NDB ANTENNAS

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1. **Introduction:**

An efficient antenna for a Non-Directional Radiobeacon would require an effective height of between 600 and 220ft, depending upon the operating frequency in the range of 190 to 535kHz.

This could only by achieved by using an extremely tall structure that is neither economical nor practical, especially for low power installations, sited close to airport runways. The effective heights of antennas in common use vary between 20 and 100ft. This technical note discusses the disadvantages of these electrically short antennas, methods of improving their performance characteristics and the trade-off in antenna selection for a particular installation.

2.1 **Antenna Equivalent Circuit:**

The equivalent circuit of an electrically short antenna is shown in ***Figure 2.1***

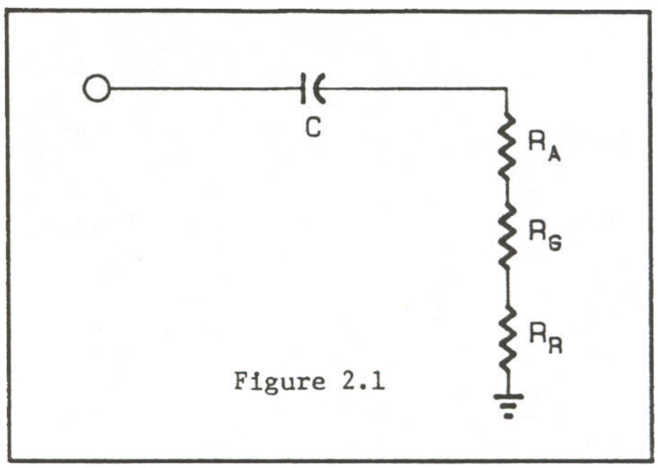


Figure 2.1

where:

- **C** is the capacity of the antenna which is determined by the length and position of the radiating elements.
- $\mathbf{R_A}$ is the equivalent series loss resistance of the antenna structure.
- $\mathbf{R_G}$ is the equivalent series loss resistance of the ground plane.
- $\mathbf{R_R}$ is the radiation resistance of the antenna that is the equivalent coupled component of the impedance of free space.

2.2 Antenna Efficiency:

The power actually radiated from the antenna is equal to $I_A^2 \times R_R$ whereas the dissipation in R_A and R_G represents wasted power. When the antenna is electrically short, R_R is usually very small compared to both R_G and the reactance X_C of capacitance C. The usual technique employed in matching the transmitter to the antenna system is to series resonate X_C using a tunable loading coil.

The overall equivalent circuit is then shown in ***Figure 2.2:***

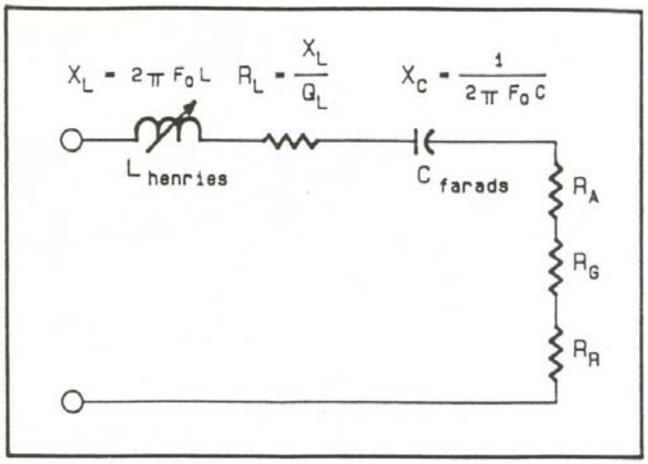


Figure 2.2

where:

- **X_L** is the inductive reactance of the loading coil, and is numerically equal to XC.

  i.e. $L = \dfrac{1}{(2\pi F_o)^2 C}$

- **R_L** is the loss resistance of the loading coil in ohms.
- **F_O** is the operating carrier frequency in Hz.
- **Q_L** is the Q factor of the loading coil.

The radiation resistance can be calculated from the expression:

$$R_R = 160\ \pi^2 \left(\frac{h_e}{\lambda}\right)^2$$ ***Equation 1***

where h_e is the effective height of the antenna (not the physical height, see paragraph 3.1), and λ is the wavelength at the operating radio frequency, F_O.

The antenna radiation efficiency is then given by the expression:

$$\text{Efficiency } N = \frac{R_R}{R_R + R_L + R_A + R_G} \qquad \textbf{\textit{Equation 2}}$$

The power radiated at the carrier frequency (P_r) is equal to P_{in} x N where P_{in} is the carrier power output of the transmitter.

