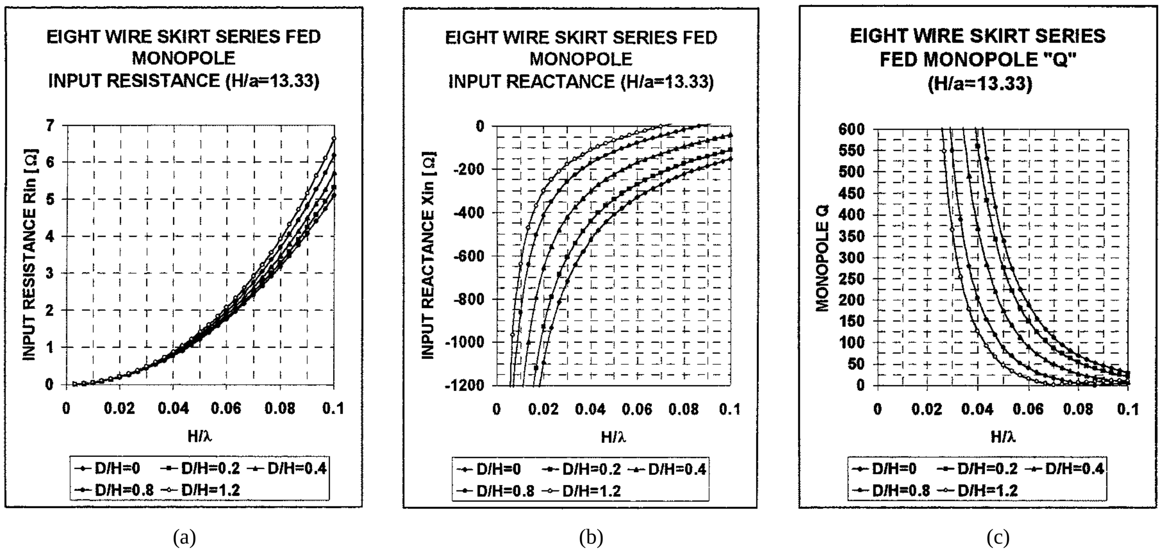


Fig. 14. (a) Series fed monopole input resistance as a function of D/H and H/λ. (b) Series fed monopole input reactance as a function of D/H and H/λ. (c) Series fed monopole $\mathbf{Q}$.

metallic plane under the monopole antenna. It can be pointed out, standard radial ground plane for very efficient half wavelength monopole antenna cannot be adequate for these small antennas because at short distance from the antenna base, the divergent wires makes the total ground impedance quite high, very close to the soil impedance and for this reason, the maximum as possible metallic plane extension must be used. If this is made, the antenna gain cannot be very far from the gain of a quarter wave monopole specially when top loaded monopole antenna factor (D/H) is close or higher to 1.

This can be seen in the Fig. 4(a)–(c). Under this conditions the far field signal is comparable, because it could be only 1.5 dB below a perfect quarter wave monopole.

This is difficult to measure accurately, taking into account the field strength variations as a function of distance, due to obstruction, like those encountered in cities and due to the field strength meter accuracy that generally are specified ± 2 dB or more. For these reasons, placing a well designed short antenna in other places, where comparison are difficult to be made, more field strength could be measured specially when an old quarter wave monopole with a deteriorated ground plane is replaced. This doesn't mean the short antenna is better than a standard quarter wave monopole. This statement must be taken with care specially when accurate measurements are not done.

For small ground service areas and reduced transmitting power (lower than 10 kW) this antenna could be useful, taking the maximum care in its design and where antifading properties can be neglected.

Fig. 5 shows the 0.0333λ and 0.0667λ, height monopole calculated near field for 1 kW input power over perfect ground plane. This shows clearly the strong electric field as well power density and magnetic field close to the monopole feeding point. Here again it can be seen the necessity to get a metallic ground plane in order to support these strong fields and the corresponding power density in order to avoid energy dissipation. It is important to insist, the more field strength or power density close to ground is produced by an antenna, ground plane must be almost perfectly conductive. Short monopole antenna is a typical strong power density case and maximum care on the ground plane is needed. This power density is more intense than in the quarter or half wave monopole antennas case, fed by the same input power [2], [3].

III. Umbrella Top Loading

Umbrella top loading is similar to the previous case, but it is a simpler form to load the monopole and generally the top guys are used in order to built the monopole top load. In this case six or eight top guys are insulated at same distance from the monopole top. Experiments with a real scale model in LF were performed by Carl Smith and Earl Johnson [3]. In this case, top tower guys form an angle with respect to the vertical tower and generally it is close to 45 degrees. In this case the guy radius at the earth level is the same as the tower height. It is pointed out here, the top load must be horizontal in order to be of maximum effectiveness. For this reason the guy slope must be gentle or more, if possible, than 45 degrees from the tower edge. Of course this action increases the guy radius or the needed real estate with an increase in the lot cost. Sometime the guy lower ends are placed over small towers in order to increase this angle and making the loading more effective [4]. Technical information on this matter is very scarce after Smith & Johnson paper. Top loaded monopole calculations and measurements have been made using a model with an angle of 45 degrees, in order to get a good view of its behavior as a function of loading radius or guy length from the tower top. Eight guy model was calculated and measured over a metallic ground plane. Input monopole resistance increases slightly with the loading diameter till a maximum depending on the monopole antenna height and starts decreasing as guy length increases. Sketch of umbrella loading monopole antenna can be seen in Fig. 6. Calculated input monopole antenna resistance as a function of antenna height and loading diameter factor (D'/H) can be seen in

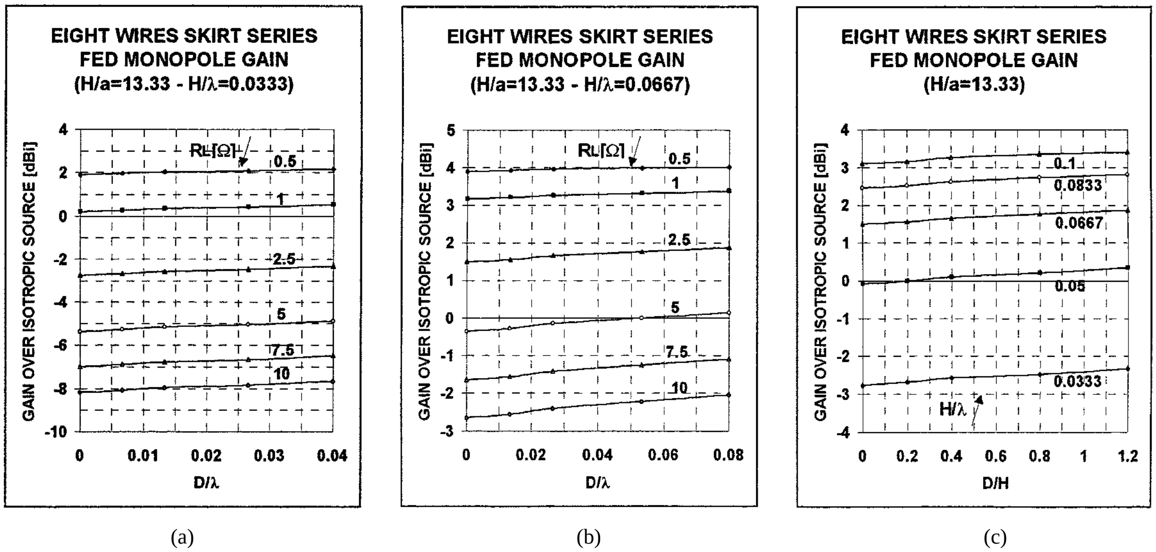


Fig. 15. (a) Series fed monopole gain as a function of D/λ and $R_{\rm L}$. (b) Series fed monopole gain as a function of D/λ and $R_{\rm L}$. (c) Series fed monopole gain as a function of D/H and H/λ for $R_{\rm L} = 2.5\ \Omega$.

Fig. 7(a). Input reactance continually decreases with a loading factor increase, and this decreases the antenna $\mathbf{Q}$. Calculated input reactance of an umbrella loading monopole as a function of antenna height and loading factor (D'/H) can be seen in Fig. 7(b). Fig. 7(c) shows the corresponding umbrella loading monopole $\mathbf{Q}$.

As a result of the input resistance as a function of loading factor, antenna gain has an optimum value and its depends on the monopole antenna height. Nevertheless this optimum gain maximum doesn't reach the value obtained with a flat top or horizontal top loading. For this reason this case must be used when small loading is needed or in case of making the radiating system of minimum cost due to its mechanical simplicity.

Fig. 8(a) and (b) show the calculated antenna gain as a function of loading diameter for different values of total loss resistance and for two different antenna heights. Fig. 8(c) shows the calculated antenna gain for a total loss resistance of 2.5 ohms for monopole antenna heights lower than 0.1λ. It can be seen clearly the lower effect of loading as the antenna height is increased.

