CHAPTER 3

VLF COMMUNICATION EQUIPMENT

Navy VLF Communication System involves both transmit and receive functions. The physical location of the equipment groups with respect to operational function dictates the equipment complements and their complexity. For the transmit function, a complex equipment configuration is required at a self-sustaining shore-based facility. The receive-function equipment is small and compact, as necessitated by its shipboard environment.

3.1 VLF RADIO TRANSMITTING STATION EQUIPMENT

Information to be transmitted from a VLF radio transmitting station is received either via landline links from a Navy Communication Center located relatively close to the station site, or via microwave link when separation between the two facilities is significant or via VHF. The information to be transmitted is processed and formatted at the Communication Center. Due to the similarity in methods and procedures used in processing and formatting information for transmission via HF Communication Systems, refer to Naval Communication Station Design, NAVELEX 0101,102, which describes preparation of messages for radio transmission.

Transmitting equipment for radio telegraph and radio teletype (TTY) communications consists of the principal signal generation equipment housed in a transmitter building, antenna matching components located in a separate helix house, and an antenna array as shown in figure 3-1. Additional operating and support equipment are also located in or near the transmitter building. The transmitter is capable of interrupted continuous Wave (ICW) or frequency shift keying (FSK) operation. The equipment consists of frequency-generators and keyers, intermediate power amplifiers (IPA), power amplifiers (PA), power supplies, amplifier and antenna tuning units, cooling equipment, dummy loads, and power generation and distribution equipment. Phase tracking receiver, time and frequency equipment.

Most transmitter components are provided in duplicate. Each of the frequency generators and FSK units drives either of two RF Amplifiers (PRE IPA and/or IPA units). Each IPA drives one to four PA units. Series operation of all PA's provides RF output at transmitter maximum rated power, while transmitting with one to three PA's enables certain of the inactive units be switched to comprise an identical single PA transmitter which can be operated into a dummy load for test.

The helix-room equipment matches the impedance between the transmitter and the antenna. Additional matching network components provide for individual or combined operation of the PA's at any frequency within the specified range.

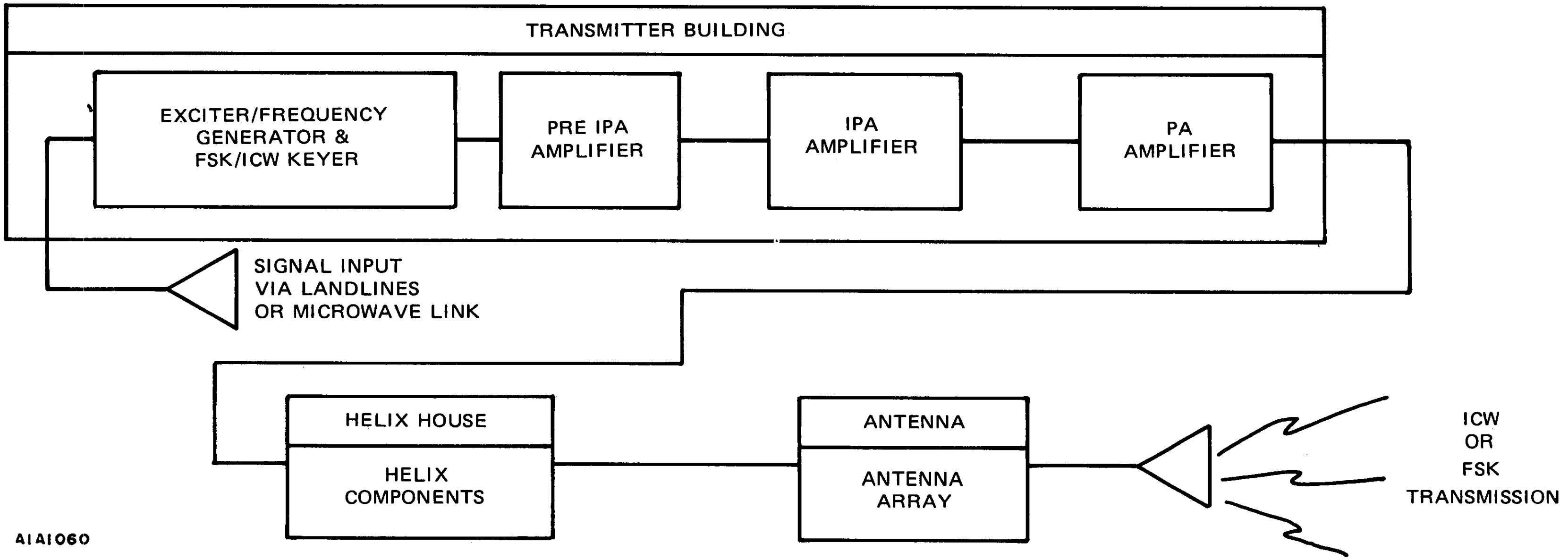


Figure 3-1. VLF Radio Transmitting Station Simplified Configuration Block Diagram

One equipment not shown, but vitally important to operation, is the Transmitter Control Console. This centrally-located unit in the transmitter building is comprised of a desk console and a bay of consoles that provide:

- A summary of transmitter operating conditions
- Primary transmitter control and tuning
- Control of transmitter keying, selection of active frequency generator and IPA
- Control and monitor of IPA operation
- Control and monitor of PA operation
- Overall control of the transmitter
- Control for antenna tuning and loading functions
- Antenna-monitoring circuits.

Also housed in or near the transmitter building is the AC distribution unit that provides switching for control power and two high-voltage systems. A watercooling system, including storage tanks and pumps to dissipate heat generated in the IPA's and PA's, is also contained in the transmitter building, although air cooling of IPA's and PA's are used at some sites.

3.1.1 VLF Transmitting Equipment Functions

The functional description of the transmitting set is based on the block diagram in figure 3-2.

The frequency-generator and FSK equipment provide the transmitter carrier frequencies with ICW or FSK keying. Local and remote keying circuits are provided. The frequency-generator uses a frequency-synthesizer to produce the transmitter frequency for both ICW and FSK modes.

The frequency synthesizer derives both the mark and space frequencies from a very stable Cesium Beam clock oscillator. The keyer then chooses which FSK frequency to transmit according to the keying pulses.

The keying circuits in the synthesizer receive the mark or space keying pulse and store it in one bit flip-flop memory for some $\tau < 20$ msec until the next allowable transmitter transition from mark to space (or space to mark).

An allowable transition occurs only when the very stable synthesized mark and space frequencies are at the same relative points in phase, which is chosen to be when both mark and space frequencies are having a positive (or negative) -going zero-crossing.

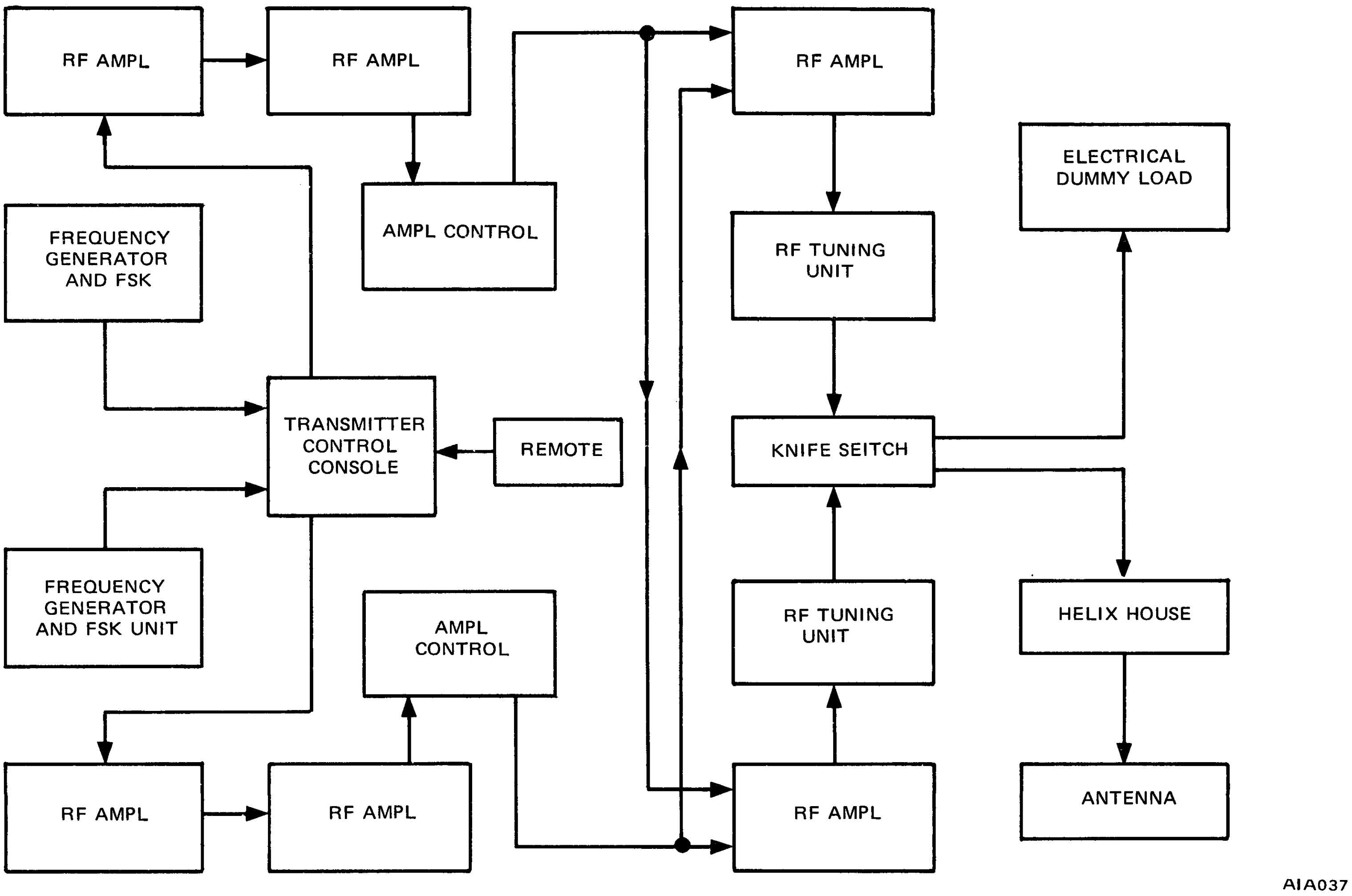


Figure 3-2. RF Signal Flow, Block Diagram (Typical)

The reason for this constrained transition is due to the high "Q" of the antenna. The typical "Q" of a VLF antenna is greater than 200. Far more energy is stored in the antenna than is radiated or consumed in any one cycle. The energy is stored alternately as electrostatic energy in the top hat and ground system, and as electromagnetic energy in the helix (tuning) coils. Since a VLF antenna operates near its voltage limitation, it will not tolerate an abrupt change in voltage or current without initiating arcing, breakdown, or other problems. The synthesized mark and space frequencies are separated by 50 Hz and so coincidence of the same relative point in phase occurs only each 20 msec. Transition from mark to space (or vice versa) at this time puts no unusual stress on the antenna.

The keyed RF signal is amplified in the keyer section of the exciter. The RF output is routed through frequency generation/selection circuits to the PRE IPA (if present) for amplification. During transmission, the PRE IPA output is applied to the IPA, which further amplifies the signal. A resistive dummy load located on top of the IPA cabinet is used to load the IPA during isolated testing of the IPA. During normal transmission, the IPA output is coupled to the PA through an isolation capacitor and grid tuning and bias variometer. The signal is amplified in the selected number of PA's. The outputs from the PA's are combined to obtain the required transmitter output power.

The signal from each PA is applied through the plate tank circuit in the RF tuning unit to the PA knife switch. The PA output tuning components tune the amplifier to resonance at the transmitter operating frequency. The RF output switch unit applies the single PA output or to the antenna matching and loading circuits. The signal then passes through the antenna resonating circuits in the helix house. The resonating circuits generally consist of coupling and tuning variometers and an antenna helix coil from which the RF signal is applied to the antenna downlead, although details of the helix house matching circuit may differ from site to site.

3.1.2 Transmitting Equipment Unit Descriptions

This additional descriptive material for certain units, presented to provide a better understanding of their complexity or operational interface, highlights typical equipment functional application rather than a specific station configuration. Specific equipment quantities are determined by station operational criteria.

Certain VLF transmitters have similar subunit designs, thus the AN/FRT-67 transmitter of Northwest Cape Australia, the AN/FRT-64 of Lualualei, Hawaii, and the AN/FRT-73 of Summit, C. F. have a major portion of interchangeable components. Also, certain units employed in these transmitters are similar to, or the same as, units found in the AN/FRT-31 transmitter at Cutler, Maine.

a. Intermediate Power Amplifier (IPA) Group. The IPA group (see figure 3-3) provides RF drive for the PA's. The IPA group uses untuned, linear RF-amplifier stages to amplify the output of one frequency generator and keyer unit to the level necessary to drive the PA's. The IPA group operates at the required output frequency. At least two IPA groups are furnished, one is used for standby or test operation while

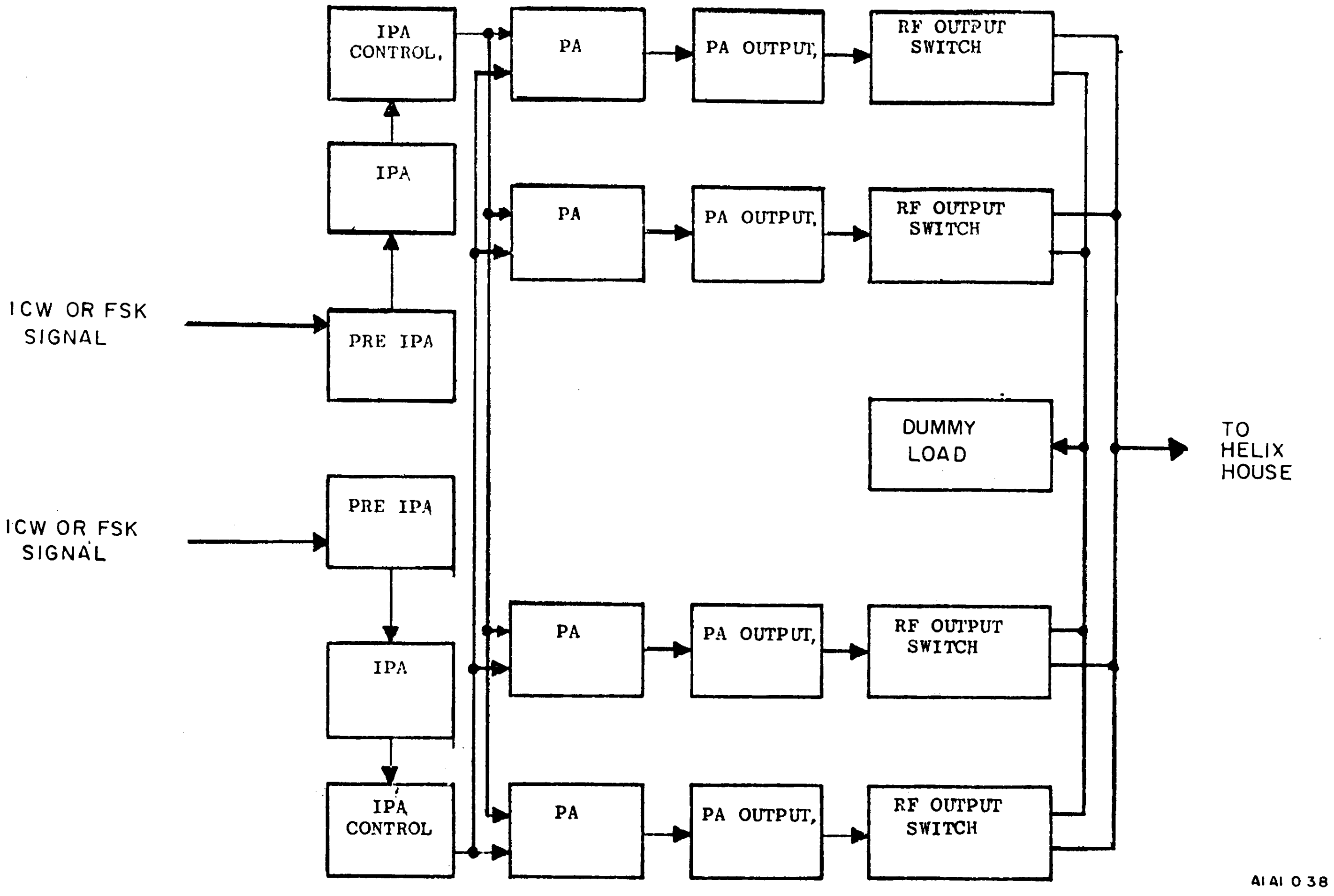


Figure 3-3. Typical IPA and PA Block Diagram (IPA Transmitter Shown)

the other is active. Each IPA group consists of at least two RF amplifiers, two power supplies, two dummy loads, controls, and power distribution and cooling equipment.