But as radiated power is equal to $I_A^2 \times R_R$ then antenna current $I_A = \sqrt{\frac{P_r}{R_R}}$

and the peak antenna voltage for the carrier is:

$$V_A \text{ peak (carrier)} = \sqrt{2} \times I_A \times X_C \text{ volts peak.}$$

At 100% modulation this voltage would be doubled if sideband attenuation is ignored.
From the above expressions it is clear that antenna efficiency will be improved by:

1. Making the effective height and hence R_R as large as possible.

2. Making the antenna capacitance as high as possible to reduce the value of X_C and X_L which, in turn, will reduce R_L and rf voltage on the radiation elements.

3. Keeping the antenna loss resistance R_A as small as possible by minimizing contact resistance and dielectric losses in the insulators.

4. Choosing an operating frequency which is as high as possible in the band 190 to 535KHz. (This may not result in an increase in signal strength at a remote point, however, due to an increase in the propagation path attenuation at the higher frequency).

5. Providing an adequate ground plane to minimize R_G. This is a very important component of the antenna system to which insufficient attention is often afforded in the antenna design. Methods of estimating ground plane resistance are given in paragraph 3.3.

Economic considerations are usually the overriding factor in selecting an antenna for a particular site. High power transmitters are usually paired with large efficient antennas whereas low power NDB's utilize less efficient structures. Typical values of antenna efficiency versus input power are shown in paragraph 6.3 of *Attachment C to Part 1 of ICAO Annex 10* attached.

2.2 Antenna Bandwidth:

Being a high Q, resonant circuit, the antenna acts as a bandpass filter with a finite bandwidth that can significantly attenuate the sidebands of the radiated signal.

This bandwidth may be obtained from the expression:

$$BW = \frac{F_o}{Q_A} = \frac{F_o (R_L + R_A + R_R + R_G)}{X_C} \qquad \textbf{\textit{Equation 3}}$$

where F_O is the operating carrier frequency in Hz.

The sideband attenuation A_S is given by:

$$A_S \text{ (dB)} = 20 \log_{10} \frac{1}{1 + Q_A{}^2 \, x \left(\frac{2F_M}{F_O} \right)^2} \text{ dB} \qquad \textit{\textbf{Equation 4}}$$

where F_M = modulation frequency in Hz

and

$$Q_A = \frac{X_C}{R_L + R_A + R_R + R_G} \qquad \textbf{Equation 5}$$

This sideband attenuation is an undesirable effect which reduces the modulation depth of the transmitted signal below the optimum level of 90 – 95%. Users employ various methods of overcoming this problem including:

1. Choice of antenna with a greater capacity and effective height. This is by far the best method but is often uneconomical, especially for low power installations.

2. Changing tone modulation frequency from 1020Hz to 400Hz. This method can significantly increase the radiated modulation depth, but the detected audio signal can be less intelligible in a high atmosphere noise background.

3. Broadbanding of antenna circuits by connecting a load resistor in series with the equivalent circuits of figure 2. This technique, of course, reduces the antenna efficiency and is only considered to be of value where the transmitter had previously provided an adequate range whilst operating below its rated output power level.

4. When operating with conventional amplitude modulated signal it is emphatically neither useful nor desirable to overmodulate the signal at the transmitter output, in an attempt to improve the radiated modulation depth. This action will simply result in excessive stress and distortion in the power amplifier of the transmitter and will actually reduce the mean level of the radiated carrier signal when the modulation is present.

In summary, a certain amount of sideband attenuation is unavoidable with a short antenna and, like antenna efficiency, must be considered as a trade off against the cost of the installation. It should be realized, that directional accuracy of the radio compass is not dependent upon the modulation, being solely a function of the signal-to-noise ratio of the carrier signal.

Low power installations seldom radiate signals with high levels of modulation depth but in most cases this does not significantly reduce the useful operating range of the installation. This subject is discussed in Attachment C to Part 1 of ICAO Annex 10 in which figure C.19 attached shows typical radiated modulation depths for various antenna systems and operating frequencies.

2.3 Antenna Input Impedance:

When the circuit in ***Figure 2*** is tuned to resonance, the input impedance of the antenna system at the carrier frequency is purely resistive and equal to:

$$Z_O = R_L + R_A + R_R + R_G \text{ ohms}$$

This usually transformed in a tapped matching transformer to a suitable terminating impedance for the transmitter of 50 or 72 ohms.