IV. Height–Radius Antenna Effect

Height–radius (H/a) parameter has a strong effect on monopoles as well in dipoles input impedance as it is well known since long time. In this specific case an increase in input resistance is of paramount importance in order to achieve an increase of gain or radiation efficiency. For this reason even a small increase can be helpful. Input impedance has been calculated for different height–radius relationships. Fig. 9 shows a cylindrical monopole antenna sketch. Input resistance as a function of height–radius (H/a) relationship can be seen in Fig. 10(a). It can be seen the slow increase in input resistance values as H/a relationship decreases. Input reactance decreases with a decrease of H/a relationship and this effect is even more important as can be seen in Fig. 10(b). This decrease in

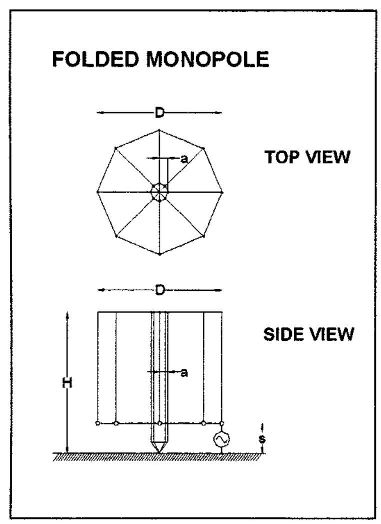
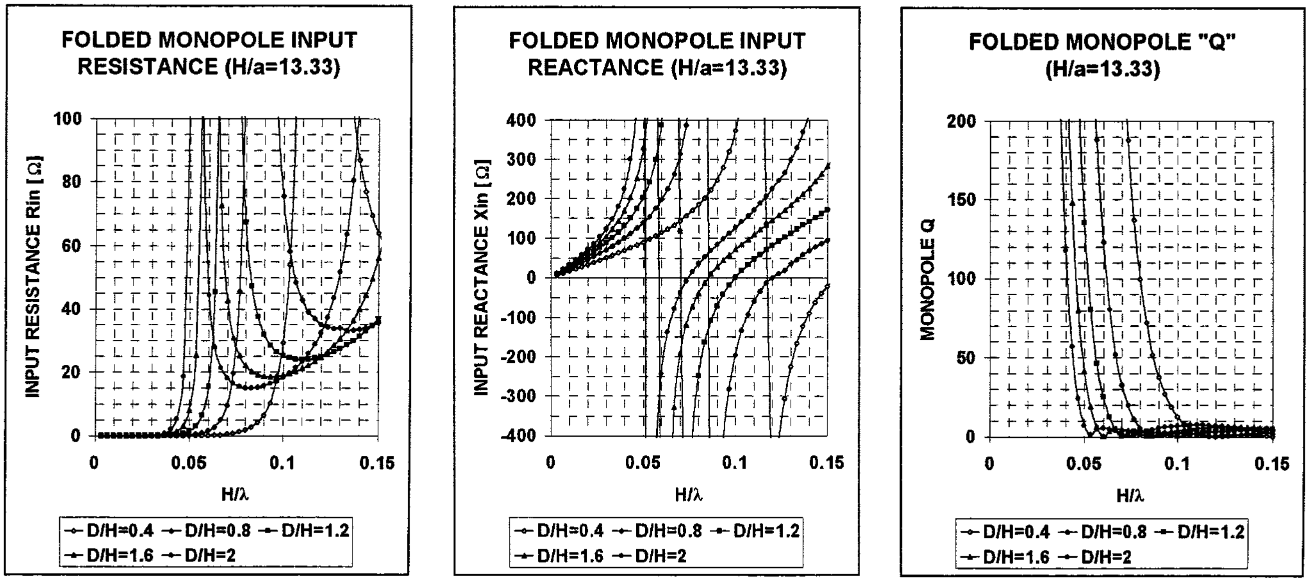


Fig. 16. Folded monopole sketch.

input reactance as H/a relationship decreases is useful because it decreases the antenna $\mathbf{Q}$. This effect is shown in Fig. 10(c). A small resistance increase means an increase in antenna radiation efficiency or gain. As an example Fig. 11(a) shows the cylindrical monopole antenna gain as a function of H/a for an antenna height of 0.0333λ and Fig. 11(b) shows this effect for an antenna height of 0.0666λ. A general view of this antenna behavior can be seen in Fig. 11(c) where the calculated antenna gain is shown as a function of H/a relationship for a total resistance loss of 2.5 ohms and for different antenna heights (H/λ). It can be seen that the increase in antenna gain is within 1 dB for H/a variation from 1000 to 10 but this gain increase is lower for higher monopoles. Very low H/a values start decreasing the antenna gain due to a decrease in directivity. Under these results the only way to increase effectively the input resistance is using a load structure on the monopole top as was seen previously. This effect was studied in order to



(a) (b) (c)

Fig. 17. (a) Folded monopole input resistance as a function of H/λ and D/H. (b) Folded monopole input reactance as a function of H/λ and D/H. (c) Folded monopole $\mathbf{Q}$ as a function of H/λ and D/H.

compare it with the previous top loaded monopole. Fig. 12 shows the calculated monopole antenna gain as a function of loading for $H/a = 13.33$. This result seems promising for low loading due to a higher input resistance compared to a thinner monopole, but similar results to the thinner loaded monopole are obtained as loading is increased. Here the loading effect is more important for lower heights as it was pointed out previously.

V. Series Fed Skirted Monopole

This monopole is fed in its base and it has a top load with eight metallic booms on whose tips are connected to eight dropping wires forming a skirt around the supporting pole. These wires are isolated in their lower tips at two or three meters over ground.

The skirt effect is decreasing basically the input reactance and this decrease depends on the skirt diameter. Unfortunately the skirt diameter increase doesn't increase substantially the input resistance and for this reason this radiating system can be used when top loaded or umbrella loaded systems cannot be employed. Fig. 13 shows the series fed skirted monopole sketch and in Fig. 14 input resistance and reactance can be seen as well the corresponding $\mathbf{Q}$. Directivity is similar to a standard short monopole and radiation efficiency depends on an extensive metallic ground plane as seen previously, due to the low input resistance. This case produces a very low gain increase with the loading effect as can be seen in Fig. 15.

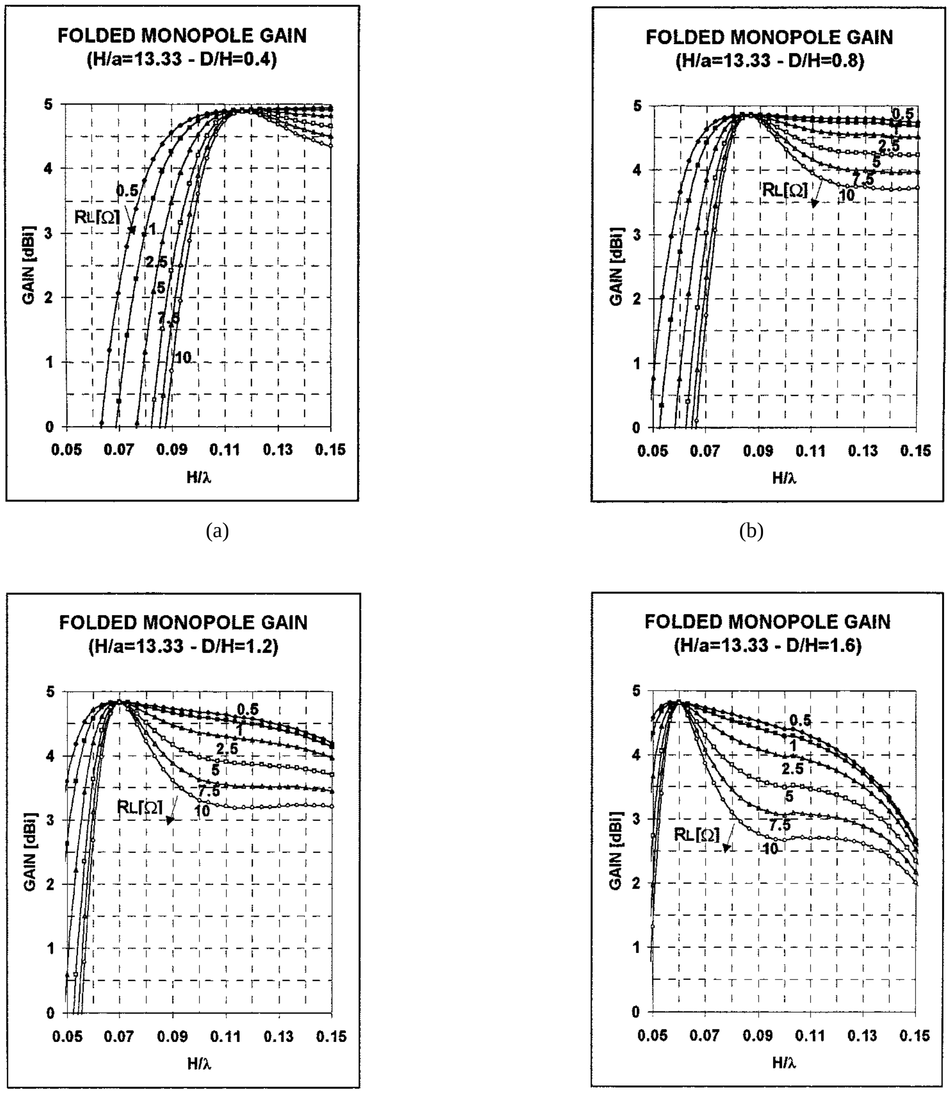
VI. Shunt Fed Monopole or Folded Monopole

A grounded monopole is always well received because of its discharging properties, its simple beacon lighting connections and equipment protection. In this case the monopole metallic structure can be connected directly to the metallic ground plane and a skirt is made up all around the metallic pole or tower using six or eight wires connected at the tower top by means of metallic booms. These wires are isolated near ground and connected between them. This is the antenna feeding point. Fig. 16 shows a folded monopole sketch.

Calculations and analysis have been made for short folded monopoles were the skirt is made up of eight wires and height is less than 0.25λ. Input impedance and directivity have been calculated as a function of antenna height and skirt diameter in order to get a knowledge of it behavior. This is the first approximation before making measurements of models with big possibilities to be useful for broadcast applications in medium frequencies.

Fig. 17(a) and (b) show the input resistance and reactance as a function of antenna height and for different skirt diameters. The supporting pole and wire skirt are producing a kind of coaxial transmission line and a characteristic impedance can be calculated in each case knowing the inner and outer diameter and wire involved in the skirt. This information is generally useful as a reference in designing a radiator for a transmitting system. As an example for a 15 meter height metallic pole with a diameter of 500 millimeters, skirt diameter of 2 meters and eight wires of 3 millimeter radius the characteristic impedance results 111 ohms.