(1) RF Amplifier (PRE IPA). The PRE IPA (not present in all VLF transmitters) receives the output of either frequency generator and provides preliminary signal amplification. The output of the PRE IPA is applied to the IPA. The PRE IPA consists of three untuned linear, push-pull RF amplifier stages and associated 4-kV plate, bias and filament power supplies. This unit contains control switches, a dummy load permitting local amplifier test operation, status indicator lamps, and meters to monitor cathode-current and plate-voltage. Control circuits provide local amplifier control with the output fed to its resistive load. Normally, the amplifier is controlled from the master console.

(2) IPA RF Amplifier. The IPA receives the PRE IPA (or frequency generator in some VF transmitters) output, amplifies the signal, and drives the number of selected power amplifiers. The IPA is a single-stage untuned, linear, push-pull RF circuit using water and forced-air cooled tubes. Front-panel cathode-current and plate-voltage meters are provided. The IPA output is applied to its associated dummy load for test operations.

(3) Amplifier Control (IPA Control). The IPA control contains the IPA output transformer, low-pass filter, and IPA group control circuits. The IPA control routes the IPA output to the IPA dummy load or to the PA's selector switches and control relays provide local, master, or automatic control of the IPA group. Normally, control is from the console equipment. Indicator lamps and meters provide status indications of the equipment.

(4) IPA Power Supply. The power supply provides plate and bias voltage for the IPA.

(5) IPA Filter. The IPA power equipment furnishes primary AC power to the IPA power supply and filters the IPA power supply DC output.

b. Power Amplifier Group. The PA group minimally consists of one to four PA's, associated tuning units and power supplies, a dummy load, and output switch unit, and antenna loading circuits (figure 3-3). Transmitter full power output is achieved with all PA's in combined operation. This equipment is the final RF amplifier stage.

(1) RF Amplifier PA Units. The PA amplifies the IPA output to the desired transmitter power level. The one to four PA units supplied can be operated individually or in combination, and are capable of providing specified RF output levels, depending on the IPA output level and the number of PA's in use. The PA unit also contains a grid tuning variometer which couples the input to the amplifier. The variometer contains an electrical frequency control unit coupled to the variometer tuning drive. A remote-indicating synchro-loop provides relative variometer-position indication.

(2) RF Tuning Unit (PA Output Unit). Each PA is supplied with an output tuning circuit to tune the PA plate circuit. The tuning circuit consists of a bank of variable oil-filled capacitors and a fixed toroidal tank inductor. The capacitors are motor-driven and controlled from the console; remote position-indicating-synchros provide relative capacity-indication for tuning. The capacitor ranges are determined by the operating requirements of each station.

(3) Electrical Frequency Control Units. These units enable rapid automatic tuning of the transmitter and matching networks components to preset frequencies (in the VLF transmitters so equipped). The electrical frequency control units are mechanically linked and located on or near each of the motor-driven amplifier and antenna tuning components. The automatic preset frequency-selector units can be set so that the motor-driven tuning components can later be repositioned to the preset resonance. Units generally contain a cam for each preset frequency; microswitches on these cams control the tuning motors of the mechanically-connected variable components which actuate the preset tuning sequence when activated. An electrical clutch facilitates manually setting the cam to a new position.

(4) Output Switching Unit. The unit contains switches for isolating, testing, and activating the PA output RF feed lines. This network may, at certain sites, contain a TEE network or a PI network for matching the PA RF output circuits to the antenna and tuning system. The TEE matching network contains two tapped coils in series between them. The network is in the output RF line leading to the helix house, while the PI network contains a series coil between two shunt capacitors. The RF switches provide output switching for each PA. Switches on the PA Control unit control the motors that operate the RF switches in the RF switching unit. The knife switches connect the output of the related PA to either a dummy load or an RF bus.

(5) Amplifier-Filter, PA Filter and Fault Amplifier. This unit provides filtering and fault protection for the PA plate power supply and contains a high voltage isolation relay, filter choke, plate fupply filter capacitors, and a PA fault amplifier. The fault amplifier in the unit uses a thyratron-controlled ignitron tube to short-circuit the power supply if an arc occurs in an amplifier tube.

(6) PA Plate Power Supply. This unit provides plate power for the PA tubes. Input power is furnished by the plate transformers and voltage regulator.

(7) Plate Voltage PA Regulator. The PA plate voltage regulator may be of the automatic step type or of the induction type and adjusts the input voltage to the PA plate transformers. High-speed circuit breakers protect the 4160 VAC power to the input side of the regulators. The normal output voltage is controlled automatically and also manually from the master console.

(8) PA Plate Transformer Unit. This unit supplies power to the PA plate rectifier.

(9) Rectifier Switching. This unit connects PA rectifier output to the appropriate power amplifiers.

c. Electrical Dummy Load. The dummy load (see figure 3-3) provides a matched load for operation/test of a single PA. The dummy load generally consists of a series-resonant network, current sensing transformer, water-cooled resistive load, ground switch, and cooling equipment.

d. Helix Room Equipment. The helix room equipment (figure 3-4) generally consists of antenna loading, coupling, and tuning circuits. The helix house matching components generally consist of (from the antenna) helix, variometer (variable inductor), shunt variometer, but other sites use direct series link coupling from the antenna series variometers to the PA tank circuits. The network is adjustable to accept the transmitter output from one or several PA's.

e. Transmitter Control Consoles. The consoles, centrally located in the middle of the transmitter equipment room, consist of at least several consoles in a semi-circle around the operator's console. This central location enables the console operator to observe and monitor individual front panels of equipment cabinets located around the room perimeter. The control consoles in front of the operator's console consolidate the controls and instruments necessary to operate the transmitter. The number of control consoles required varies according to operational criteria and station configuration.

f. Automatic Carrier Cut-Off. Some VLF sites use systems which provide limited fault correction. Antennas in thunderstorm regions and antennas operated near voltage limitation are frequently subjected to static discharge and/or lightning strokes. The arc may be sustained by FSK transmission since there is not enough time between cycle peaks for the air to deionize. (With ICW an arc caused by static or lightning extinguishes at key-up.) Antenna system arcing causes the PA plate (and cathode) current to rise until the tube overloads actuate to take the transmitter off the air, throwing the plate AC circuit breaker. Restoral time for transmitter may be lost. The carrier cut-off system is to remove the transmitter carrier before the long duration overload circuitry actuates and to automatically restore it after a much shorter duration to minimize information flow interruption. One circuit as Yosami senses the rise in PA tube cathode current and then operates the ICW key-up function in the keyer. This in turn interrupts the carrier input to the IPA and PA for an interval set at about 100 msec; 100 msec is long enough to extinguish an arc. At the most, only 2 teletype characters are lost, and rebroadcast of a message will normally not be required. If the fault was not caused by such an extinguishable arc, then the cathode current continues to rise until it fires the crowbar.

3.1.3 Transmitting Antennas

Transmitting antennas at Naval VLF Radio Transmitting Stations are large physical structures with multiple towers 200 to 500 meters high. Because VLF antennas are usually short in terms of wavelength, antenna efficiency is an important consideration; transmitting antennas must be as large as possible to increase efficiency and system bandwidth. Because of the high transmitter powers required and resultant high antenna voltages, transmitting antenna size must be large to maximize antenna power handling capacity.

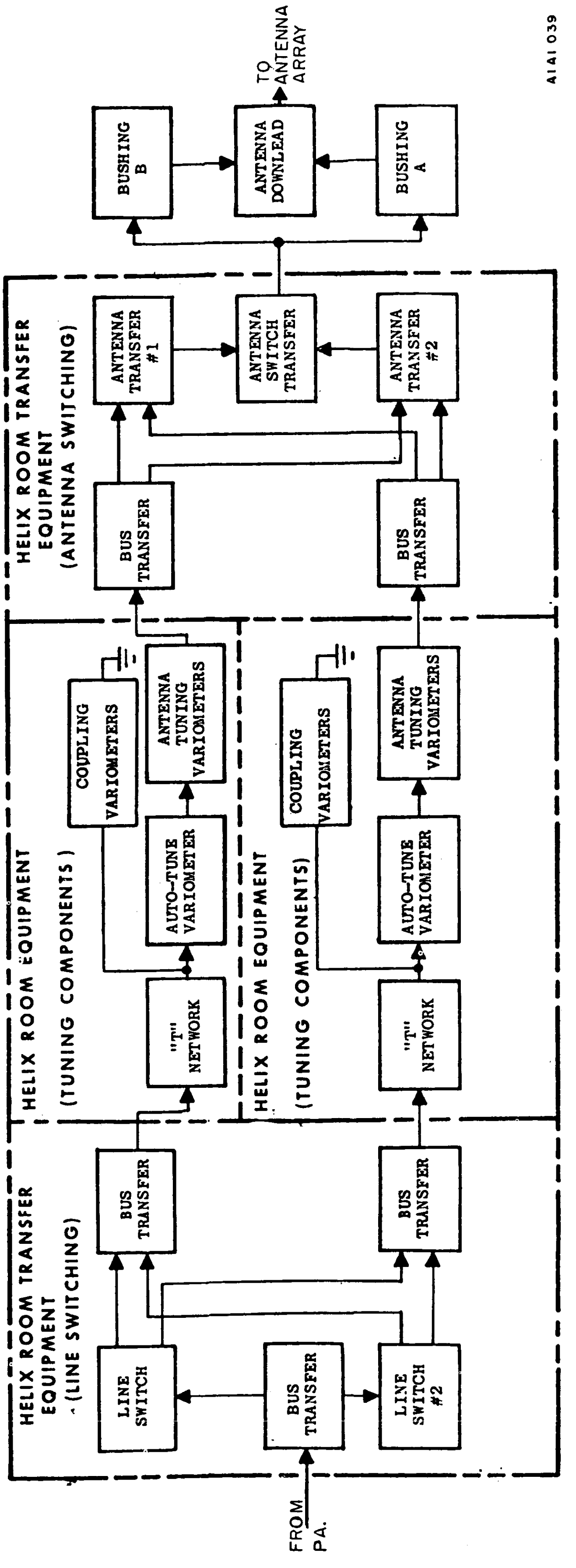


Figure 3-4. Helix Room Equipment, Functional Block Diagram for AN/FRT-67 Transmitter

a. Antenna Types. The most common type of VLF transmitting antenna is the vertical tower with an extensive flat top for capacitive loading and copper ground system to reduce ground losses. The flat-top array and ground radial systems require a large land area. This need for large land areas results in antenna configurations that are tower-supported types on flat, level terrain, and antenna arrays which adapt to natural valley or mountainous land areas. Representative antenna configurations are shown in figures 3-5 through 3-8. Note that the Trideco antenna (figure 3-7) is a modification of the Goliath antenna (figure 3-6). Variations of these basic antennas are used at the seven VLF transmitting stations. At Jim Creek, Washington, the natural canyon configuration is used; Cutler, Maine uses two parallel trideco antennas which are normally operated in parallel, but each of which may be operated singly (non-simultaneously). The latest modification at the Annapolis station combines radial panels and a portion of the original antenna parallel-wire top-hat. Some of the significant antenna-configuration features are reviewed below.

(1) Jim Creek, Washington. A valley-type antenna was adapted to this location. The valley floor is about 700 feet (210 meters) above sea-level, flanked on the north by 3200-foot (980 meter) Wheeler Mountain and on the south by 3000-foot (920 meter) Blue Mountain. The antenna consists of 10 zig-zag catenaries supported on short towers near the top of the mountain ridges (see figure 3-9). Each half of the antenna is connected to its own tuning helix so that each half of the antenna may be operated independently if desired. This arrangement, although operationally desirable, has the disadvantage of requiring two tuning helixes without the normal advantage obtained from dual tuning points.