Because of the high Q of the antenna circuit, however, the input impedance Z_S at the sideband frequencies is higher than that at F_O and is given by the expression:

$$Z_S = Z_O \left[1 + 2 jQ_A x\left(\frac{F_M}{F_O}\right)\right] \qquad \textbf{\textit{Equation 6}}$$

It is important to recognize the effect of this impedance difference upon the transmitter output stage. The RF currents supplied at the sideband frequencies, for a given voltage modulation depth setting, will be less than they would have been when working into a purely resistive 50 ohm load. This means that if the voltage and current waveforms at the transmitter output are examined using an oscilloscope, the voltage waveform will exhibit a greater modulation depth than the current waveform. The current waveform, on the other hand, will exhibit a modulation depth which is equal to that of the actual radiated signal. It is interesting to note that this situation may be reversed if the feeder cable connecting the transmitter to the antenna approaches and electrical length of $\lambda/4$.

This line then acts as a quarter wave transformer by its characteristic impedance at the carrier frequency F_o but mismatched at the sideband frequencies $F_o \pm F_M$. Thus, at the input end of this transmission line, the higher impedance at the sideband frequencies will be transformed to an impedance which is lower than the characteristic impedance of the cable. Where this is the case, the current waveform at the transmitter output wold exhibit a greater modulation depth that the voltage waveform. <u>When adjusting the transmitter circuits, care should be exercised to ensure that neither the voltage nor the current waveform is overmodulated at the transmitter output amplifier.</u>

Some antenna tuning units utilize the loading coil to parallel resonate the antenna capacity. The technique produces decreased impedance at the sideband frequencies and at the carrier frequency when detuned. Often the loading coil forms part of a π network used to achieve impedance matching without the use of a matching transformer. This technique further compounds the effect of lowering the input impedance at the sideband frequencies. The performance of the parallel resonance circuits is otherwise very similar to the series resonate type but being less popular, it is not covered in detail in this report. <u>The use of parallel resonant tuners is not recommended with NAUTEL transmitters.</u>

3. Estimating Antenna Parameters:

In order to select and NDB antenna for a particular installation, it is often necessary to estimate its characteristics. The following data may be used for this purpose.

3.1 Effective Height:

The effectiveness of an NDB antenna is determined by the product of the antenna current and the vertical distance through which it flows. Considering the example of a base insulated vertical mast radiator of height h without to loading, fed with a current I at the base as shown in figure 3.1(a). The current flowing in the mast will taper to zero at the top such that the average mast current is equal to I/2. Hence, its effectiveness as a current radiator is proportional to I/2 x h.

Another way of expressing this product is I x h_e where h_e = the effective antenna height = h/2.