This quasi coaxial line is in parallel to the antenna input port and of course its effect will be present in the antennas input impedance. Observing the input antenna impedance curves as a function of antenna height a parallel resonance appears where resistance is very high and reactance is going through zero from inductive to capacitive values. Previous to resonance when antenna height is lower than 0.05λ, resistance is very low practically zero and completely unuseful for an efficient radiating system. As resonance is approached, resistance raises very fast acquiring very high values. After the resonance the resistance values have an useful plateau or quasi constant resistance value zone with a capacitive reactance. Antenna $\mathbf{Q}$ is lower than 10 permitting a good match and bandwidth.



(a) (b)

(c) (d)

Fig. 18. (a) Folded monopole gain as a function of H/λ and R_L. (b) Folded monopole gain as a function of H/λ and R_L. (c) Folded monopole gain as a function of H/λ and R_L. (d) Folded monopole gain as a function of H/λ and R_L.

Unfortunately antenna height is not very small and this zone depends on the skirt diameter as can be seen in this figure.

For greater skirt diameters this zone corresponds to a lower antenna heights. In case of interest, study must be done in order to design the radiating system that fulfill the requirements. Even if the antenna is not very short, resistance between 30 and 50 ohms are very simple to match to a 50 ohm transmission line by means of an antenna tuner and these relatively high resistance values can give a good efficiency with a moderate size ground plane. Depending on the antenna height, the capacitive reactance is not very high and with low variations permitting an adequate AM bandwidth for this antenna lower than a quarterwave height. Antenna gain has been calculated for different loading factors (D/H) and as a function of antenna height, in order to help in the system design decisions. (Fig. 18). In this case the elevation radiation pattern is practically a cosine function and for this reason it can be useful for a low power station were low cost is paramount.

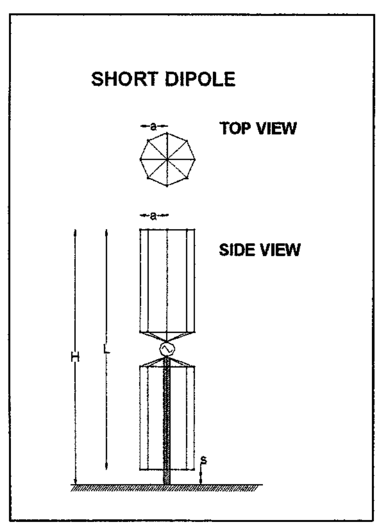
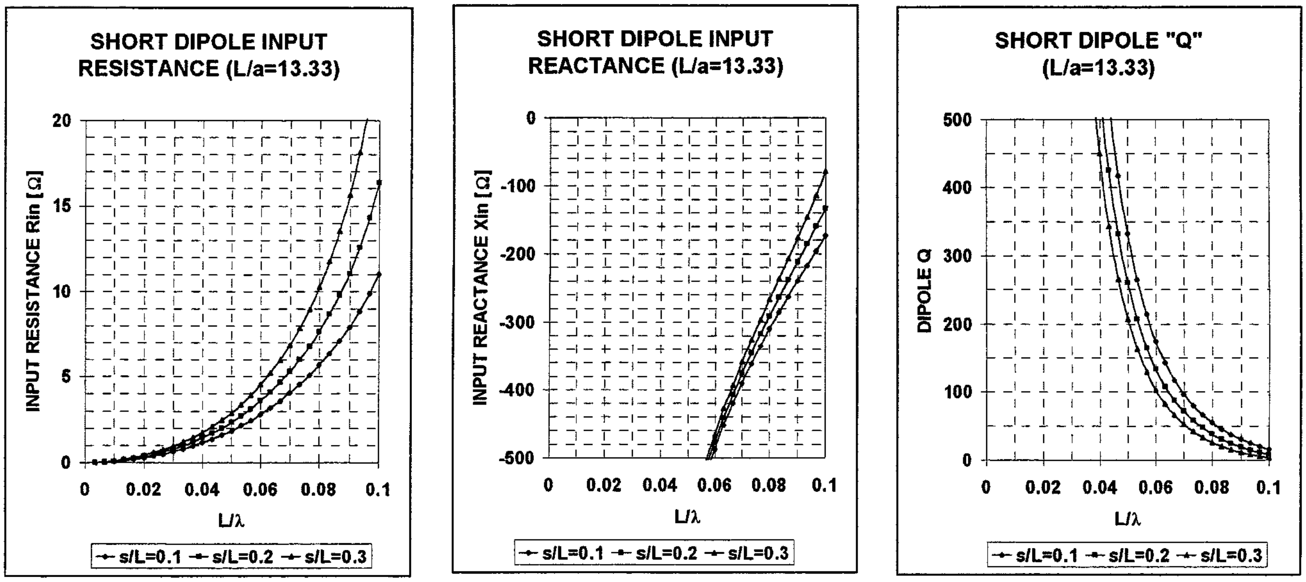
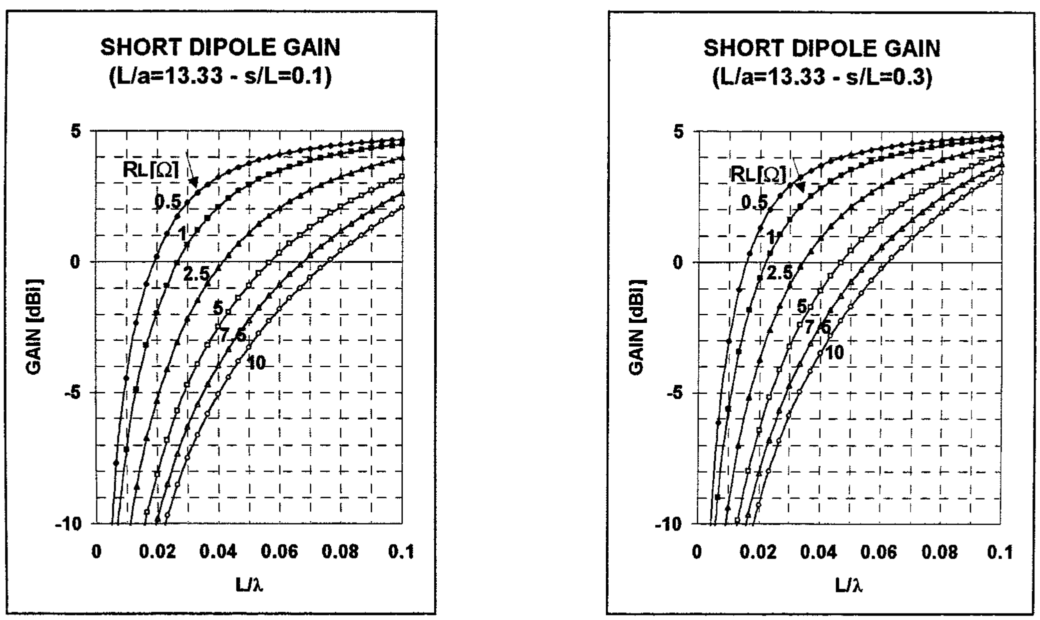


Fig. 19. Short dipole sketch.



(a) (b) (c)

Fig. 20. (a) Short dipole input resistance as a function of L/λ and s/L. (b) Short dipole input reactance as a function of L/λ and s/L. (c) Short dipole $\mathbf{Q}$ as a function of L/λ and s/L.



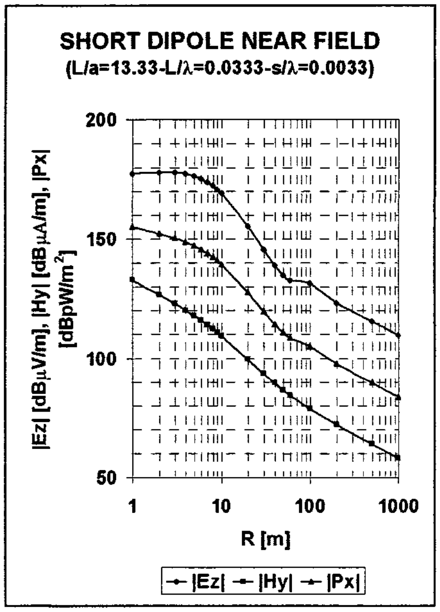
(a) (b)

Fig. 21. (a) Short dipole gain as a function of L/λ and R_{L}. (b) Short dipole gain as a function of L/λ and R_{L}.

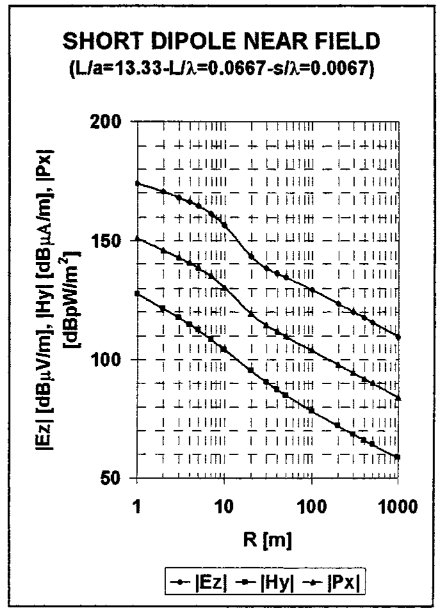
VII. Short Dipole

Short dipole can be another antenna to be used and with dimensions close to a short monopole. In this case the feeding point is located approximately in the middle of the physical structure. Lower dipole wing can be connected to ground in its middle. Fig. 19 shows a sketch of a short dipole. Short dipole is more flexible than a monopole because its separation from ground can be modified and this separation(s) modify substantially the field intensity over ground close to the antenna. For example, electric field strength can be close to 20 dB below the corresponding monopole electric field strength in the antenna base. This lower field strength can be useful in order to decrease ground plane losses.