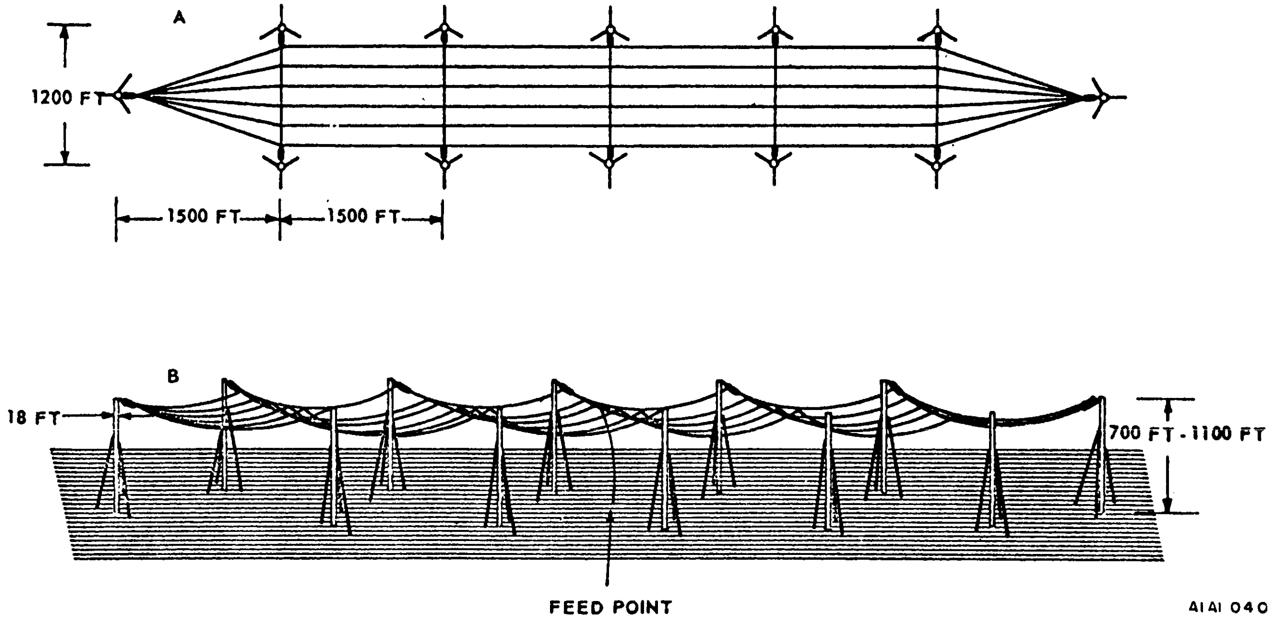


Figure 3-5. Triatic Type Antenna

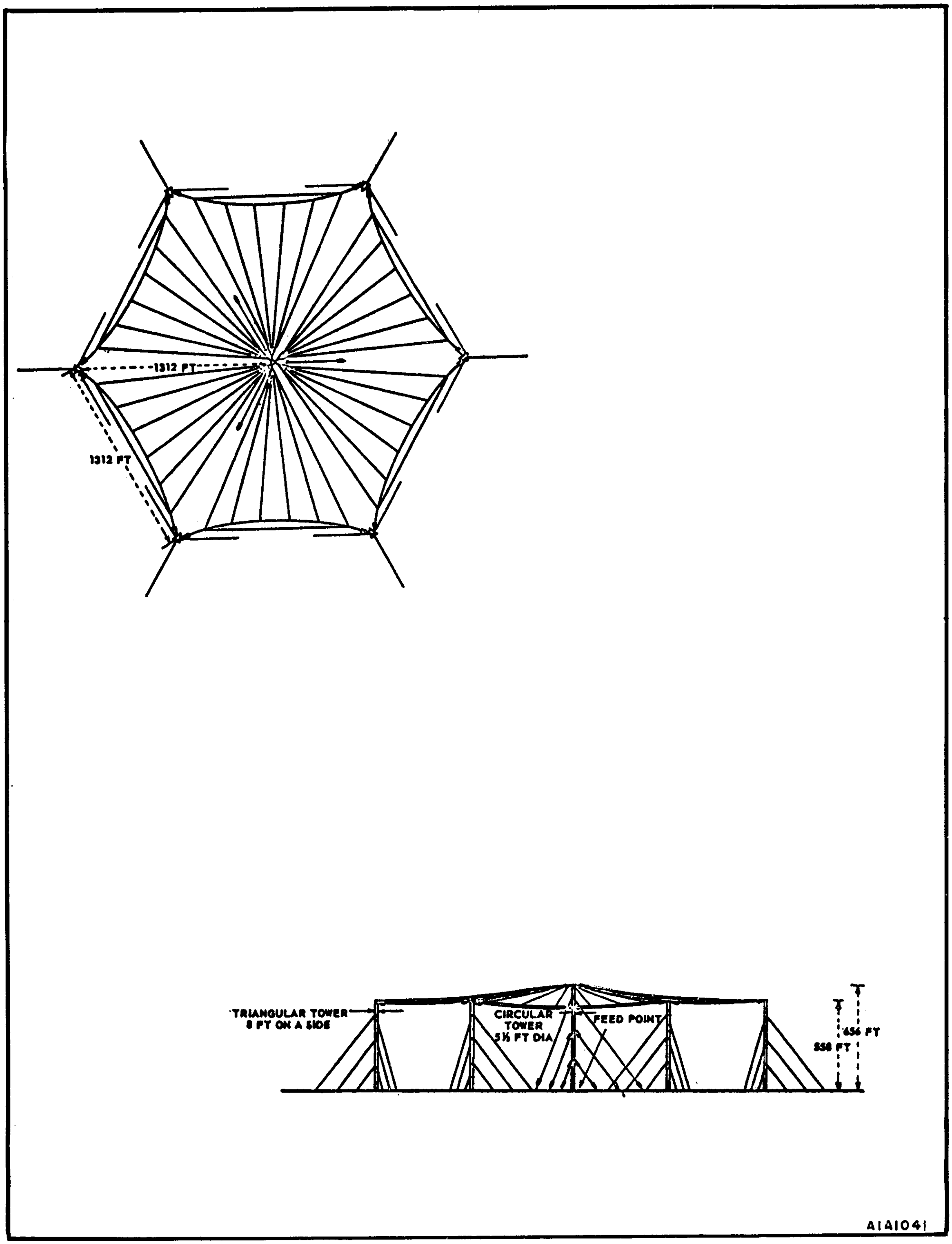


Figure 3-6. Goliath Type Antenna

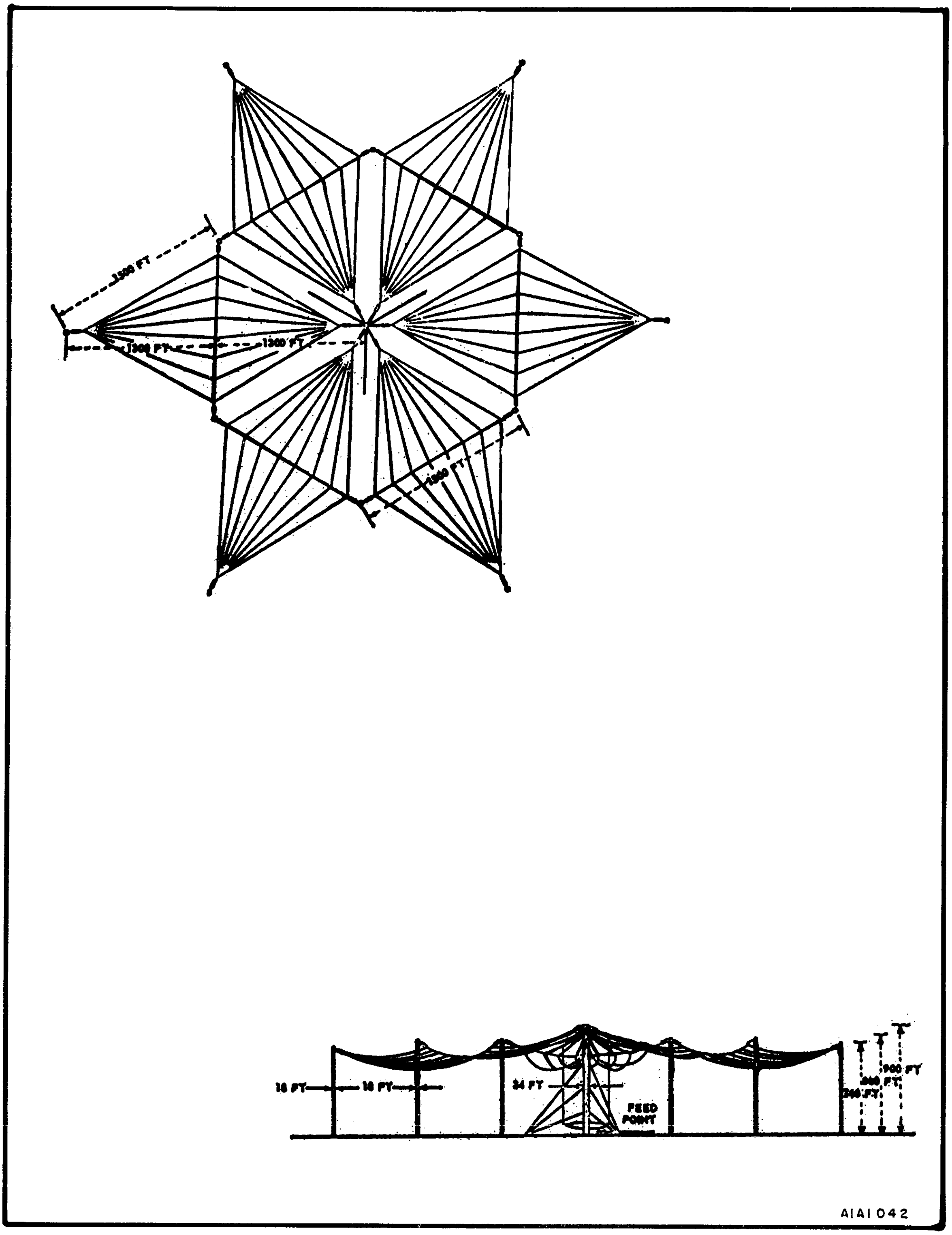


Figure 3-7. Trideco Type Antenna

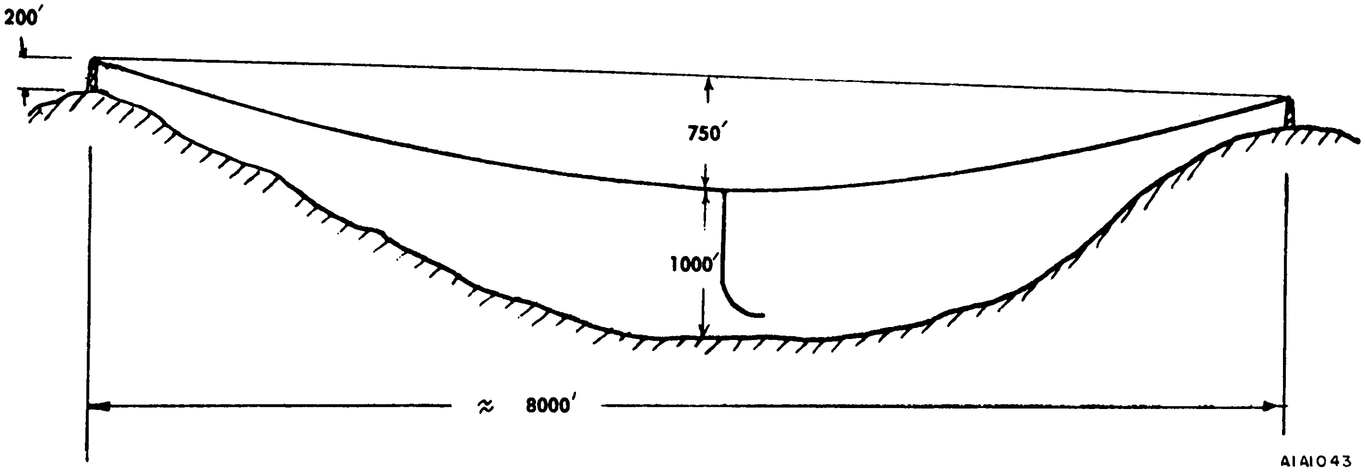


Figure 3-8. Natural Canyon-Type Antenna

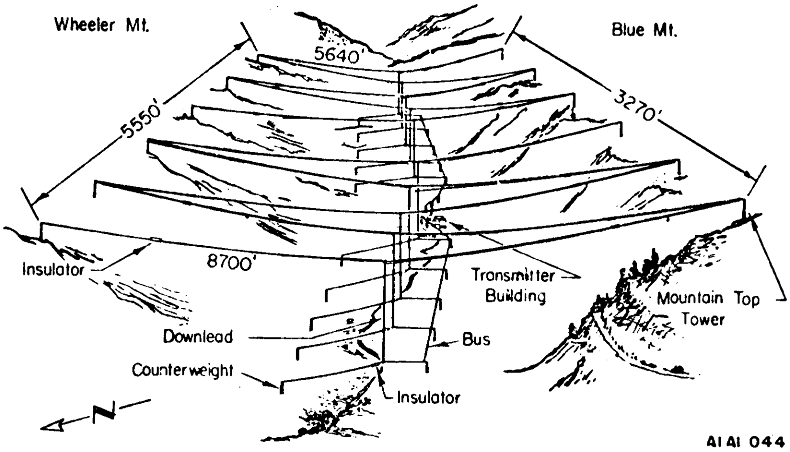


Figure 3-9. Jim Creek Antenna, Pictorial View

(2) Cutler, Maine. This facility has dual antennas, each composed of 13 towers arranged in a six-point star pattern, each star covering one square mile of ground. The 26 towers, ranging in height from 800 feet at the perimeters to 980 feet for the center towers, create a forest of steel frameworks silhouetted against the sky. The complete transmitting facility, including the ground plane which consists of 2500 miles of AWG 6 copper wire extending beyond the tower perimeter (3070-foot radius) to the peninsula's water edge and greater than 200 sea anchors, covers more than 2000 acres.

The antenna system is composed of two identical (north and south) trideco arrays, occupying an entire peninsula. The general layout of the arrays is shown in figure 3-10. Each array is essentially a base-fed monopole with a top hat of six diamond-shaped panels arranged symmetrically around the monopole. The six down-leads are interconnected at a helix house at the center-tower base. Midway between the array center-towers is the transmitter building. The two arrays are parallel-fed by a single transmitter utilizing coaxial cable to each helix house. A very elaborate radial ground system is used. The northern geographic location also necessitated inclusion of features in the antenna-structure design to prevent damage from heavy icing. Means are provided for relieving ice loading tension by counterweights, and for applying 50-hertz power to each array top hat in turn for deicing.

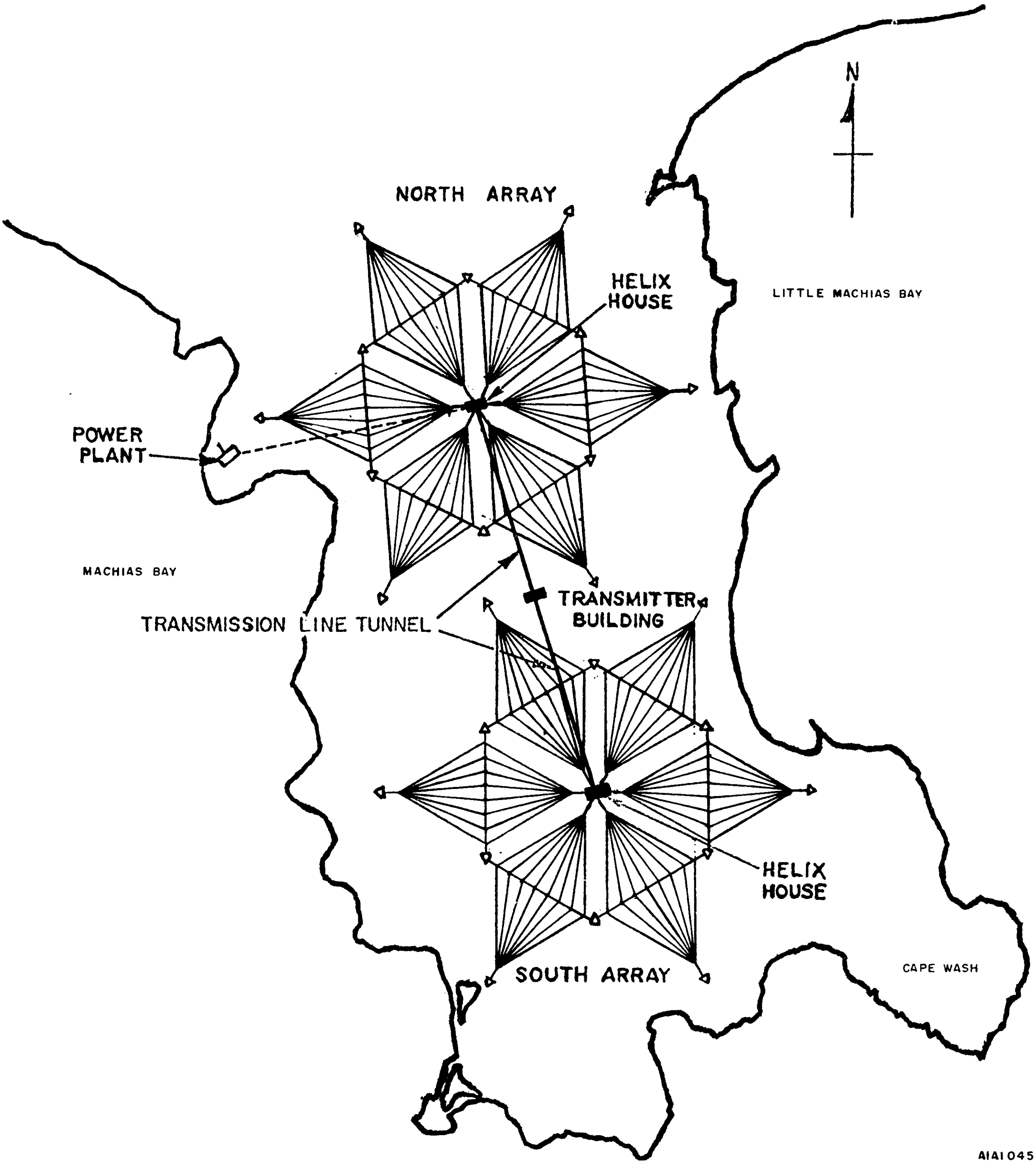


Figure 3-10. Cutler, Maine Antenna-Installation, Plan View

(3) Annapolis, Maryland. This antenna has been modified many times since initial installation. The most recent, completed in 1971, consists of a 1200-foot tower isolated from around and fed at the 300-, 600-, and 900-foot levels, and an elaborate top-hat. The top-hat configuration uses a triatic array in conjunction with a slightly modified Goliath configuration (refer to figure 3-11). The modified Goliath section is composed of three panels in 120° sectors. Use of discrete top-hat sectors provides a means for dividing and lowering panels in each sector for maintenance.