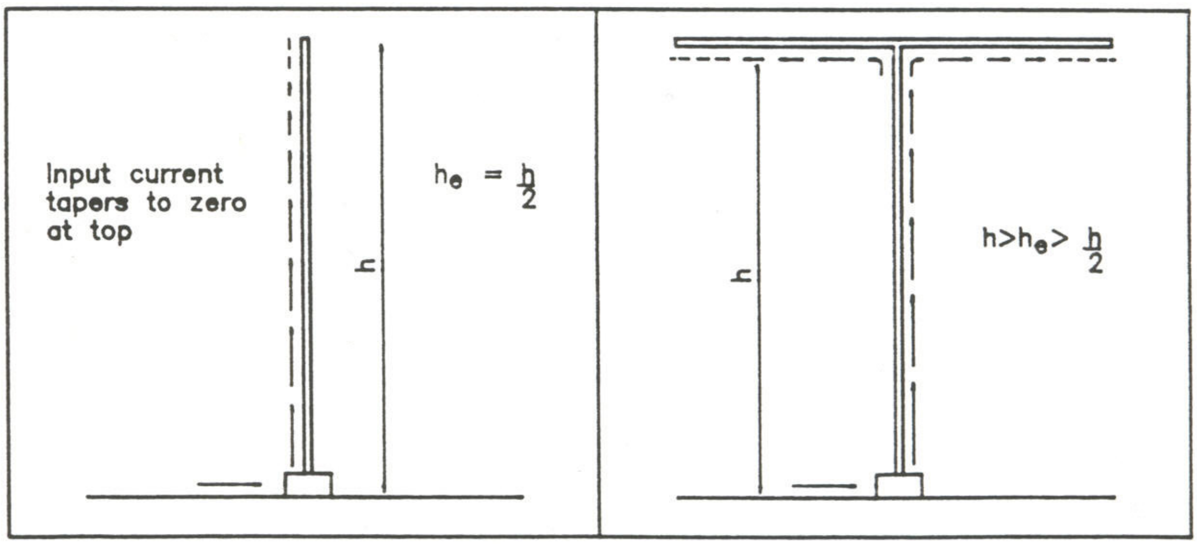


Figure 3.1 (a) **Figure 3.1 (b)**

Considering a second example, shown in ***Figure 3.1 (b),*** of a base insulated, top loaded vertical radiator, it can be seen that the current then tapers to zero at the extremities of the capacity top hat. The average current flowing in the vertical section is clearly increased above that in the first example; hence, the effective height h_e is said to be increased.

In quantitative terms, the increase in h_e is dependent upon the relative values of the capacities of the mast and the top hat, such that the effective height, h_e is given by:

$$H_e = h\left[1 - \tfrac{1}{2}\left(\frac{C_M}{C_M + C_H}\right)\right] \qquad \textit{Equation 7}$$

Where:

- **h** = actual height
- $\mathbf{C_M}$ = capacity of vertical section
- $\mathbf{C_H}$ = capacity of horizontal section

(*See paragraph 3.2 to estimate the capacity of antenna sections*).

Top loading is often achieved by the use of guys which are electrically connected to the top of the tower with insulators placed part way down their length. It is obvious that if these insulators are positioned close to the ground the top capacity will be increased but the average height of the top hat will be reduced. As a compromise, the insulators are usually placed at a vertical height above ground level equal to 4/7 of the height of the tower.

A third example may be considered in which the mast is grounded and an insulator is placed between the top of the mast and the capacity top hat. With this arrangement, the loading coil must also be positioned at the top of the mast. The total input current I then flows through the full height of the mast therefore $h_e = h$.

As shown in equations (1) and (2), the radiation resistance $R_R \propto h_e^2$ and efficiency $N \propto R_R$ (approximately).

Hence, efficiency $N \propto h_e^2$ (approximately).

It is, therefore, important to obtain as much effective height as possible which, in turn, is achieved by positioning the loading coil as high as possible on the antennas structure.

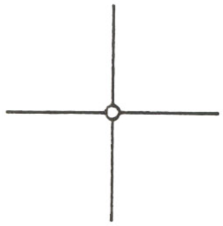
3.2 Antenna Capacity:

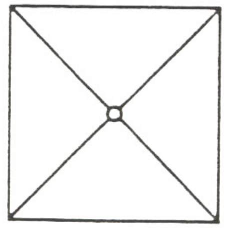
Increasing the antenna capacity increases the system bandwidth and efficiency by reducing the necessary value of loading coil inductance together with its series loss resistance.

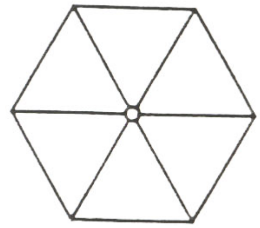
Antenna capacities can be roughly estimated using the following data:

Antenna	Approximate Capacitance Allowance
Base-insulated vertical lattice tower	5 – 6pF per foot
Whip or other than vertical radiator	4pF per foot
Single horizontal or vertical wire	3pF per foot

Where more than a single wire is used, the effective capacity per foot is reduced by mutual coupling between the wires therefore they should be positioned as far apart as possible. Considering the plan view of the top loading umbrella perpendicular to the mast, the following capacitance can be estimated for the total length of the radiating elements.







When top loading guys are used, the capacity per foot is reduced because they do not lie in a single plane and the coupling between the guys are vertical radiator is increased. Where four top loading guys at 45° to the mast are used, a capacity of 1.5pF per foot may be estimated.

3.3 Ground Loss Resistance

Calculation of the effective series loss resistance of particular ground mat configuration is rather complex and is not covered in detail here. Instead, examples of some commonly used arrangements for monopole radiators using sets of radial conductors equal in length to the monopole height, placed symmetrically in the ground around the antenna are shown. These may be used as a guide to estimate the ground loss resistance for similar configurations. Although the ground plane has no effect upon the horizontal radiation pattern, a somewhat unsymmetrical ground plane is best suited for T antennas.