Fig. 20 shows short dipole input resistance and reactance as a function of frequency or relative to wavelength antenna height. It is interesting seeing an increase in input antenna resistance compared with the monopole of same height but reactance values are higher due to a relative shorter physical-wavelength structure. For example this increase is close to 100% compared to an $H/a = 80$ monopole of the same height and even higher if the monopole ground plane separation is increased. Increase in



(a)



(b)

Fig. 22. (a) Short dipole near field as a function of distance. (b) Short dipole near field as a function of distance.

ground plane-lower dipole tip separation increases slightly the input resistance but almost no reactance variation is obtained. These calculations must be confirmed by measurements in the future and this research could be important to be done. If this is confirmed the radiation efficiency can be improved substantially. Fig. 21 shows short dipole gain as a function of frequency and total resistance loss as parameter. Fig. 22 shows an example of the short dipole near field as a function of distance. It is interesting to observe, the near field behavior close to the antenna base. Of course the theoretical field strength at the unit distance is the same for any short antenna over a perfect ground plane or 109.55 dBi at 1 km for 1 kW radiated, corresponding to a directivity close to 4.77 dBi.

Nevertheless these lower field strength values compared to a monopole are still more than 20 dB higher than the half wavelength grounded dipole near field strength as it was pointed out [5].

VIII. Crossed Field Antennas (CFA)

This antennas was attracting the attention specially due to scarce information about its behavior and specially due the high gain claiming by its "inventors." This antenna is nothing new and its behavior is similar to a short monopole of the same height. It has a short cylindrical monopole structure as a radiating system, called the "E plate," and a metallic plate under it and parallel to the ground plane, called the "D Plate". Lately in order to increase its radiation performance and facilitate its tuning, a top load was added. Monopole height is not important but if its height is too low, radiation efficiency deteriorates because of its very low radiation resistance as it was seen in the short monopole case. The D plate size is not really important because it not increases the radiation power

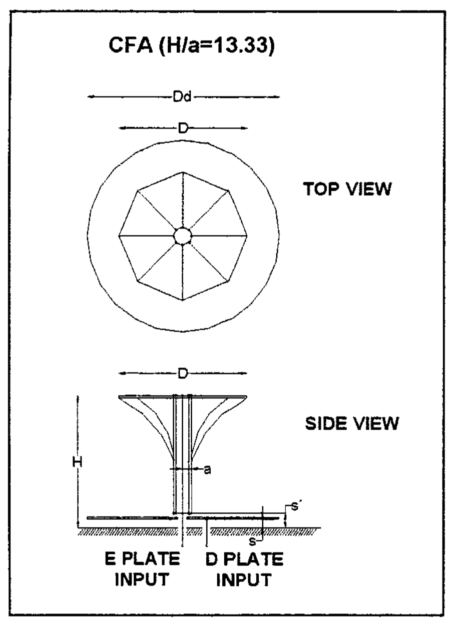
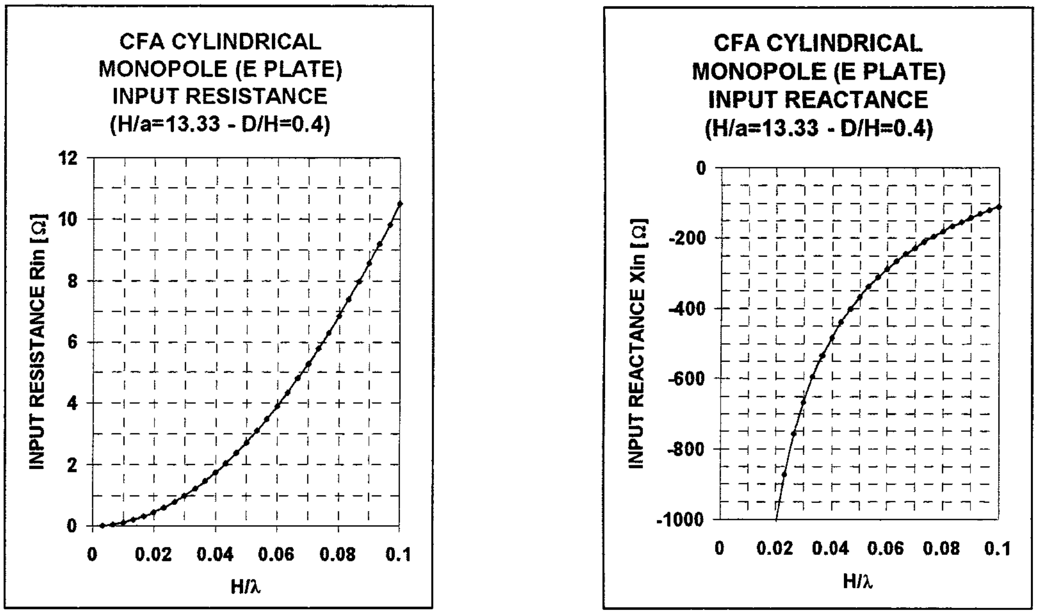


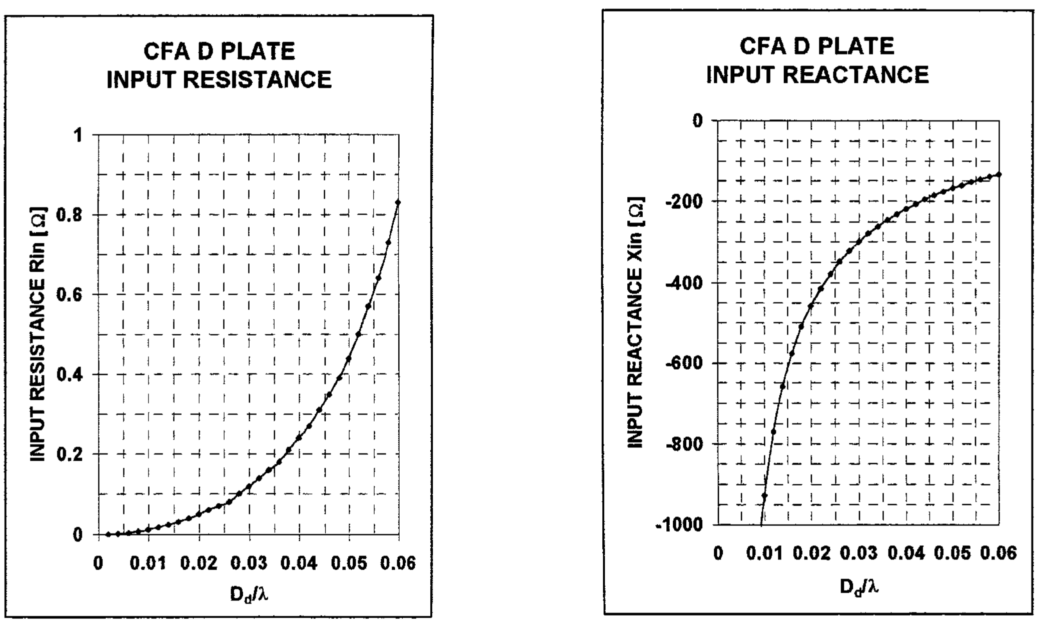
Fig. 23. CFA sketch $H = 1$ m, $D = 0.4$ m, $\mathrm{Dd} = 0.6$ m.

of this array and its effect is to modify the very near field in the antenna vicinity trying to obtain E and H fields in phase in the surrounding space. The radiated field at several wavelength is similar with or without it. It complicates the antenna feeding system because its inventors connect two generators at the antenna system. One between the monopole (E plate) and the metallic ground plane and one between the D plate and the metallic ground plane and 90 degrees phase difference between them. Because antenna gain does not increase with this complicated tuning system, the best way is to eliminate the D plate and using only one generator



(a) (b)

Fig. 24. (a) CFA monopole calculated input resistance. (b) CFA monopole calculated input reactance.



(a) (b)

Fig. 25. (a) CFA D plate calculated input resistance. (b) CFA D plate calculated input reactance.

and tuning system, increasing at the same time the antenna efficiency because any additional loss in these extremely low radiating resistance systems is highly beneficial. Of course if this is done, the "invention" disappear and a standard cylindrical short monopole is obtained. Directivity of this antenna is similar to a short monopole of the same height regardless the kind of feeding, in phase or 90 degrees phase difference between both plates. Antenna gain depends, like in any kind of short monopole, on the best metallic ground plane of maximum of possible extension. A reduced metallic ground plane deteriorates the antenna performance as it was pointed out previously.

Fig. 23 shows a sketch of a CFA over ground plane. Calculated cylindrical monopole (E plate) input impedance can be seen in Fig. 24 for a 1 meter high model with a top load hat of 0.45 meter diameter and in Fig. 25 the input impedance of the D plate of 0.6 meter diameter at 0.1 meter over the metallic ground plane. In both figures the input impedance is displayed as a function of height or plate diameter wavelength relationship.