The base of the 1200-foot tower is isolated electrically from the ground, and this tower requires AC power to operate the tower lights. For smaller antennas, an isolation transformer is used to supply AC power for tower lighting, but for large installation, especially those using extremely high voltages (250 kV) such as this one, a motor-generator set with a dielectric shaft has been developed. The motor is at ground potential with a porcelain outer cylinder, a dielectric shaft coupled to the generator on the tower. Thus, the generator is isolated from ground and at the potential of the antenna. The generator output-wires provide power to the lights and the tower elevator.

(4) Balboa, Canal Zone. The antenna illustrated in figure 3-12 is a basic triatic antenna with minor dimensional difference in tower height and tower separations.

(5) Lualualei, Hawaii. The original antenna, which was similar to the triatic configuration at Balboa, Canal Zone, has been replaced by two 1500-foot radially top loaded (12 radials each) tower arrays which may be operated singly or in parallel. One of the two original helix houses and the original transmitter building are used with the new tower array (see figure 3-13).

(6) Northwest Cape, Australia. The antenna illustrated in figure 3-14 is a trideco antenna with six discrete diamond shaped top hat panels. The transmitter building contains two helix rooms that may be switched to the helix roof bushings, which feed the junctions of six individual 4-wire cage leads on the roof of the building. These 4-wire cage leads are joined to each individual top hat panels 8-wire down lead fan. Each top hat panel may be lowered to the ground for repair or maintenance and the transmitter is capable of operation with a 5-panel configuration.

(7) Yosami, Japan. This is a classic triatic configuration suspended from 8 insulated towers. All 8 towers are the original 810 foot (250 meter) towers which are electrically insulated from ground. Voltages induced from tower to ground are about 20 percent of the top hat voltage. The top hat was replaced in 1951 due to bomb damage to the original top hat which operated from 1929 to 1945. From each of two 100-foot feed towers near the transmitter and helix building, 8 wires rise up to the first triatic and then run the length of the top hat. These 16 element wires terminate on the last triatic. In 1964 the antenna was double-ended by adding a tuning network to ground at the last triatic, which improved radiation efficiency to 23 percent at 17.4 kHz. There is an elaborate "crows-foot" counterpoise 10 feet above the ground under the top hat and for 500 meters beyond in every direction to reduce near field losses. This is in turn connected to an elaborate ground connection scheme. (See figure 3-15.)