Frequency	Qty of Radials	Ground Conductivity - Permittivity			
		.03 – 40	.01 – 30	.003 – 22	.001 – 15
190kHz	30	0.37	0.65	1.63	4.34
190kHz	60	0.26	0.50	1.28	3.35
300kHz	30	0.51	0.87	1.95	4.82
300kHz	60	0.33	0.66	1.58	3.86
400kHz	30	0.70	1.07	2.22	5.07
400kHz	60	0.47	0.81	1.81	4.13
535kHz	30	1.01	1.47	2.68	5.40
535kHz	60	0.71	1.12	2.22	4.51

It can be seen that the ground loss resistance is highly dependent on the type of ground in the immediate vicinity of the antenna.

3.4 Antenna Loss Resistance

This resistance is usually quite small and can be ignored in all but the most efficient antennas. A figure of R_A = 0.1 ohm could be used as a rough approximation.

3.5 Sample Calculations of Antenna Characteristics

Consider a base insulated, 150ft lattice tower with umbrella top loading consisting of four radials each 50ft long. Its ground plane uses 60 x 150ft radials. The antenna is fed from a 1kW transmitter at 300kHz modulated at 1020Hz. Estimate the antenna reactance, effective height, radiation resistance, ground loss resistance, efficiency, bandwidth, sideband attenuation and peak voltage (assume a coil Q of 300). Ground conductivity – permittivity is .001 – 15..

3.5.1 Antenna Capacities:

Mast capacity C_M = 6 x 150 = 900pF

Top hat capacity C_H = 4 x 50 x 1.5 = 300pF

Total capacity = 1200pF

Antenna reactance $X_C = -j\left(\frac{1}{2\pi F_O C}\right) = -j\left(\frac{1}{2\pi x 300 x 10^3 x 1200 x 10^{-12}}\right)$

X_C = -j 442 ohms

The loading coil reactance must be +j 442. Assuming of coil Q factor of 300 the coil loss resistance

$R_L = \frac{442}{300} = 1.47$ ohm

3.5.2 Radiation Resistance

From ***Equation 7***

Effective height he = h $\left[1 - \frac{1}{2}\left(\frac{C}{C_M + C_H}\right)\right]$

$= 150\left[1 - \frac{1}{2}\left(\frac{900}{900 + 300}\right)\right]$

h_e = 93.75ft

wavelength at 300kHz $= \frac{300 \times 10^6 \text{ m}}{300 \times 10^3} = 1000\text{m}$

= 3280ft

from ***Equation 1***

Radiation resistance $R_R = 160 \times \pi^2 \times \left(\frac{93.75}{3280}\right)^2$ = 1.29 0hms

3.5.3 Ground Loss Resistance:

From table in paragraph 3.3 the ground loss resistance will be 3.86 ohms.

3.5.4 Antenna Efficiency:

From ***Equation 2***

$$\text{Antenna Efficiency N} = \frac{R_R}{R_R + R_L + R_A + R_G} \times 100\%$$

$$= \frac{1.29 \times 100\%}{1.29 + 1.47 + 0.1 + 3.86} = 19.1\%$$

Hence, radiated carrier power = $1\text{kW} \times \frac{19.1}{100} = 191\text{W}$

The radiated power = $I_A^2 \times R_R$ = 191W

Hence, antenna current $I_A = \sqrt{\frac{191}{1.29}}$ = 12.16 amps rms (carrier only)

3.5.5 Antenna Bandwidth:

From equation ***Equation 5***

$$\text{The Q of the antenna system} = \frac{X_C}{R_L + R_A + R_R + R_G}$$

$$Q_A = \frac{442}{1.47 + 0.1 + 1.29 + 3.86} = 65.38$$

from equation ***Equation 3***

Antenna BW $\frac{F_O}{Q_A} = \frac{300kHz}{65.38}$ = 4.58kHz

From equation ***Equation 4***

$$A_S = 20 \log \left[\frac{1}{1+Q_A{}^2\left(\frac{2F_M}{F_O}\right)^2} \right] \text{ dB}$$

Sideband Attenuation

$$= 20 \log \left[\frac{1}{1+65.38^2\left(\frac{2040}{300x10^3}\right)^2} \right] \text{dB}$$

= 1.56 dB
or mod depth is reduced by 16.51%

i.e. if mod depth were 95% at the input, the radiated mod depth would be 95 x .0.835 = 79.3%.

Hence, effective modulation component of antenna current = I_A x .793.

3.5.6 Peak Antenna Voltage:

At the peak of the modulation envelope the antenna voltage is given by

Vp = (I_A + .793 I_A) √2 X_C
= 1.793 x 12.16 x √2 x 442 = 13,628 peak