Low resistance and high capacitive reactance are seen for a frequency were the monopole height is close to 0.0333λ and 0.0667 for both structures. Similar values were obtained for cylindrical monopoles. Because of this, its tuning system needs

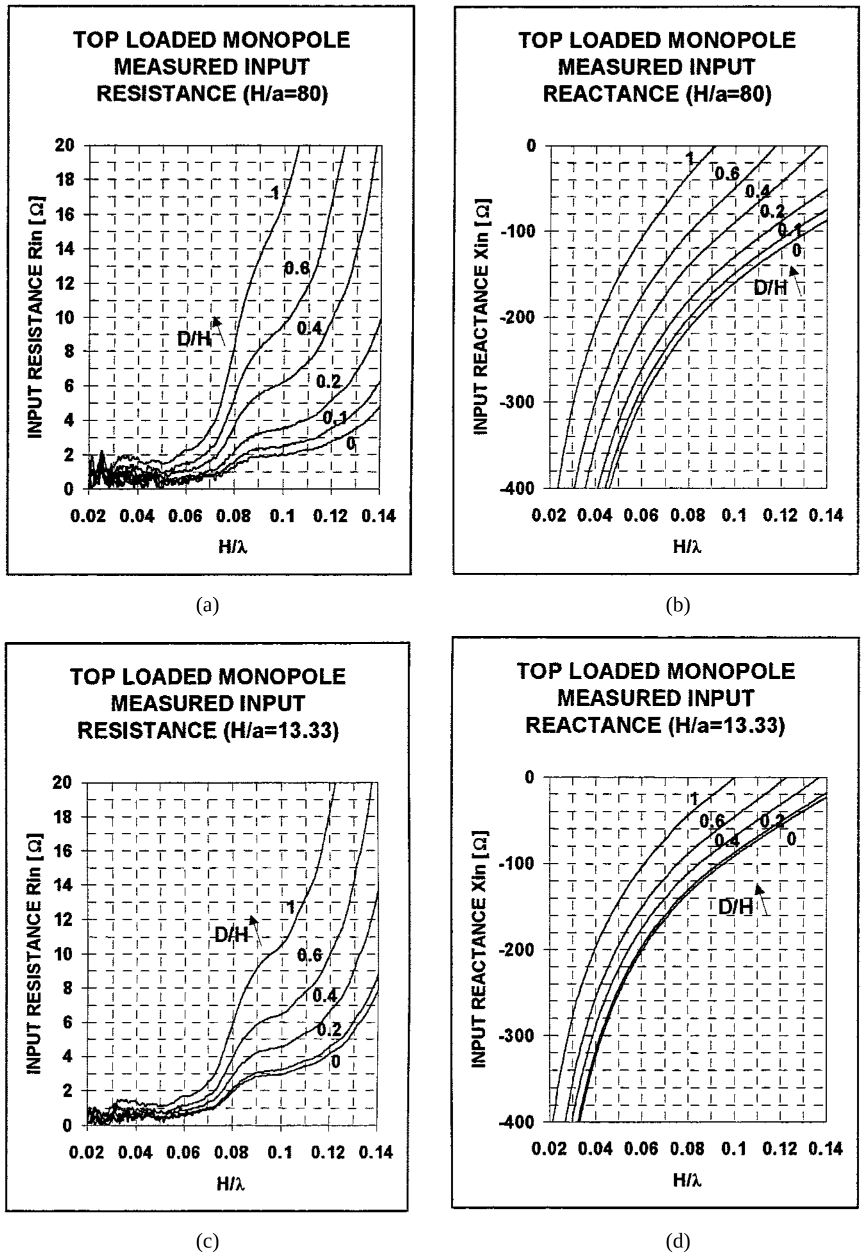


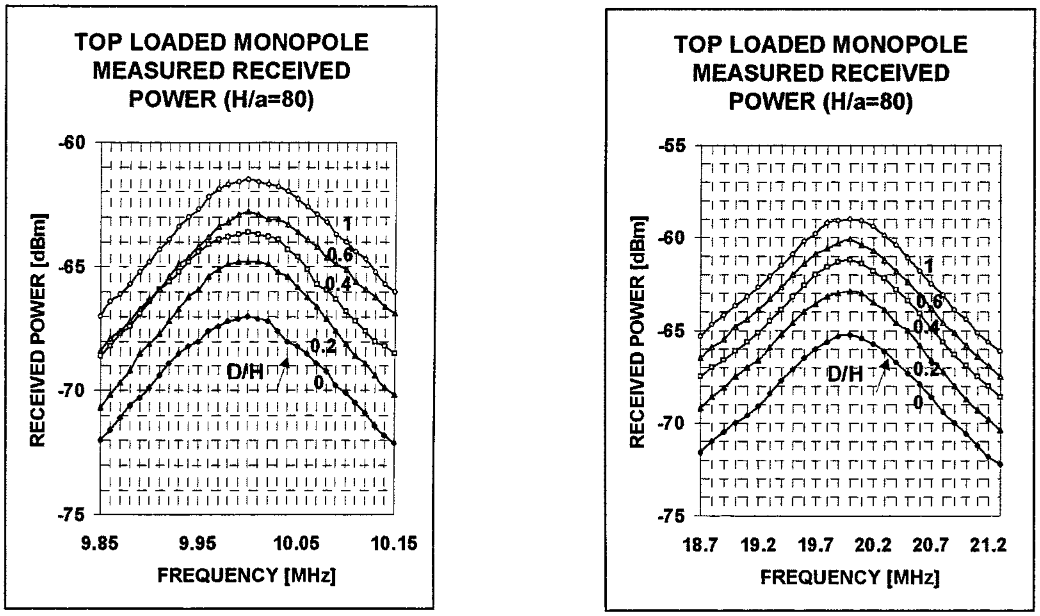
Fig. 26. (a) Top loaded short monopole measured input resistance as a function of H/λ. (b) Top loaded short monopole measured input reactance as a function of H/λ. (c) Top loaded short monopole measured input resistance as a function of H/λ. (d) Top loaded monopole measured input reactance as a function of H/λ.

a very high Q inductors and capacitors and a very good metallic ground plane.

Radiation pattern is a cosine function of the elevation angle, and for this reason this antenna is intended for low power applications (power lower than 10 kW) were diurnal service area is reduced and antenna antifading properties are not considered an important issue. For higher power applications standard monopole or dipole closer to half wavelength height must be used, in order to get maximum radiation efficiency and the best antifading properties. Calculated elevation radiation pattern is not shown here because it is simple cosine function, well known, with a maximum at ground level and the radiated power decreases to a half at 45 degree elevation $(-3\ \text{dB})$. Radiated power is proportional to a square E or H field as it is well known and it must be as low as possible at high elevation angle for MF AM transmitting applications. Of course this radiation pattern is not desirable for a perfect MF AM system.

IX. Experimental Results

Experiments were carried out over a metallic ground plane and in a real ground environment using reduced scale models at frequencies of 10 and 20 MHz. Monopole height was chosen as 1 meter or 0.0333λ and 0.0667λ respectively for both frequencies. Input impedance was measured by means of an impedance meter (HP 4291A) placing the test fixture in the input monopole antenna port under the ground plane in order to obtain the maximum accuracy. Using a piece of coaxial line always errors in the impedance translation are involved and the input impedance



(a) (b)

Fig. 27. (a) Top loaded monopole received power as a function of frequency and D/H. (b) Top loaded monopole received power as a function of frequency and D/H.

is not measured precisely. This is a delicate matter due to the low resistance values involved and the instrumentation accuracy in measuring them. Tuning systems are attached directly under the ground plane and the monopole antenna connection is very short. Tuning systems are made up of "T" type impedance match in a low pass version network. Two type of inductances were used, air core inductors and Q2 ferrite core inductors. In the first case low loss inductors are obtained with Q higher than 200 and in the second case Q obtained is around 30. Metallic ground plane is made up of aluminum sheets and the reference monopole is installed over the same ground plane at a distance of 5 meters. In this case wave propagation is performed over a very high conductivity medium practically ideal. 5 meter is a distance of 0.1667λ for 10 MHz and 0.3333λ for 20 MHz. It would be a distance of 50 and 100 meters at a real scale model of 1 MHz or at an intermediate distance between near and far field. Of course reactive near field is at lower distance for a monopole antenna. One meter monopole loaded with a 50 ohms resistance has been used as an electric field probe and a calibrated loop (ETS mod. 6509) as electric and magnetic probe. Received power is obtained by means of a spectrum analyzer (HP 8563E) were any possible interference is completely avoided and power is measured at the actual frequency with good accuracy. In any measured case, useful power to noise ratio or useful power to interference power is always more than 30 dB so to assure that the power measured is only the received power from the monopole model. During measurements received power and input impedance of the transmitting system is always under control. At the central frequency, input tuner impedance is maintained as close as possible to 50 ohms (VSWR lower than 1.1) so to guarantee the maximum transmitted power in each measured model and always the same value. This is very important during the antenna model efficiency or gain comparison. This comparison can be made directly in dB referred to the short monopole without top loading or to the quarter wave monopole, that can be used as reference. Absolute gain is more difficult to determine due to the reference probe calibration. Generally loop calibration is specified with an accuracy of ± 2 dB, much more than needed for precise measurements and at the same time absolute probe value depends strongly on the place were the probe is installed. Calculations according to measured values over metallic ground plane and with probes close to it, give a disagreement with certified values on more than 5 dB. Nevertheless knowing the inductor losses and the transmitted power and using Friis [6] link equation, quarter wave monopole has given a radiation efficiency close to 97 percent or very close to 5 dBi absolute gain. This is a very good standard reference for any other short antenna placed in the same place as the quarter wave monopole. Taking into account the best tuning of any short antenna and with transmitted power and input impedance under strict control, comparison can be considered adequate and very close to the actual gain and efficiency values. Fig. 26 shows input resistance and reactance values measured for a monopole antenna with different top loading and with $H/a = 80$ and $H/a = 13.33$, for 1 meter height. Top loading is made up as an eight star wire structure. It is interesting comparing the reactance results where almost no difference is seen for the higher top loading cases.

Fig. 27 gives the measured received power as a function of frequency close to 10 and 20 MHz. At 10 MHz $(H/\lambda = 0.0333)$ the received power increase for 1 meter diameter top loading was 5.5 dB while for the same loading the received power increase was 6 dB at 20 MHz $(H/\lambda = 0.0667)$.