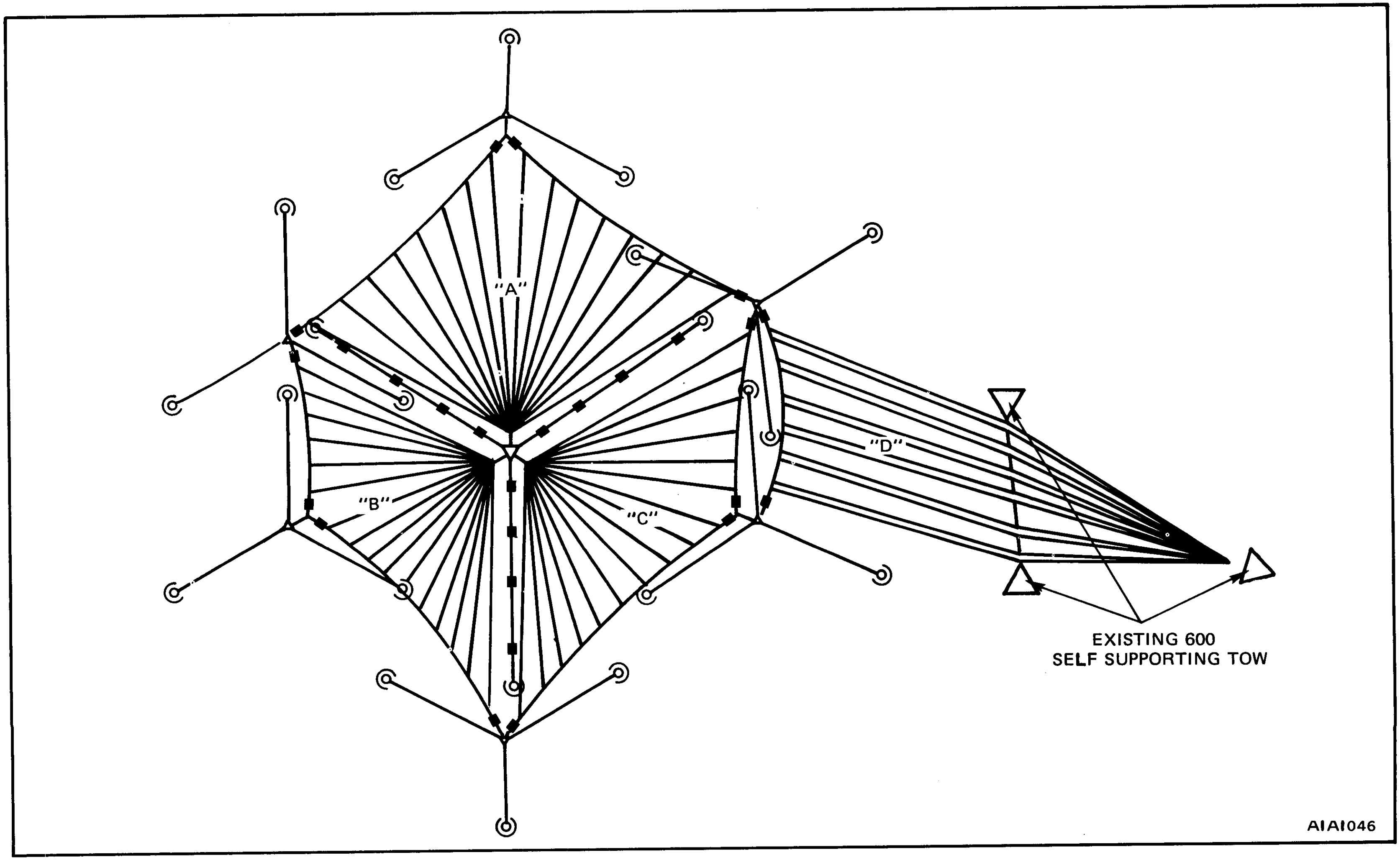


Figure 3-11. Annapolis Top Hat Arrangement

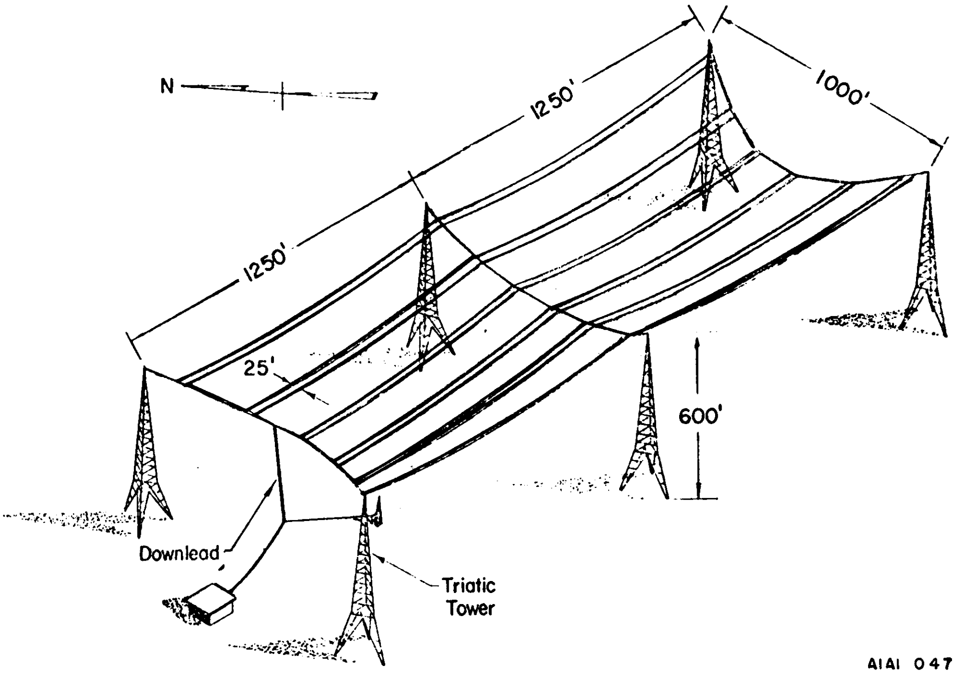


Figure 3-12. Balboa (Summit) Antenna, Pictorial View

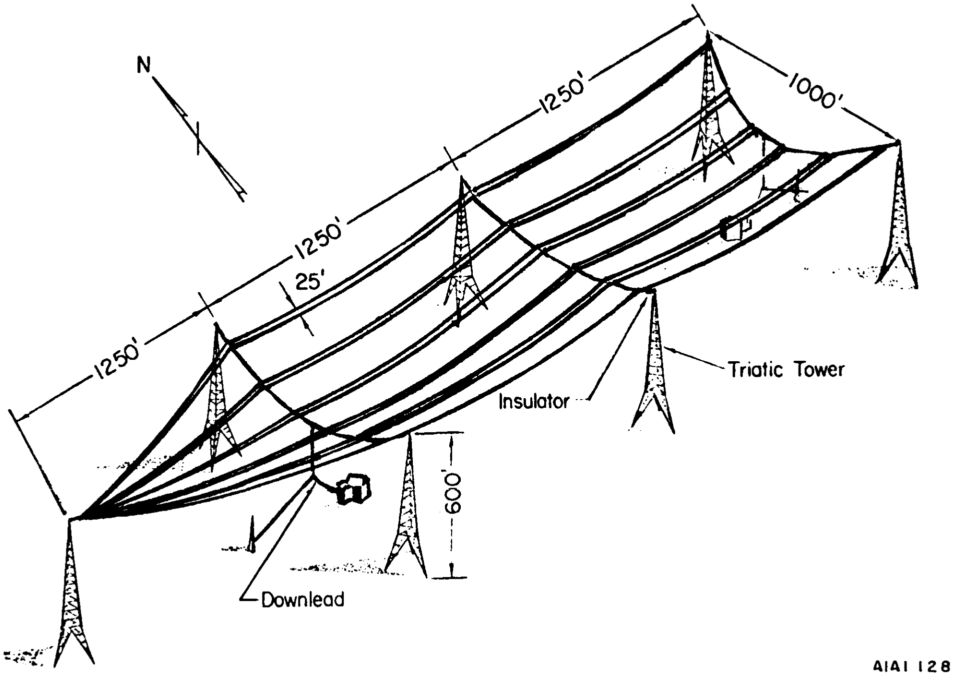


Figure 3-13. Lualualei Antenna, Pictorial View

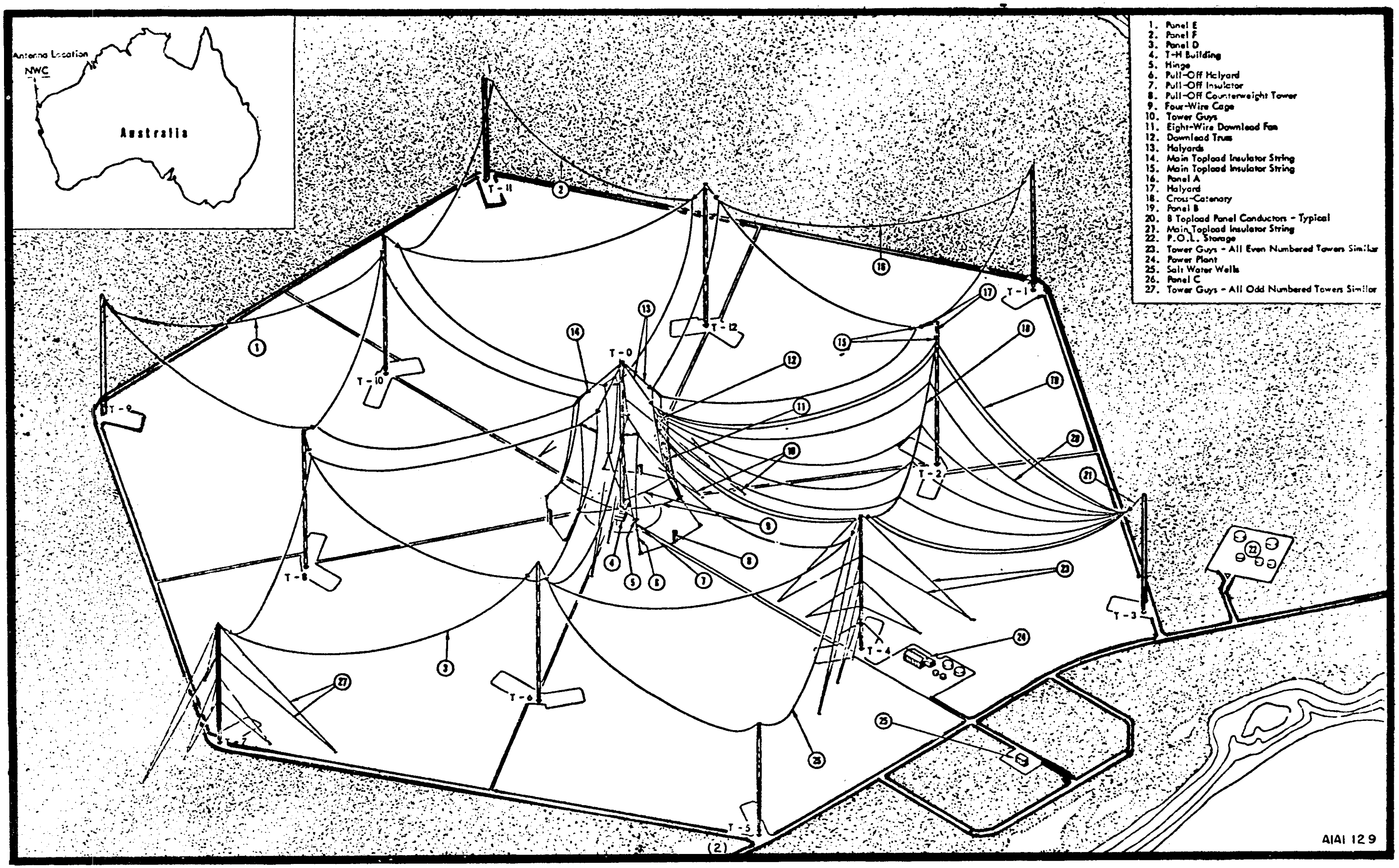


Figure 3-14. Australia, Antenna Location

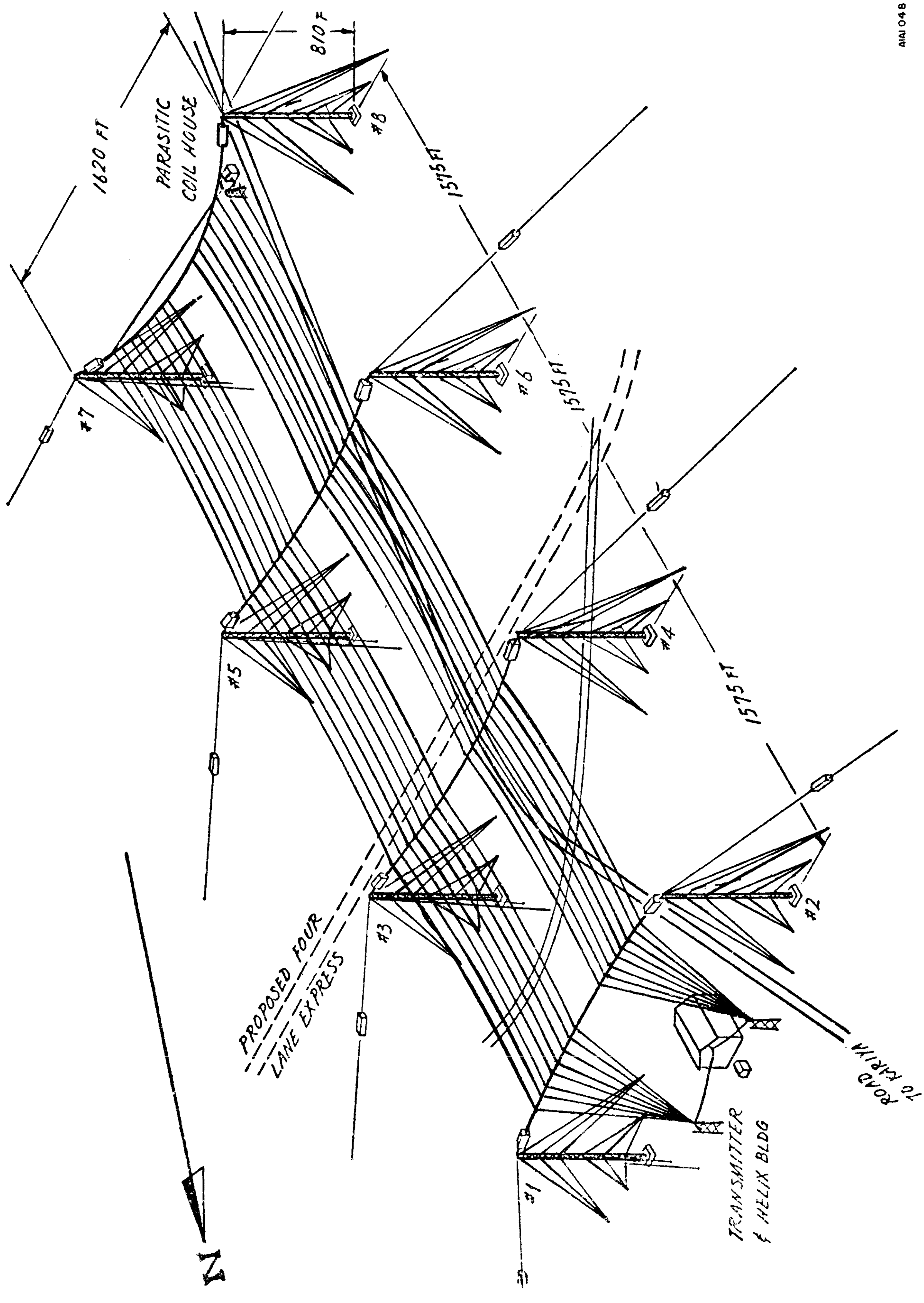


Figure 3-15. Yosami, Japan Antenna, Pictorial View

b. Antenna Characteristics. Establishment of precise standards of antenna characteristics and performance is not possible due to the many inter-related variables. Characteristics are determined theoretically, and empirically using models, in terms of common parameters and confirmed by on-site measurements. The typical equivalent circuit for a VLF transmitting antenna, shown in figure 3-16, is used to identify antenna characteristics. Examination of the equivalent circuit shows that the important parameters of the antenna itself are capacitance, inductance, loss resistance, and radiation resistance. The basic circuit constants are:

C_s - Actual (static) antenna capacitance in farads (apparent capacitance, as measured at the antenna base, is not the true antenna capacitance) due to the shunt capitance of the helix house bushing.

L_a - Antenna inductance in henrys (important in determining antenna resonant frequency). If a wide frequency range is important, low L_a is desirable. Effective antenna inductance is not constant; L_a of the simple series-circuit increases as resonance is approached.

L_i - Tuning-coil inductance (in henrys); must balance the capacitive reactance as seen at the antenna base.

The remaining circuit constants are various effective resistance (in ohms) including:

R_r - Radiation resistance.

R_c - Copper resistance (accounts for power losses due to currents flowing in the antenna top-hat and other wires, etc.).

R_{sd} - Series dielectric resistance (accounts for losses in antenna insulators).

R_g - Ground resistance (accounts for power lost in the ground system of the antenna).

R_i - Resistance of the tuning inductance.

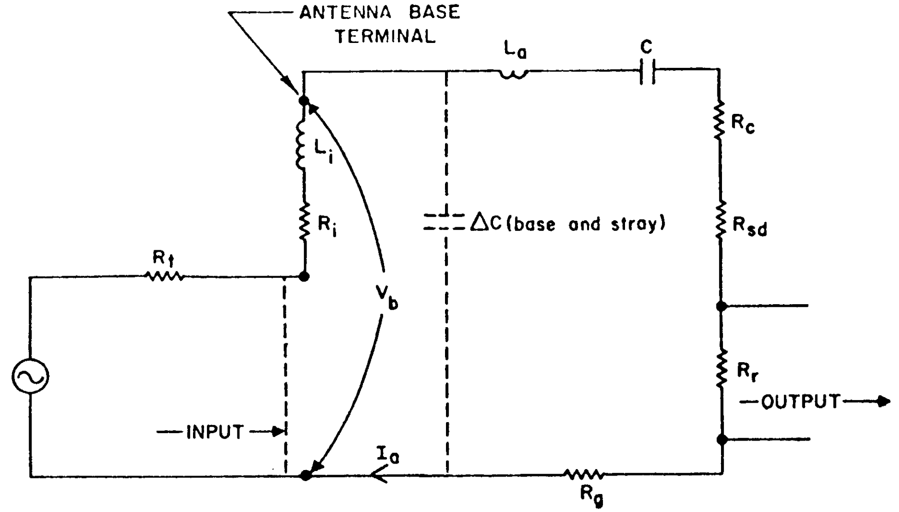
R_t - Internal resistance of the transmitting amplifier.

From these basic circuit constants, the following antenna electrical properties can be identified:

P_r - Effective power radiated from the antenna (watts).

$P_{r\ ss}$ - Maximum power-radiating capability of the antenna-system (determined usually by the voltage-breakdown characteristics of the antenna itself).

$P_{r\ ts}$ - Maximum power radiating capability of the transmitting system (determined either by $P_{r\ ss}$ or by transmitter input power limitation).



Where. R_i = Resistance of inductance
R_c = Copper loss resistance
R_{sd} = Equivalent series dielectric resistance
R_r = Radiation resistance
R_g = Ground loss resistance
R_t = Equivalent transmitter feed line resistance

Figure 3-16. Equivalent VLF Transmitting Antenna Circuit

η_e Effective height of antenna (in meters).

η_a Antenna efficiency (power radiated divided by power into antenna base) = $\frac{R_r}{R_a}$

η_{as} Antenna-system efficiency (power radiated divided by power into antenna tuning system) = $\frac{R_r}{R_a + R_i}$

η_{at} Transmitting system efficiency (power radiated divided by effective power into final amplifier) = $\frac{R_r}{R_a + R_i + R_t}$

$Q_n = 1$ The 100%-efficiency antenna Q (X_a/R_r)

b_3 dB, n = 1, The 3-dB bandwidth antenna at the 100%-efficiency point.

V_b = Antenna base voltage $\cong I_a X_a$

V_t = Antenna top hat voltage $\cong V_b/[1-(\frac{f}{f_r})^2]$ for $f < \frac{f_r}{2}$

Significant measured values required to determine the above properties are:

f_r = Antenna self resonant frequency

X_a Antenna reactance as measured at its base.

R_a Antenna resistance as measured at its base.

$R_a + R_i$ Resistance as measured at input to the antenna tuning inductance.

I_a Antenna Current.

(1) Losses in the Near Field. Inherent in every antenna system is a loss caused by part of the antenna current flowing in the earth. In general, these losses are divided into H-field losses, caused by currents flowing tangent to the surface of

the earth, and E-field losses, caused by currents flowing normal to the surface of the earth. The E-field currents are assumed to penetrate the surface to a depth δ (skin depth) beyond the termination of the antenna metallic ground system. These losses are further divided into near-field losses (electrostatic-field and induction-field losses) and far-field losses (propagation losses).

For an electrically small monopole mounted above the earth (see figure 3-17), the theoretical E-field E_z (the rms normal electric field component in volts per meter), is given by

$$E_z = \frac{Ih_e}{2\pi C_o}\left[\frac{1}{\omega r^3} + \frac{j}{cr^2} - \frac{\omega}{c^2 r}\right] \tag{3-1}$$

and the theoretical H-field $H\varphi$ (the rms tangential magnetic field component in amperes per meter) is given by

$$H_\varphi = \frac{Ih_e}{2\pi}\left[\frac{j}{r^2} - \frac{\omega}{cr}\right] \tag{3-2}$$

where:

I = monopole base current in amperes

h_e = effective height of the monopole in meters

ε = permittivity of free space (8.85×10^{-12} farad per meter)

r = distance from the monopole in meters

c = velocity of light in free space (3×10^8 meters per second)

ω = angular frequency in radians per second ($2\pi f$, where f is in Hertz).

In Equation (3-1) the term $1/\omega r^3$ is the electrostatic component of the near field, the term j/cr^2 is the inductive component of the near field, and the term ω/c^2 is the radiation term which comprises the far field. In Equation (3-2), the induction term j/r^2 represents the near field, while the radiation term ω/cr represents the far-field. Note that when f is substituted for c in Equation (3-1), the magnitude of the induction field is equal to the radiation field when r is equal to $\lambda | 2\pi$:

$$H_\varphi = \frac{Ih_e}{2\pi}\left|\frac{j}{r^2} - \frac{2\pi f}{\lambda f r}\right| = \frac{Ih_e}{2\pi}\left|\frac{j}{(\lambda/2\pi)^2} - \frac{i}{(\lambda/2\pi)^2}\right|$$

Thus, the losses occurring within the distance $\lambda/2\pi$ from the monopole (which defines the radian sphere) are inherent losses in the antenna system, while those beyond this distance are considered propagation losses.

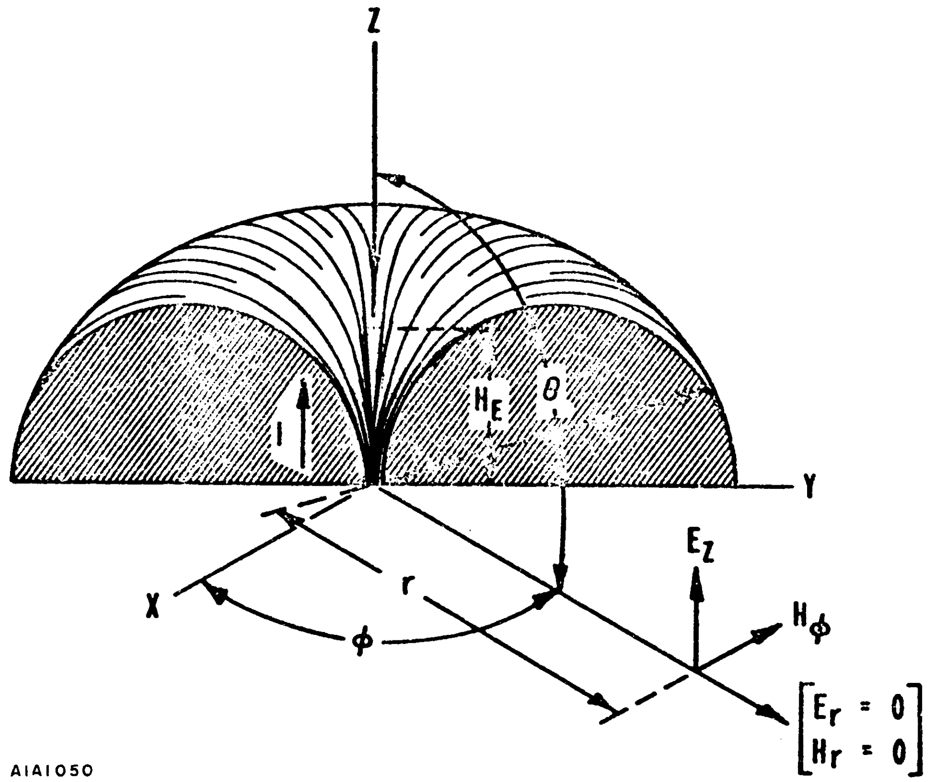


Figure 3-17. Electric Field, Small Monopole Above Earth

The power loss per square meter, P_L, associated with the H-field can be derived from Maxwell's equations:

$$\Delta P_L = \frac{1}{\sigma\delta} \left| H_\varphi \right|^2 \tag{3-3}$$

where:

σ = conductivity in mhos per meter

δ = skin depth in meters.

To obtain the total H-field loss (P_{TL}) in the uncontrolled area, ΔP is integrated over the surface area about the antenna from the radius of the controlled area to the radius of the radian sphere:

$$P_{TL} = \int_0^{2\pi} d\theta \int_{r_1}^{r_2} r\,dr\, \Delta P_L \tag{3-4}$$

where:

r_1 = radius of the controlled area

r_2 = radius of the radian sphere.

To express P_{TL} more simply, the near-field component of Equation (3-2) is substituted into Equations (3-3) and (3-4), and integrated:

$$P_{TL} = \int_{o}^{2\pi} d\theta \int_{r_1}^{r_2} rdr \frac{1}{\sigma\delta} \left[\frac{Ih_e}{2\pi r^2} \right]^2$$

$$= \frac{I^2 h_e^2}{4\pi^2 \sigma \delta} \int_{o}^{2\pi} d\theta \int_{r_1}^{r_2} \frac{dr}{r^3}$$

$$= \frac{I^2 h_e}{2\pi \sigma \delta} \int_{r_1}^{r_2} \frac{dr}{r^3}$$

$$= \frac{I^2 h_e}{4\pi \sigma \delta} \left[\frac{1}{r_1^2} - \frac{1}{r_2^3} \right] . \qquad (3\text{-}5)$$

The preceding analysis applies exactly only if the fringing field in the vicinity of the ground plane edge still resembles that of an infinitesimal monopole, at many sites the ground system wired area is so limited that the proximity to the antenna top loading makes a significant difference between the actual field and that of an infinitesimal monopole; in the latter case the above expression does not hold and numerical integration must be utilized to compute the loss. The controlled area is the area about the antenna where the ground system (and therefore the losses) can be controlled. Beyond this area, the ground system does not exist and this is referred to as the uncontrolled area.

Equation (3-5) yields the tangential current-losses associated with the H-field. The normal current losses associated with the E-field occur within the skin depth δ . If, as is usually the case, the distance between the limits r_1 and r_2 is much greater than δ , the E-field losses are negligible compared to the H-field losses. Thus, generally only H-field losses need be considered in evaluating antenna efficiency.

(2) Maximum Theoretical Efficiency. The case where the controlled area does not extend to a distance equal to the radian sphere (i.e., $r_1 < r_2 = \lambda/2\pi$), will be considered and it will be assumed that within the controlled area there are no losses. To establish the ideal case, the maximum theoretical efficiency in such an antenna system will be determined. Antenna efficiency, η_a, in percent is given by:

$$\eta_a = \frac{R_{rad}}{R_{rad} + R_{loss}} \times 100 \qquad (3\text{-}6)$$

where:

R_{rad} = antenna radiation resistance in ohms

R_{loss} = antenna loss in ohms suffered in the uncontrolled area.

The radiation resistance is given by:

$$R_{rad} = 160\pi^2\left(\frac{h_e}{\lambda}\right)^2 \tag{3-7}$$

$$= \frac{160\pi^2 h_e^{\,2} f^2}{C^2}$$

where:

h_e = antenna effective height

λ = free-space wavelength = $\frac{c}{f}$

C = speed of light = 3×10^8 m/sec.

The loss resistance in the uncontrolled area is obtained by dividing the total power loss given by Equation (3-5) by the current squared:

$$R_{loss} = \frac{P}{I^2} = \frac{h_e^{\,2}}{4\pi\sigma\delta}\left[\frac{1}{r_1^{\,2}} - \frac{1}{r_2^{\,2}}\right] \tag{3-8}$$

Substituting Equations (3-7) and (3-8) into Equation (3-6) yields:

$$\eta_a = \frac{160\pi^2 \frac{h_e^{\,2}}{\lambda}}{160\pi^2\left(\frac{h_e}{\lambda}\right)^2 + \frac{h_e^{\,2}}{4\pi\sigma\delta}\left[\frac{1}{r_1^{\,2}} - \frac{1}{(\lambda/2\pi)^2}\right]} \times 100$$

$$= \frac{100}{1 + \frac{R_s}{160\pi}\left[\frac{\lambda^2}{(2\pi r_1)^2} - 1\right]} \tag{3-9}$$

where:

$R_s = 1/\sigma\delta$, the equivalent surface resistance in ohms per square.

From Equation (3-9) it is noted that maximum efficiency is independent of effective height for the case where R_{loss} is zero within r_1. Since R_s is inversely proportional to $\sigma^{1/2}$, the second term in the denominator is a function of $1/\sigma^{1/2}$, $1/f^{3/2}$, and $1/r^2$. Thus, maximum possible efficiency is a function of the size of the area that can be controlled, the conductivity of the surrounding area, and the frequency.

Using 15 kHz as the lowest VLF frequency, the theoretical maximum efficiency that can be achieved for various conductivities, calculated as a function of size of the controlled area, is plotted in figure 3-18.

(3) Maximum Practical Efficiency. Maximum theoretical efficiency cannot be attained because of other losses within the antenna system that were assumed to be zero. These losses, which must be considered to obtain maximum practical efficiency, are:

- Conductor losses
- Insulator losses
- Matching network losses
- Ground losses within the controlled area.

Of these, matching network and ground-system losses within the controlled area significantly affect efficiency; conductor and insulator losses in many instances may be considered negligible. At the low end of the frequency band, however, it is sometimes necessary to degrade efficiency in order to obtain sufficient bandwidth for the mode of emission selected.

(4) Matching Network Losses. A practical value for the loss-resistance in the matching network, may be determined by assuming a maximum inductor (coil) Q of 2000 at 15 kHz. Using Litz wire, and given sufficient surrounding volume for the inductor, 2000 is a practical upper limit of Q. The inductor loss resistance (R_i) (minimum) in ohms can then be calculated:

$$R_i = \frac{X_c}{Q} \tag{3-10}$$

where:

X_c = antenna capacitive reactance in ohms

Q = Q of the coil (2000 for this application).

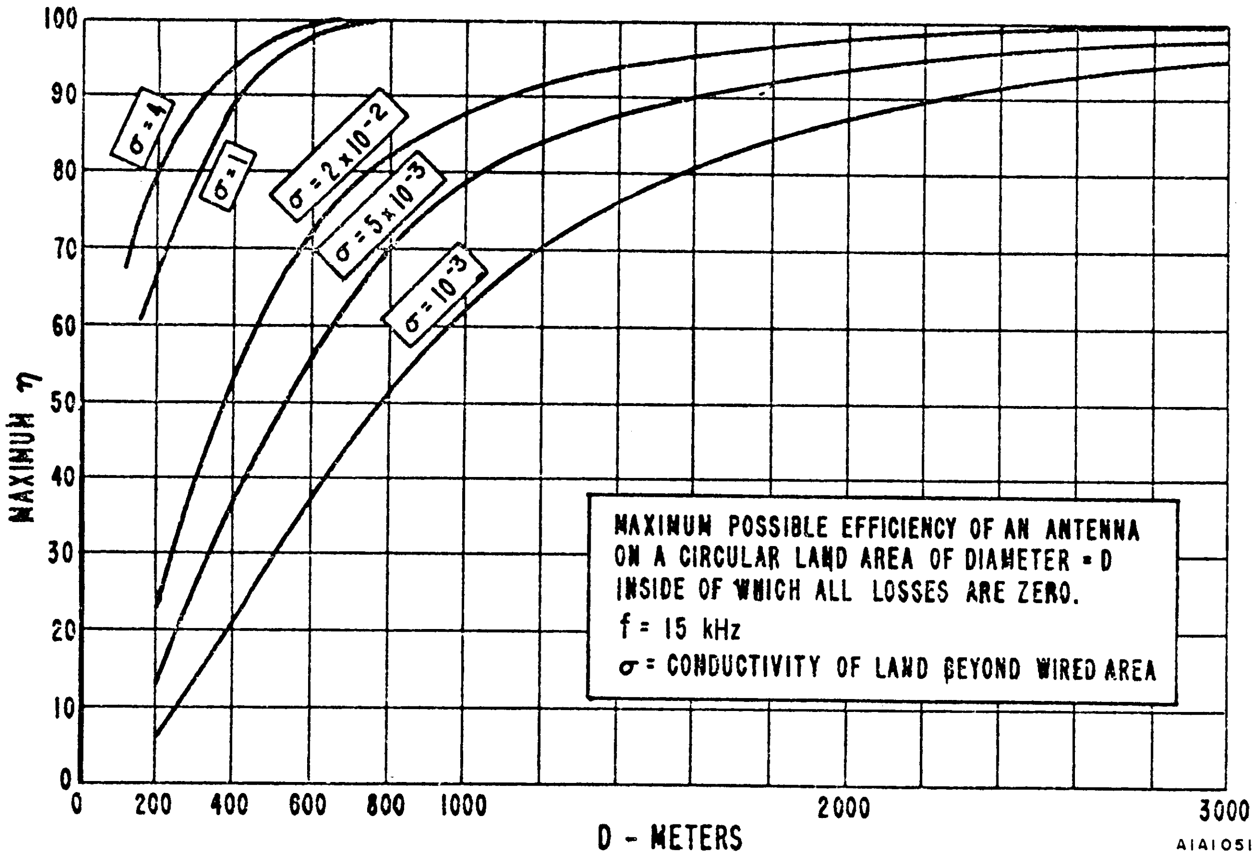


Figure 3-18. Maximum Theoretical Efficiency

It should be noted that the coil loss resistance given by Equation (3-10) and the maximum theoretical efficiency given by Equation (3-9) are both independent of effective height.

(5) Ground Losses Within the Controlled Area. The ground loss resistance within the controlled area is a function of wire density and ground conductivity. The maximum H-field losses within the controlled area can be obtained from:

$$R_{gw}\ \max = \frac{780}{2\pi\lambda}\left\{h_e \ln\left(\frac{h_e\theta}{2\pi ae}\right) - r_o \ln\left(\frac{r_o\theta}{2\pi ae}\right) - h_e^{2}\left[\frac{1}{r_1}\ln\left(\frac{r_1\theta_c}{2\pi a}\right) - \frac{1}{h_c}\ln\left(\frac{r_2\theta_c}{r\pi a}\right)\right]\right\} \qquad (3\text{-}11)$$

where:

θ = angle between radials ($\pi/180$ p where p = number of radials per degree)

a = wire radius

e = base of natural logarithms (~2.72)

r_o = inner radius of wired area

r_1 = outer radius of wired area.

Maximum loss is independent of earth conductivity, but not of effective height. In general for ground systems that are not approaching worst-loss conditions, the loss in the wired portion of the controlled area increases as the 3/2 power of frequency. This is evident by examining the equivalent circuit shown in figure 3-19 in which the series combination of surface resistance R_S and surface reactance jR_S are in parallel with the reactance of the ground wire X_L. Since R_S increases as the square root of frequency, X_L directly as the frequency, the parallel combination (total loss with the ground system) will increase as the 3/2 power of frequency. However, since the worst-loss ground condition can never be exceeded, R_{gw} max will increase proportionally to f. This is evident if $\lambda = c/f$ is substituted in Equation (3-11); figure 3-20, plotted from this equation, shows loss resistance R_{gw} max as a function of effective height for various wire densities. (A wire density of one radial per degree is used as a standard to obtain maximum practical efficiency).

The E-field losses in the wire area, ΔP_ϵ (associated with currents flowing normal to the surface of the earth) can be calculated from the following equation:

$$\Delta P_\epsilon = \frac{d}{\pi}\ln\left(\frac{d}{2\pi a}\ \frac{\epsilon\omega}{\sigma}\ |E_o|\right)^2$$

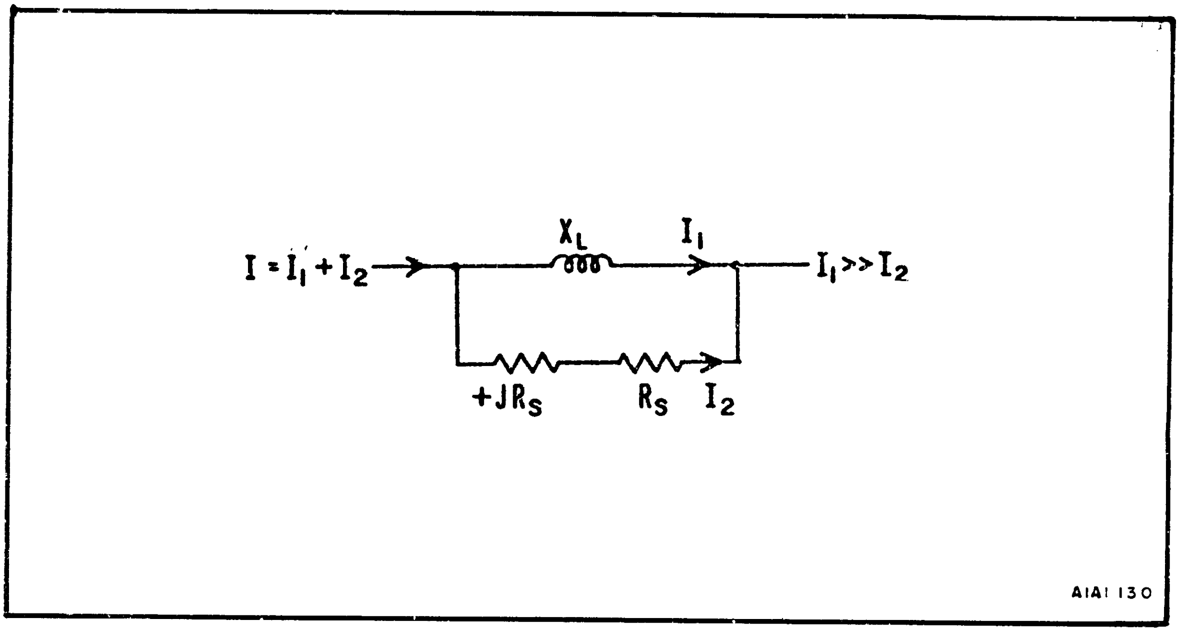


Figure 3-19. Equivalent Circuit of Wired Portion of Antenna Ground System

where:

d = distance between wire elements

ϵ = permittivity of the earth

E_o = magnitude of the vertical E-field (all other terms are as defined before.)

For a wire density of one radial per degree, the E-field losses are insignificant compared to the H-field and matching-network losses. If timber were standing within the controlled area, the E-field losses can be significant, but it is assumed that all timber can and will be cleared from the area.

(6) Maximum Radiated Power and Bandwidth Efficiency Product. Maximum radiated power in the antenna voltage limited case may be determined from:

$$P_{R\,ss} = \frac{640\Pi^4}{C^2} V_{TM}^2 h_e^2 C_s^2 f^4$$

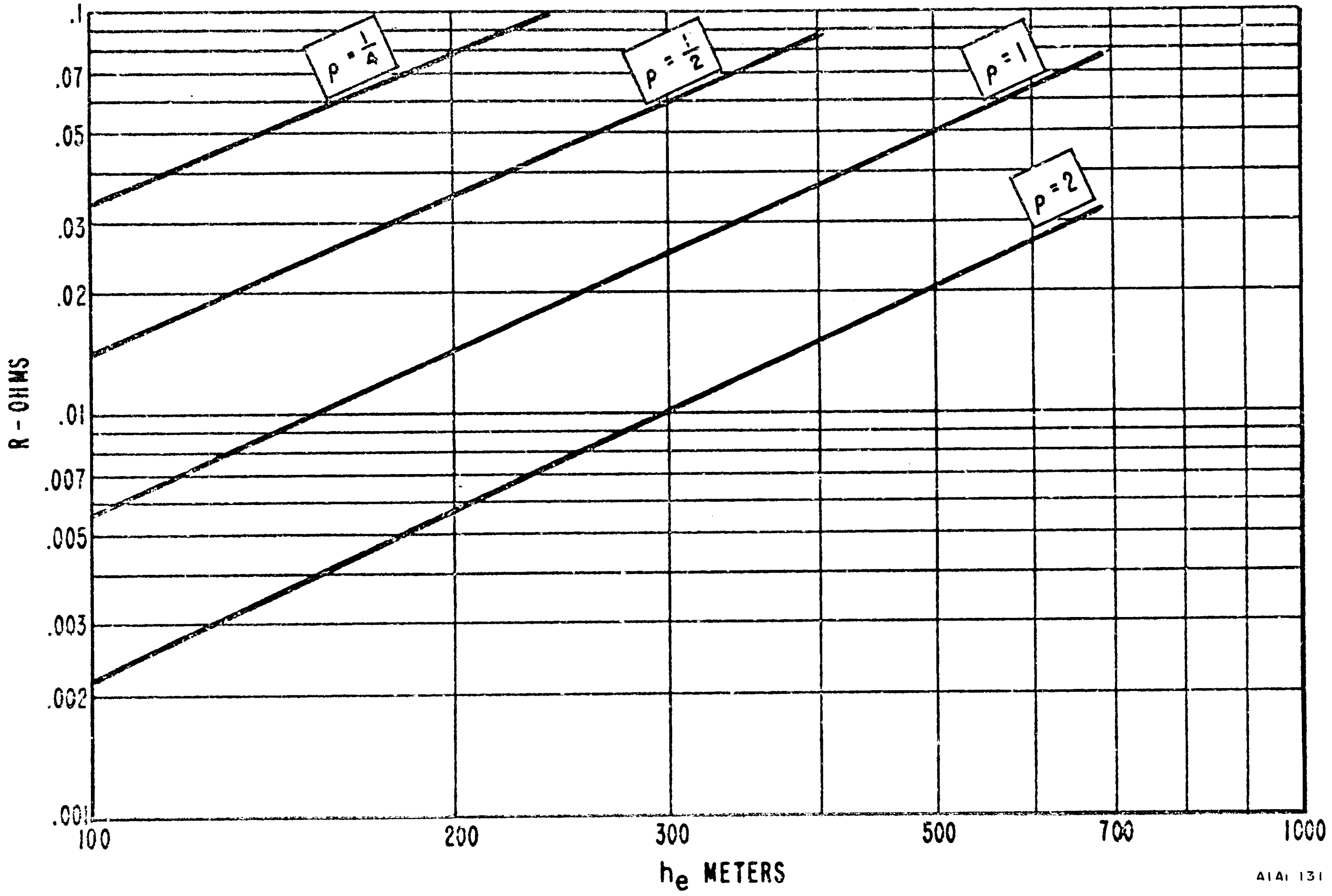


Figure 3-20. Loss Resistance as a Function of Effective Height for Various Wire Densities

where:

$P_{R\ ss}$ = Antenna radiating capability in watts for voltage limited antenna

V_{TM} = Maximum antenna top hat operating voltage level in volts RMS

C = Speed of light - 3×10^8 m/sec

f = Frequency in hertz

C_s = Antenna static capacitance in farads

h_e = Effective height in meters.