Crossed Field Antenna (CFA) model has been made with the same height as the monopole model. Height is 1 meter, monopole diameter 75 millimeters and top load has 0.45 meters obtaining an $H/a = 13.333$ relationship. Its input impedance was measured as function of frequency or antenna height for

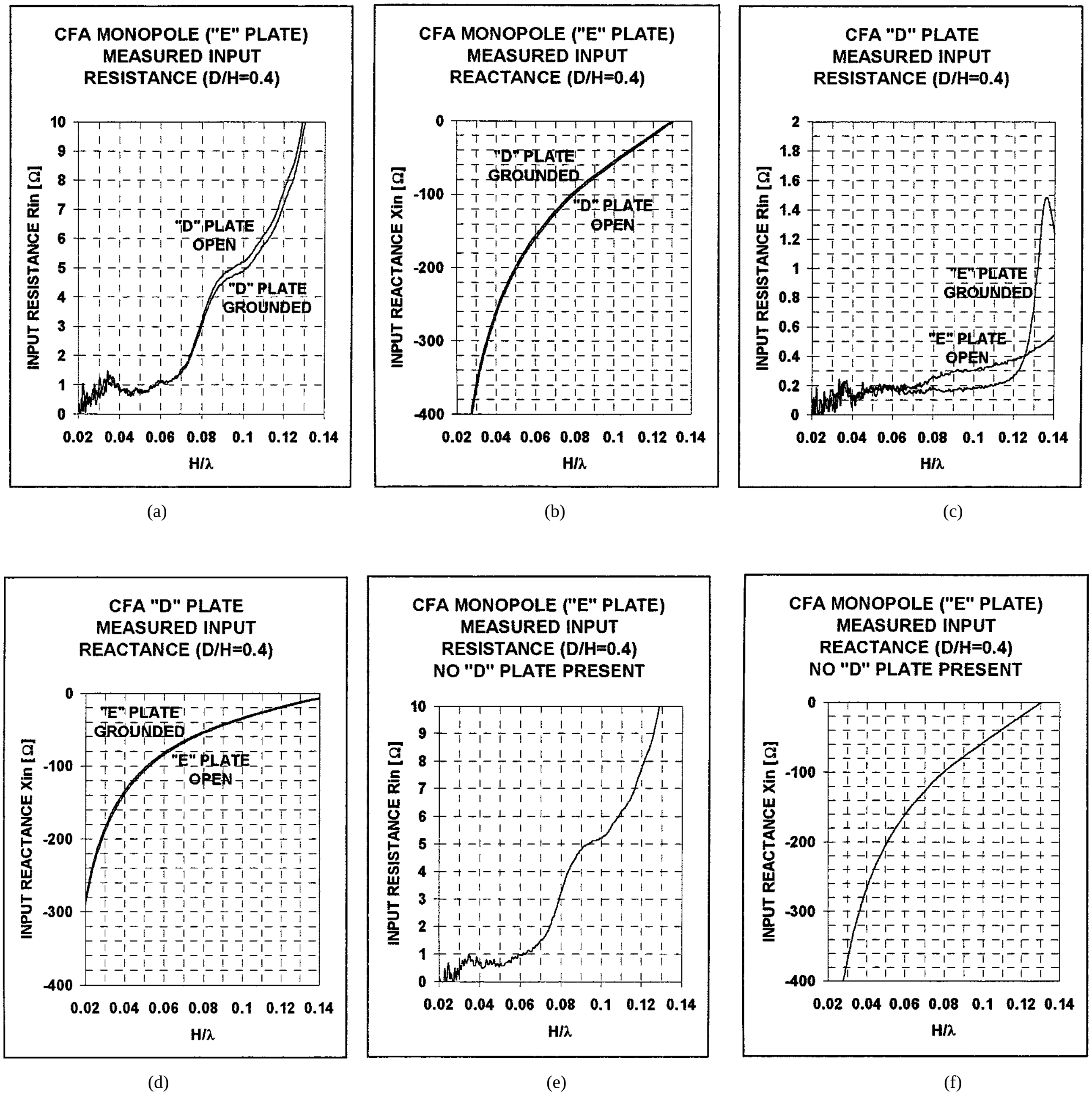


Fig. 28. (a) CFA monopole (E plate) measured input resistance as a function of H/λ. (b) CFA monopole (E plate) measured input reactance as a function of H/λ. (c) CFA D plate measured input resistance as a function of H/λ. (d) CFA D plate measured input reactance as a function of H/λ. (e) CFA monopole (E plate) measured input resistance as a function of H/λ (no D plate). (f) CFA monopole (E plate) measured input reactance as a function of H/λ (no D plate).

the E plate and D plate. At the same time input impedance for the E plate was measured with the D plate disconnected and connected to ground. Same measurements were made for the D plate with E plate disconnected and connected to ground. In this last case or E plate connected to ground, some interaction can be observed in the resistance values. Very small differences have been observed on the other measurements. Fig. 28 shows the input impedance measured for this antenna model.

This antenna was tuned with two "T" matching systems one for the E plate (monopole) and the other for the D plate and they were tuned one at a time charging the other port with 50 ohms at the tuning system input. After several operations due to both structure interaction the best tuning for both inputs was obtained. A 90 degree delay line precisely calibrated with the impedance meter was connected to the D plate and checked in order to get always 50 ohms input. Both input were connected to another "T" matching system and 50 ohms input for the entire system was obtained. Power received at 10 MHz and 20 MHz with the previous probe can be seen in Fig. 29 and compared with the short monopole without $(D/H = 0)$ and with loading $(D/H = 1)$. $(H/\lambda = 0.0333$ or $H/\lambda = 0.0667)$ are the corresponding heights at the measured frequencies.

Increase in receiving power was 2.8 dB compared to a short monopole $(H/a = 80)$ without any top loading at 10 MHz. The same measurement was made connecting the D plate to ground and the CFA monopole was retuned. An increase of 3.6 dB over

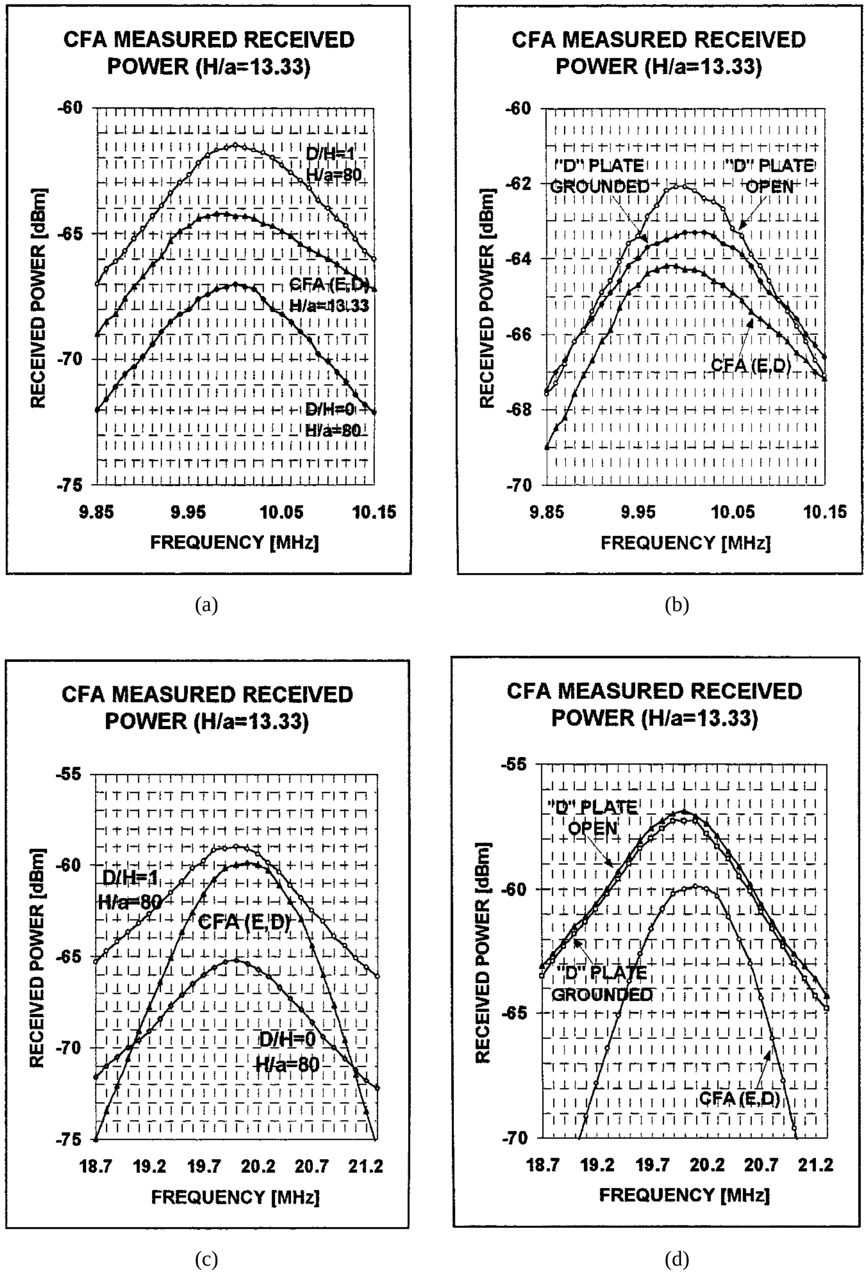
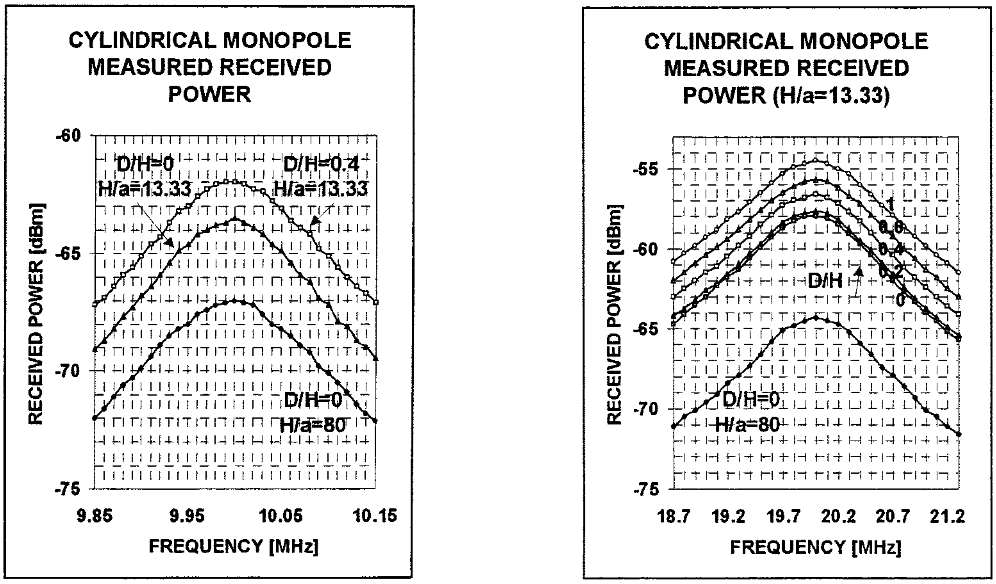


Fig. 29. (a) CFA measured received power compared with a top loaded monopole. (b) CFA measured received power (D plate open and grounded) as a function of f. (c) CFA measured received power compared with a top loaded monopole. (d) CFA measured received power (D plate open and grounded) as a function of f.

the short monopole was obtained. Nice surprise! Disconnecting the D plate and retuning the CFA monopole the receiving power increase was 4.9 dB!!. Fig. 29(b). The D plate was removed and the CFA monopole was retuned obtaining an increase of 5 dB over the short monopole perfectly tuned. This is a standard cylindrical monopole $(H/a = 13.33)$. The same measurements were carried out at 20 MHz obtaining an increase of 5.0 dB for the CFA antenna compared to the short monopole of the same height $(H/\lambda = 0.0667)$ but 1 dB less than a top loaded monopole $(D/H = 1)$ as can be seen in Fig. 29(c). With the D plate connected to ground and the CFA monopole retuned, the increase was 7.5 dB and with the D plate disconnected the increase was 7.8 dB.