The maximum power relation is shown graphically as a function of effective height in figure 3-21 for the lowest VLF frequency (15 kHz) and an antenna top hat operating voltage of 250 kV. (Present state of the art.) Most present VLF communications antennas are voltage limited at the lower VLF frequencies.

With regard to voltage limitations, it is sufficient to note that once a particular antenna system configuration is chosen, antenna voltage will depend on the power supplied to the antenna system by the transmitter, frequency of operation, and the voltage breakdown characteristics of the insulation. When the safe design limiting voltage is reached, the antenna will radiate at maximum capability, $P_{R\ ss}$. Under this condition:

$$P_{R\ ss} = \eta_{as}\ P_{transmitter}$$

where:

$P_{transmitter}$ = transmitter output power in watts required for V_{TM}

It should be noted that at frequency at which full power output from the transmitter will not result in a top hat voltage that exceeds the maximum design value, V_{TM}, the radiated power will be given by:

$$P_R = \eta_{as}\ P_{TM}$$

where:

P_{TM} = maximum transmitter output power in watts

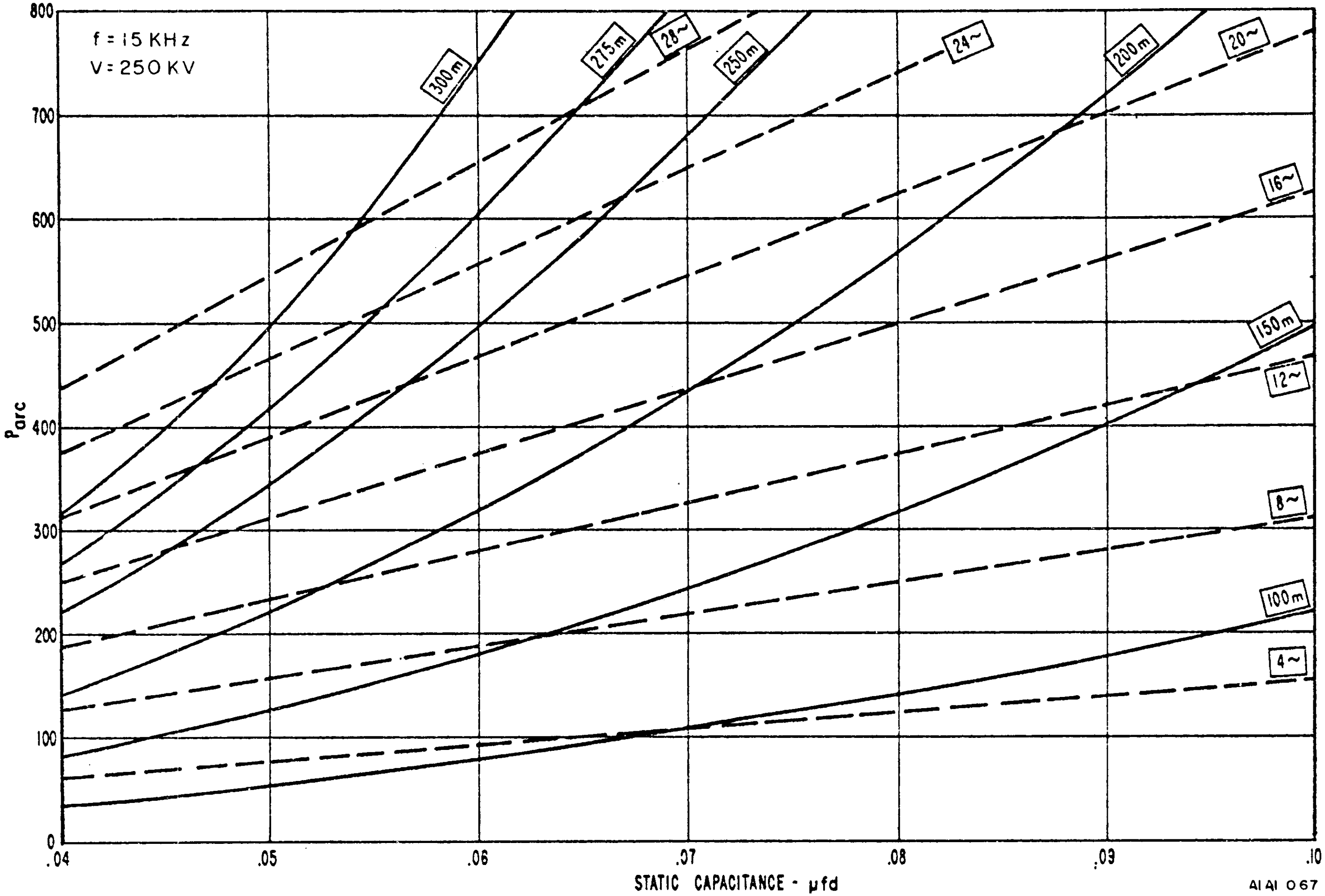


Figure 3-21. Antenna Electrical Characteristics

The size of the land area allocated to the antenna has a definite effect on bandwidth, efficiency, and power radiating capability. Land area has a bearing on the physical height (and thus antenna effective height) of towers that can be erected. Land area also determines the maximum possible static capacitance of the antenna since the antenna can be extended only until it covers the land area available. If an existing antenna is thus expanded in area without increasing its physical height, the capacitance will increase and the effective height will, in general, remain constant or increase very slightly. In figure 3-21, this represents a point moving along a particular h_e line. If an antenna of relatively small effective height and moderate capacitance is raised in height physically, the result will be an increase in effective height and a decrease in capacitance. In general, the decrease in capacitance of an antenna whose flat-top dimension is several times its average physical height is rapid at first, the capacitance under these conditions being nearly proportional to 1/h. As flat-top and physical height dimensions become comparable, the decrease in capacitance becomes slower, and finally constant, as physical height continues to increase.

From figure 3-21, it is evident that as capacitance is increased without changing height, the result is a translation along the h_e line concerned. If an antenna is raised in height without changing the top-hat dimensions, the point on the graph will, in general, describe a curve which shows a decrease in capacitance and an increase in h_e (i.e., the point moves to the left and upward). As the dimensions become comparable, the point moves upward more steeply.

The antenna system inherent or intrinsic bandwidth-efficiency product is given by:

$$b_{as}\,\eta_{as} = \frac{320\Pi^3}{C^2}\, f^4\, h_e^2\, C_s$$

where:

b_{as} = antenna system inherent (intrinsic) bandwidth in Hz.

It is evident that increasing antenna effective height will more readily result in a greater bandwidth-efficiency product; however, there is a practical cost effective tower height limit beyond which increased antenna static capacitance obtained by addition top loading is utilized to increase bandwidth-efficiency product.

Attempts have been made to incorporate active synchronous tuning networks into VLF antenna systems to increase bandwidth and data rate. Saturable reactor synchronous VLF antenna tuning is presently at Cutler, Maine. Studies have also been undertaken to determine the feasibility of using multistage passive tuning networks to obtain broader bandwidth with little loss in efficiency. If these types of bandwidth improvement are utilized, a VLF antenna will be capable of FSK operation (50 Hz shift) at the lower VLF frequencies. At these frequencies most VLF antenna systems are currently limited to low data rate ICW operation due to insufficient bandwidth.

The variation of antenna power radiating capability and usable efficiency with frequency is shown in figure 3-22 for a constant top-hat voltage of 250 kV (present operating limit). The maximum efficiency that can be used if the antenna is to have a bandwidth of 50 Hz is illustrated by the dashed curves; the other set of curves illustrates maximum power radiating capability of an antenna as a function of frequency.

(7) Effect of Shunt Capacitance. Previous studies indicate that the power radiating capability of an electrically small, voltage-limited antenna is proportional to the square of the summation of the antenna dipole moments. For a electrically short antenna for which voltage and phase can be assumed constant; the radiating capability of the antenna, P_r, can be expressed by:

$$P_r \propto \left[\sum_{N=1}^{N} C_n h_n \right]^2$$

where:

C_n = capacitance of the nth element of the antenna

h_n = effective height of the nth element of the antenna.

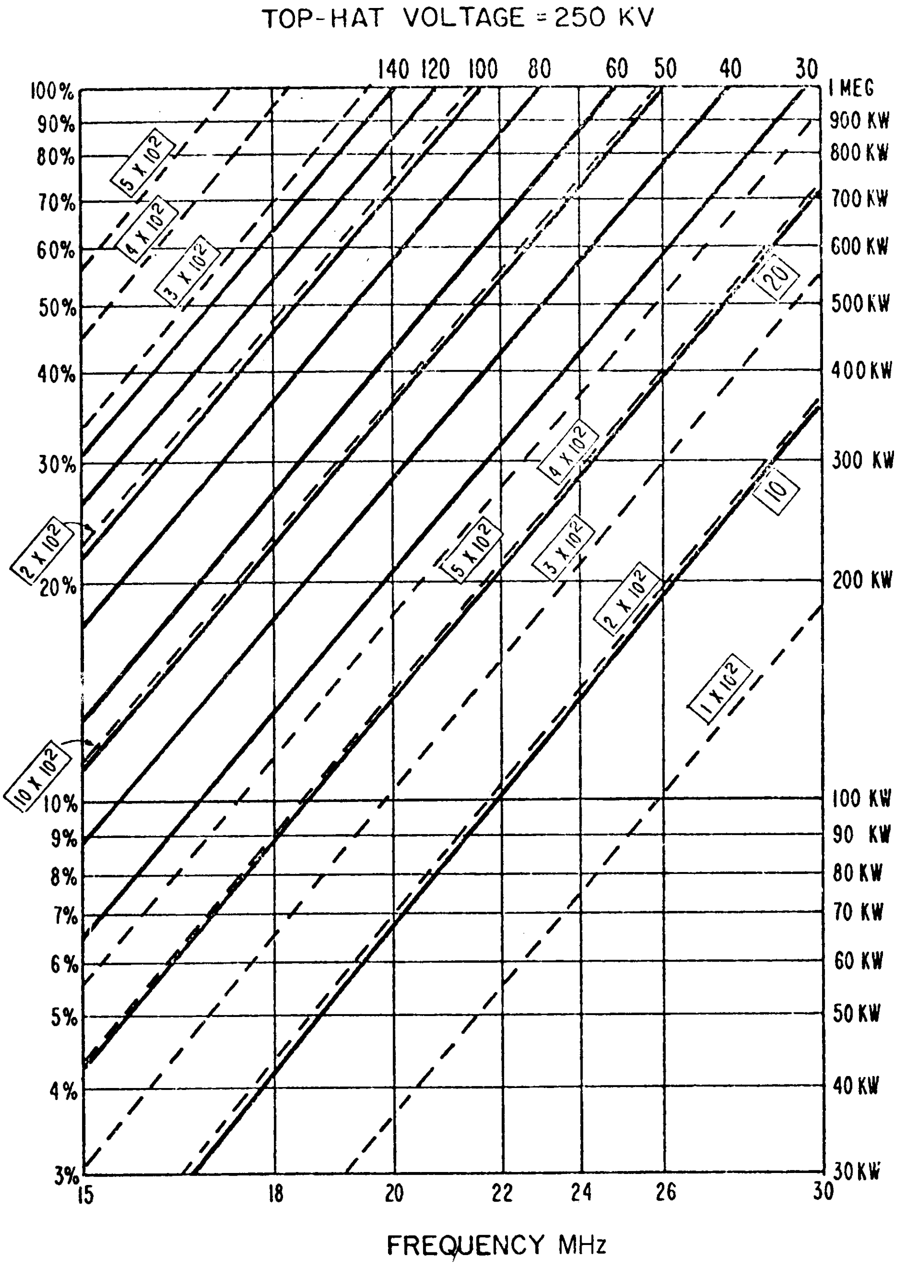
From this expression, it is obvious that, provided h_n is positive, any capacitance added to the antenna will increase its power radiating capability. However, if C_n is a shunt capacitance to a grounded structure in which currents are induced in opposition to the radiating currents, the effective height associated with this shunt capacitance will be negative and the power radiating capability of the antenna will be reduced.

If a shunt capacitance, ΔC, is placed across the base of the antenna, (see figure 3-16) such as might result from a metal insulator shield) and if the original static capacitance, C, and effective height, h_e, remain constant, then, in terms of the original effective height, h_e, the new apparent effective height, h_e, will be given by:

$$h'_e = \frac{h_e C}{(C + \Delta C)} \qquad (3\text{-}12)$$

From this expression, it is obvious the apparent effective height is reduced appreciably if ΔC is very large. (A large shunt capacitance is one reason for the low effective height at Jim Creek). For operation well below self resonance, the ratio of new original top-hat voltage-limited power-capability is

$$\frac{P'_r}{P_r} = \left[\frac{(C + \Delta C)^2 \, (h'_e)^2}{C^2 \, h_e^2} \right] \qquad (3\text{-}13)$$



—— MAXIMUM POWER RADIATING CAPABILITY VS FREQUENCY FOR ANTENNAS OF VARIOUS $(h_e \times C)^2$ WHERE h_e IS IN METERS AND C IN μfd.

--- MAXIMUM USEABLE EFFICIENCY IF BANDWIDTH IS TO BE 50 HERTZ FOR ANTENNAS OF VARIOUS $h_e^2 \times C$.

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Figure 3-22. Antenna Characteristics Nomograph

When Equations (3-12) and (3-13) are combined, it is evident that the (resonated) top-hat voltage-limited power capabilities are unchanged by the added capacity.

The effect on antenna system bandwidth can be otained by determining the equivalent series antenna capacitance C' and resistance R_a'. When $R \ll 1/\omega C$ and $\Delta C \ll C$,

$$C' \simeq C\left(1 + \frac{\Delta C}{C}\right)$$

and:

$$R_a' \simeq \frac{R_a}{\left(1 + \frac{\Delta C}{C}\right)^2}$$

The ratio of the transmitting system bandwidth with ΔC to that without ΔC now becomes

$$\frac{b}{b} = \frac{\left(1 + \frac{\Delta C}{C}\right)\left[R_t + R_i + \frac{R_a}{\left(1 + \frac{\Delta C}{C}\right)^2}\right]}{R_t + R_i + R_a}$$

where:

R_t = equivalent transmitter feedline resistance

R_i = resistance of the helix coil.

For the antenna only (i.e., R_t and $R_i = 0$), the bandwidth ratio will be $1/(1 + \Delta C/C)$, a decrease in bandwidth as ΔC is increased. The effect on antenna system efficiency can be determined by comparing Equation (3-9) with the new efficiency,

$$\eta'_{as} = \frac{\frac{R_{rad}}{(1 + \Delta C/C)^2}}{\frac{R_a}{(1 + \Delta C/C)^2} + R_i}$$

where:

R_{rad} = radiation resistance.