In both cases 10 and 20 MHz ($H/\lambda = 0.0333$ and 0.0667) the CFA with both E and D plate excited, gave less received power in the receiving system or less transmitting gain. Removing the D plate the increase was 8.4 dB. It can be pointed out, connecting the D plate to ground less tuning systems are needed and this is equivalent to a gain increase as it was measured. Fig. 30(a) and (b) shows the received power for a cylindrical monopole $(H/a = 13.33)$ with different top loading. Similar results as in the previous case have been obtained at 10 and 20 MHz.

It seems that these increases in receiving power are excessive but they are due to the tuning systems inductance losses because the tuning systems have used the ferrite core inductors and any small increase in radiation resistance increases significantly the radiated power when system losses are involved. For this reason tuning inductors were replaced by air core inductors in order to get better efficiency in the short antennas and having closer results the the theoretical values.



(a) (b)

Fig. 30. (a) Top loaded cylindrical monopole received power as a function of frequency. (b) Top loaded cylindrical monopole received power as a function of frequency.

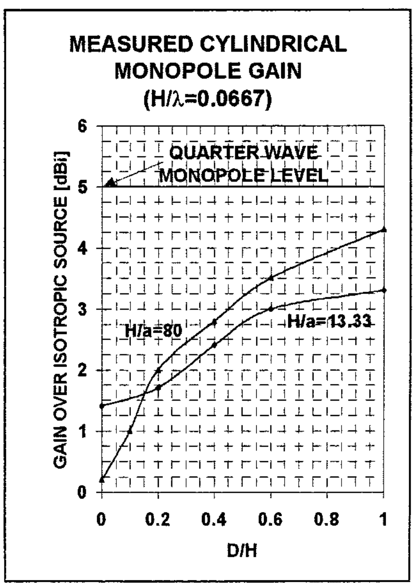


Fig. 31. Top loaded cylindrical monopole measured absolute gain over metallic ground plane.

New measurements were made at 20 MHz over metallic ground plane. In this case a quarter wave monopole was used due to shorter physical dimensions and both short monopoles ($H/a = 80$ and $H/a = 13.33$) with different top loading. Nevertheless, CFA was not measured again because its behavior determined by measurement is not as their inventors claim, (gain better than a quarter wavelength monopole or compared to a half wave monopole) and it can be replaced by a simple and more efficient loaded monopole, as was determined by measurements.

Fig. 31 shows the short monopole antenna ($H/a = 80$ and $H/a = 13.33$) absolute gain measured over metallic ground plane as a function of the top loading factor (D/H), using a quarter wave monopole as reference. In this case air inductors have been used to perform the measurements, in order to get results as close as possible to the theoretical predictions. Maximum gain improvement measured over metallic ground plane was 4.1 dB for a monopole $H/a = 80$ and $D/H = 1$. For a monopole $H/a = 13.33$ and $D/H = 1$ was 3.1 dB at a frequency of 20 MHz or $H = 0.0667\lambda$ in both cases compared to a short non loaded monopole $(H/a = 80)$ of the same height. These results are very close to the calculated predictions as it was seen previously.

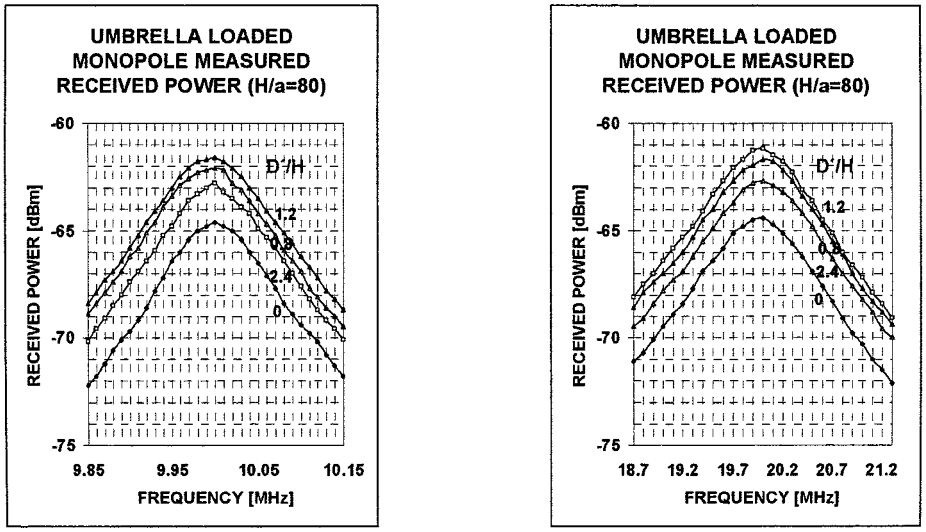
This example is very important because it shows the small difference in gain between short and quarter wave monopoles when losses are low, specially for top loaded monopoles.

Measurements on umbrella loading monopole have been carried out for the same height as in the previous monopoles ($H/a = 80$ for $H/\lambda = 0.0333$ and $H/\lambda = 0.0667$).

Increase in input resistance with loading is not significant as in the top loading case as is was predicted in the theoretical calculated cases, and this increase has a maximum. This behavior was determined theoretically and measurements indicate exactly the same. For this reason gain increase has a maximum depending on the antenna height. Fig. 32 shows the umbrella loading received power measurements at 10 and 20 MHz ($H/\lambda = 0.0333$ and $H/\lambda = 0.0667$).

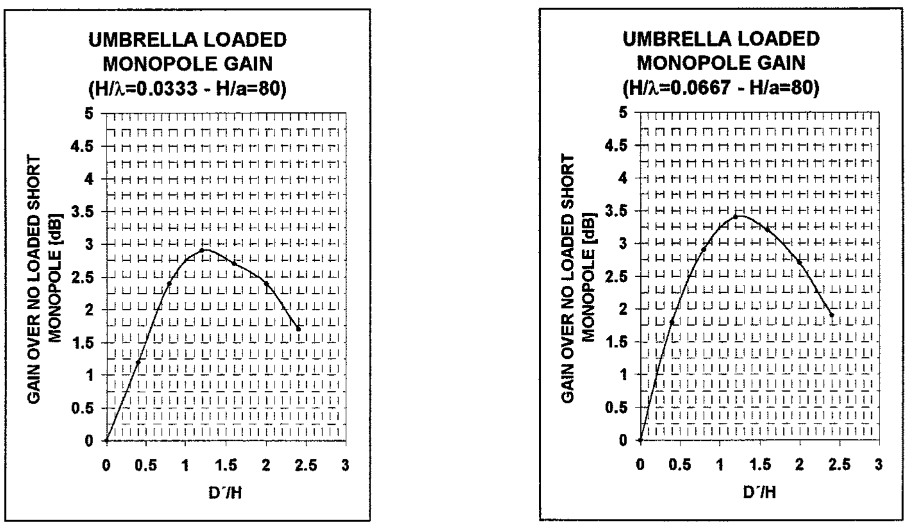
The resulting gain over short monopole without any top load is displayed as a function of loading factor value (D'/H) and it can be seen in Fig. 33. In this case the loading diameter is two times the isolated guy length for 45 degrees sloping angle. In these measurements, tuning systems were employing air core coils and for this reason for 20 MHz it can be compared with the previous cases measured over the same metallic ground plane and the absolute gain over a quarter wave monopole can be obtained. This absolute maximum gain is 3.6 dBi achieved for $D'/H = 1.2$ or $D'/\lambda = 0.08$, $H/a = 80$ and $H/\lambda = 0.0667$.

Top loaded monopoles were measured over real ground at 20 MHz. In this case quarter wave monopole was installed



(a) (b)

Fig. 32. (a) Umbrella loaded monopole received power as a function of frequency. (b) Umbrella loaded monopole received power as a function of frequency.



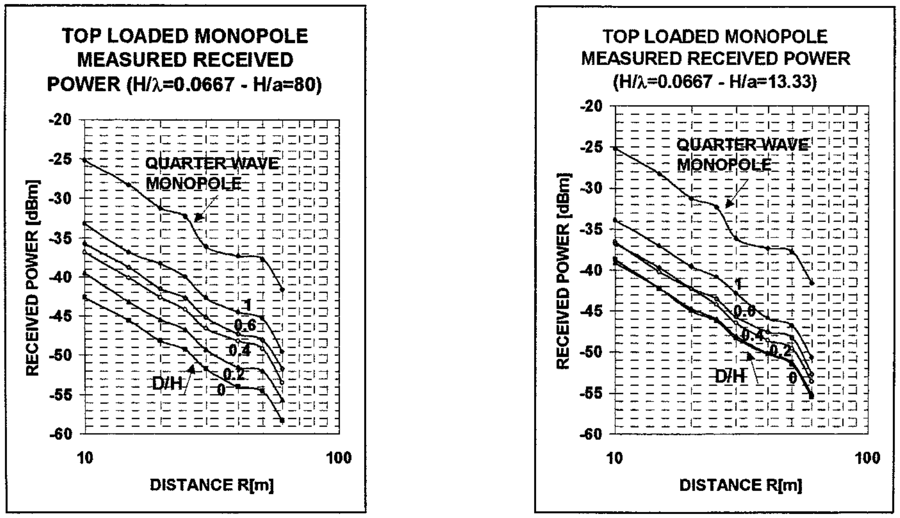
(a) (b)

Fig. 33. (a) Umbrella loaded monopole measured gain over non loaded short monopole. (b) Umbrella loaded monopole measured gain over non loaded short monopole.

over a square metallic ground plane placed over grassy terrain. Metallic ground plane radius was 1 meter approximately or 0.0667λ, quite small compared with the operating wavelength. This small ground plane will produce a reduce radiation efficiency for the quarterwave monopole but more reduction is expected for short monopole antennas. In this case a transmitter (ICOM 726A) with an automatic tuner was used. Output power was adjusted at 10 watts for every measurement and no reflected power was read in the reflectometer as each antenna model was perfectly tuned. Received power was measured with a spectrum analyzer (HP 8563E) and a 50 ohms loaded short monopole $(H/\lambda = 0.0667)$ was placed over a small aluminum sheet at several distances.

Distance was varied from 5 to 60 meters in order to simulate the surface wave propagation of MF AM band. The maximum distance corresponds to 4 wavelength or 1.2 kilometers for 1 MHz. Fig. 34 shows the corresponding received power for each monopole antenna. Unattenuate field strength slope for a perfectly conductive ground quarter wave monopole has been calculated and placed in order to determine the loss in dB in each monopole case. Even the quarterwave monopole has a loss due to the employed small ground plane and the automatic tuner losses, estimated in 1.5 dB or an absolute gain of 3.60 dBi (efficiency close to 70%).

Fig. 35 shows the absolute gain determined for these short antennas in this small metallic ground plane conditions where maximum gain for a loading factor $D/H = 1$ of a monopole $H/\lambda = 0.0667$ is around -4 dBi and smaller for lower loading. This figure presents perfectly well the imperfect ground plane effect on monopole antennas and specially on the shorter antennas where this effect is even more noticeable. For a quarter wave monopole with an input resistance close to 40 ohms efficiency was reduced to a 70% approximately but efficiency reduction is more important and close to 13.5% for a top loaded



(a) (b)

Fig. 34. (a) Top loaded monopole received power as a function of distance over real ground. (b) Top loaded monopole received power as a function of distance over real ground.

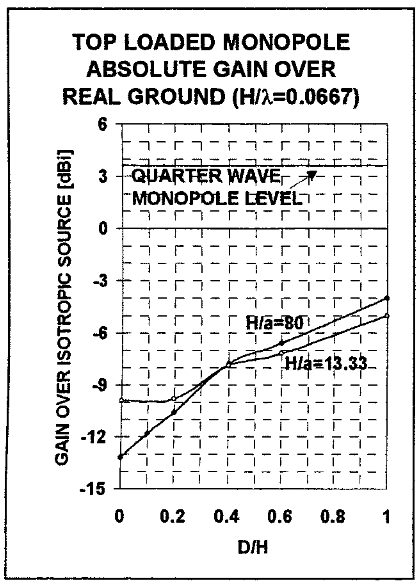


Fig. 35. Top loaded monopole measured absolute gain over real ground.

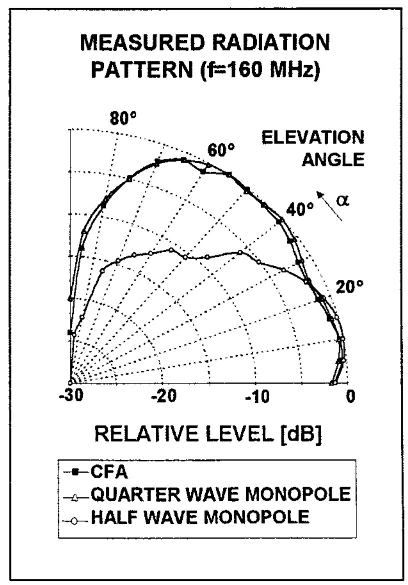


Fig. 36. Measured vertical radiation patterns.

monopole with 1 meter diameter hat ($D = 0.0667\lambda$, $H = 0.0667\lambda$, $D/H = 1$). This efficiency decrease is even more noticeable for no loaded monopole of the same height were the efficiency would be close to 1.6% $(D/H = 0\ H = 0.0667\lambda)$.

The only way to improve this behavior is making the metallic ground plane as big as possible and a minimum loss tuner. Several dB can be gained this way as it was shown previously over a metallic surface. Of course this is impossible in reality but extensive metallic ground plane under the radiating antenna is paramount. From all calculations performed and measurements, the top load is a simple and effective way to increase the short antenna gain even if directivity does not increase, but surface wave field strength can be improved significantly approaching the the quarter wave monopole gain.

Vertical radiation patterns of a quarter monopole and a half wave monopole models over a metallic ground plane in VHF region have been measured.

The CFA VHF model vertical radiation pattern has been measured in the same ground plane. CFA patterns is quite similar to quarter wave monopole or short monopole because the difference between them is insignificant. This comparison can be seen in Fig. 36. In these measurements maximum radiation is not at zero degree elevation due to ground plane edge effects but this effect modify the performance of any antenna. The important here is showing no "magical effects" in the CFA radiation behavior because this is similar to a short monopole as measurements indicate.

X. Conclusions

Different short antennas have been analyzed by calculations and in the model cases, where the better gain could be achieved, measurements over reduced models were performed.

It was determined by calculations and measurements the top loaded and umbrella loaded monopoles gains. This is not too far from a quarter wave monopole when almost perfect ground plane is used.

Mesurements over a CFA antenna show similar behavior like a cylindrical monopole of the same height and top load and for this reason cylindrical monopole is preferred to be used due to its simple tuning system. At the same time its measured radiation pattern gives the evidence of its directivity and gain. Like any short antenna its gain depends strongly on a perfect ground plane.

All the work performed in the past by a lot of technician, engineers and scientist is perfectly founded and radiated energy depends on very efficent antenna. Short antennas can be improved substantially by means of a perfect ground plane and top loading, but they never can be more efficient or outperform an optimum monopole or dipole close to half a wavelength.

For this reason for a high power installation were maximum field strength over the earth and optimum antifading properties are needed, traditional tall antenna, monopoles or dipoles, are still the best choice by a responsible engineer.

APPENDIX
MEASURED ABSOLUTE GAIN

Over metallic ground plane:

$$\frac{\mathbf{H}}{\lambda} = 0.0667 \quad \mathbf{f} = 20 \text{ MHz}$$

Reference quarter wave monopole:

$$\mathbf{G} = 5 \text{ dBi} \quad \eta = 97\%$$

Short monopole:

$$\frac{\mathbf{H}}{\mathbf{a}} = 80 \quad \frac{\mathbf{D}}{\mathbf{H}} = 1 \quad \mathbf{G} = 4.3 \text{ dBi} \quad \eta = 90\%$$
$$\frac{\mathbf{H}}{\mathbf{a}} = 80 \quad \frac{\mathbf{D}}{\mathbf{H}} = 0 \quad \mathbf{G} = 0.2 \text{ dBi} \quad \eta = 35\%$$

Short monopole:

$$\frac{\mathbf{H}}{\mathbf{a}} = 13.33 \quad \frac{\mathbf{D}}{\mathbf{H}} = 1 \quad \mathbf{G} = 3.3 \text{ dBi} \quad \eta = 71\%$$

CFA:

$$\frac{\mathbf{H}}{\mathbf{a}} = 13.33 \quad \frac{\mathbf{D}}{\mathbf{H}} = 0.4 \quad \mathbf{G} = 2.5 \text{ dBi} \quad \eta = 59\%$$

Over real ground:

$$\frac{\mathbf{H}}{\lambda} = 0.0667 \quad \mathbf{f} = 20 \text{ MHz} \quad \mathbf{GP} \text{ radius} = 0.0667\lambda$$

Reference quarter wave monopole:

$$\mathbf{G} = 2.6 \text{ dBi} \quad \eta = 51.3\%$$

Short monopole:

$$\frac{\mathbf{H}}{\mathbf{a}} = 80 \quad \frac{\mathbf{D}}{\mathbf{H}} = 1 \quad \mathbf{G} = -5 \text{ dBi} \quad \eta = 10.5\%$$
$$\frac{\mathbf{H}}{\mathbf{a}} = 80 \quad \frac{\mathbf{D}}{\mathbf{H}} = 0 \quad \mathbf{G} = -14 \text{ dBi} \quad \eta = 1.3\%$$

Short monopole:

$$\frac{\mathbf{H}}{\mathbf{a}} = 13.33 \quad \frac{\mathbf{D}}{\mathbf{H}} = 1 \quad \mathbf{G} = -6 \text{ dBi} \quad \eta = 8.4\%$$

CFA:

$$\frac{\mathbf{H}}{\mathbf{a}} = 13.33 \quad \frac{\mathbf{D}}{\mathbf{H}} = 0.4 \quad \mathbf{G} = -8 \text{ dBi} \quad \eta = 5.3\%$$

ACKNOWLEDGMENT

The author wishes to thank Mr. J. Skora for his assistance in model measurements and working on personal computer in order to convert thousand of data into curves, a more simple method to get a quick view of the antenna impedance and efficiency behavior, D. Schweitzer who was supporting the initial measurements and the mechanical model work and all the CITEFA Antenna and Propagation Division Personnel for their permanent help and support.

The author also wishes to thank A. Djordjevic and B. Kolundjza for their permanent support and advice.

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