When tuning inductance has low-losses (R_i is small compared to R_a), efficiency will not be greatly reduced.

(8) Corona on Top Hat Conductors. It was shown previously that the power radiated by a VLF antenna varies as the square of the antenna voltage. This voltage cannot be raised without limit because of the limitation of corona or electrical breakdown of the air dielectric surrounding the antenna conductors (and because of maximum insulator voltage arc over limitations). The radial electric field emanating from the antenna conductors will cause corona when a critical value is exceeded. The phenomena of corona on set is complex. This paragraph covers basic rules for antenna modifications which are consistent with high-voltage operation. The quasi-static radial E-field on a conductor is a function of the amount of current leaving the conductor as displacement current per unit length, the frequency, and the radius of the conductor. (see figure 3-23). The relationship is:

$$E_r = \frac{1}{2\pi\omega\epsilon r}\,\frac{dI}{dZ} \qquad (3\text{-}14)$$

where:

E_r = radial E-field at the wire surface

r = radius of the wire

ϵ = permittivity of free space (8.85×10^{-12} farad per meter)

$\frac{dI}{dZ}$ = current-gradient along the wire.

An expression for the current gradient along the wire is:

$$\frac{dI}{dZ} = j\omega C'V$$

Substituting this expression in Equation (3-14) and taking the magnitude of E_r, we have

$$\left|E_r\right| = \left|\frac{VC}{2\pi\epsilon r}\right| \qquad (3\text{-}15)$$

For which V, the voltage on the wire, is a function of length, being a maximum at the end. For a low-loss, open-circuit transmission line, the voltage V_s is given as:

$$V_s = V_r \cos \beta\ell \qquad \text{or} \qquad V_r = \frac{V_s}{\cos\beta\ell} \qquad (3\text{-}16)$$

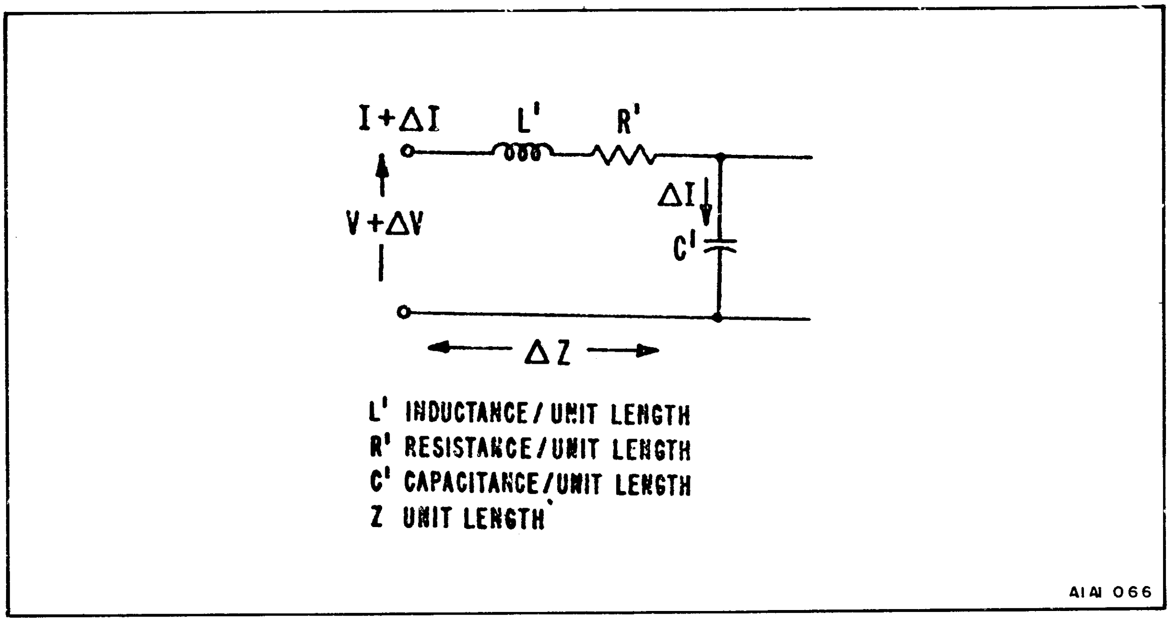


Figure 3-23. Circuit Equivalent of Small Section of Line

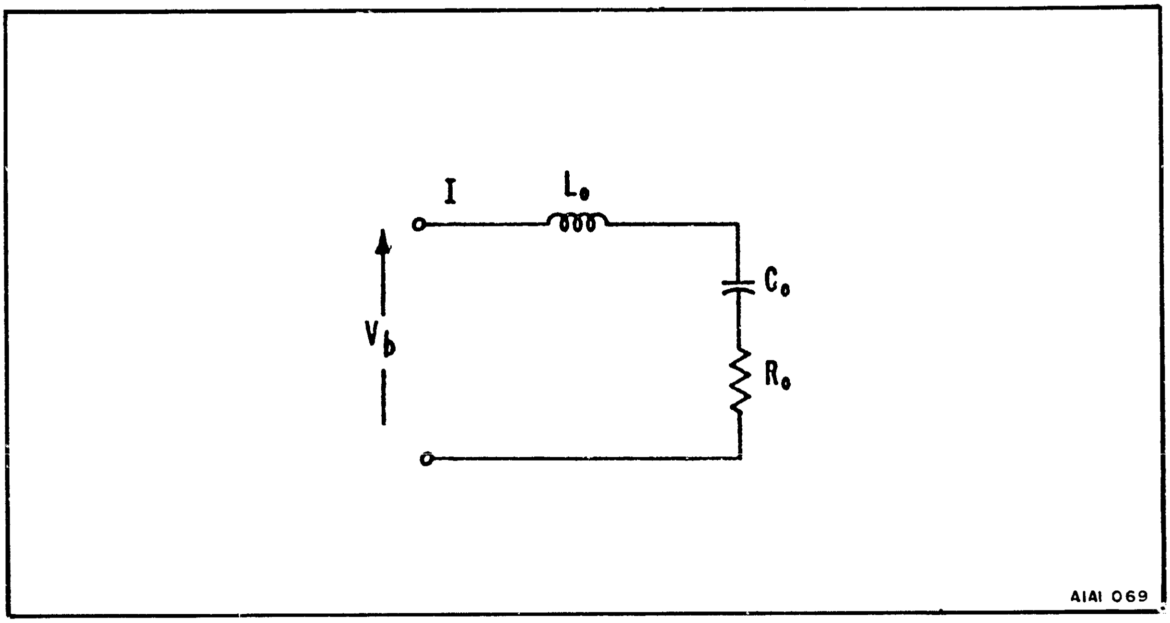


Figure 3-24. Lumped Circuit

where:

ℓ = distance from the end of wire

V_r = voltage at the end of the line

$\beta = \frac{\omega}{c}$

From these relationships, it can be seen that the radial E-field on a conductor can be reduced for a fixed input voltage, by:

- Reducing the capacitance per unit length of the wire.
- Increasing the radius of the wire, $C \propto 1/\ln(2h/r)$.
- Decreasing the inductance per unit length.
- Reducing the electrical length of the wire.

Electrically short, top-loaded antennas can be considered, to a first order approximation, a lumped circuit (see figure 3-24). For such antennas, the antenna base voltage, Vb, can be approximated by:

$$V_b = I\left(\omega L_o - \frac{1}{\omega C_o}\right) \tag{3-17}$$

where:

I = antenna base current

L_o = antenna inductance

C_o = antenna capacitance.

The antenna top-hat voltage is given by

$$V_r \cong \frac{I}{\omega C_o} \tag{3-18}$$

Antenna capacitance should be increased as required to reduce top-hat voltage and/or corona subject to the four conditions which minimize corona:

- The capacitance per unit length of a single wire above ground can be reduced by placing a second wire at the same potential near to and parallel to the existing wire. This procedure (often referred to as "caging") reduces the capacitance per length per wire, but gives a net increase in antenna capacitance.

- The capacitance per unit length of a single wire above ground is proportional to 1/In(2h/r), where h is the height of the wire above ground and r is the radius of the wire. Therefore, increasing the diameter of a wire decreases the radial E-field and increases antenna capacitance. The disadvantage of increasing wire diameter as compared to caging is that increasing wire diameter generally adds more weight to the top hat than would caging.

- The inductance per unit length can be decreased by increasing wire diameter by caging, i.e., where the cage arrangement is considered to have an equivalent diameter.

- Reducing the electrical length of a wire reduces its capacitance, thereby increasing its radial E-field. An antenna top hat should be centrally fed, thereby reducing the maximum electrical length of the antenna.

(9) Polarization. Traditionally, vertical polarization has been utilized for VLF transmitting antennas. Ground-wave polarization characteristics illustrated in figure 3-25 indicate the great advantage (80-100 dB over sea water) of vertical polarization ground wave propagation to distances of 100 - 1000 miles.

At distances beyond several hundred miles the ground wave assumes diminishing importance with respect to the sky wave. The geometrical-optical theory of sky-wave field-strength furthermore indicates a direct proportionality between the received field strength and the earth and ionospheric reflection coefficients, and these reflection coefficients are larger for horizontal than for vertical polarization. From the standpoint of improved efficiency and economic construction the feasibility of utilizing horizontal antennas for VLF transmission has motivated studies and test programs to evaluate its potential usability. The usefulness of such an antenna has been the subject of test programs conducted by the Naval Weapons Center. A dual-dipole fast-wave horizontal VLF transmitting antenna consisting of two parallel dipoles 19.2 km long was constructed for these tests.

Measurements show that the antenna has a broad bandwidth (20 percent at several self-resonant points in the VLF band, and that the radiation efficiency is proportional to the number of dipoles used. The estimated cost is less than 1 percent of the cost of equally-efficient vertical VLF transmitting antennas now being used by the Navy. Environmental conditions such as rainfall have very little effect on antenna performance.

Other factors not yet resolved include higher voltage ratings for components; matching problems, transmitter isolation vs. cost, efficiency, etc.; additional antennas, transmitters required to cover large azimuthal angles; and site installation and construction costs.

At present there are no practical advantages warranting use of horizontal polarization at VLF. As new studies and test programs are scheduled and conducted, their results may resolve the usefulness of such an antenna for VLF communications in specific areas.

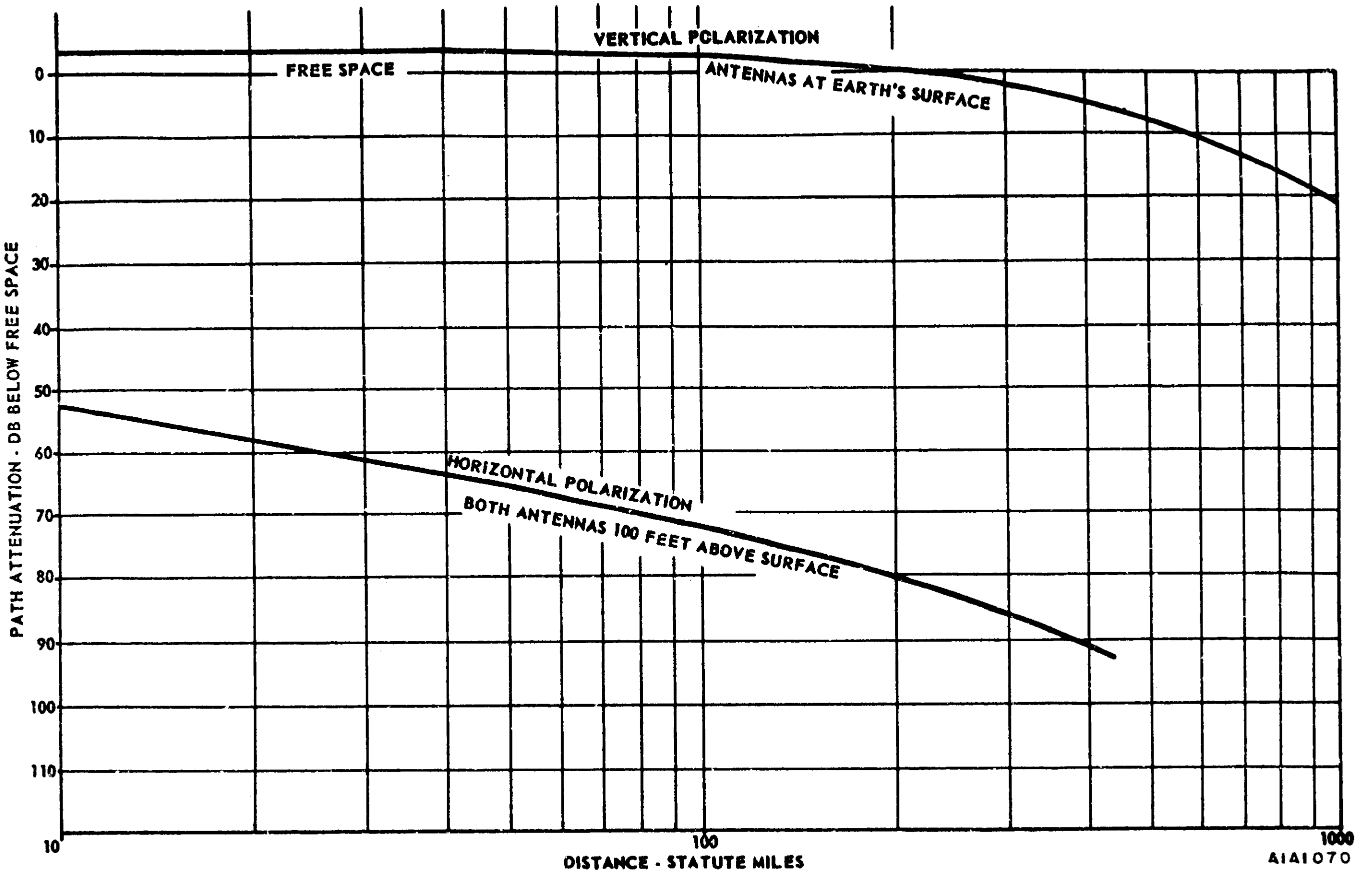


Figure 3-25. Comparison of Horizontal and Vertical Polarizations Over Sea Water, Ground Wave Only

Vertical polarization provides the following advantages:

- Antenna can be used to provide omnidirectional communications

- Transmission over the ocean is better for vertical than for horizontal polarization

- The electrically short antenna, though requiring additional land to accommodate its top-hat, does not require the greater ground area required for a comparably-powered horizontally-polarized antenna.

Techniques presented in "VLF Radio Engineering" (paragraph 2.4) by A.D. Watt, can be used to compute expected ground system loss resistances for essentially any VLF antenna by proper summation of losses once the E and H fields and the ground wire distributions are determined over the surface near the antenna. This reference also includes information pertaining to vertical electromagnetic fields, E- field power and wire-surface interface losses, and other related subject matter useful to design engineers and planning personnel, but which may require computer use for computation.

Most VLF and LF antenna installations include a radial-wire or an extensive grid-wire ground system. Either ground system is designed to complement the specific antenna array and is required for proper antenna operation. The elements that comprise a typical LF ground dystem are shown in figure 3-26. A large number of radial wires buried in the ground extend from the antenna feed point. Copper mesh is commonly included near the feed points to reduce ground losses in these regions of high current concentrations and serve as a convenient termination for the inner ends of the radials. The number of radials used is determined on a site basis. When radial wires are placed a short distance above the earth, the system is called a counterpoise ground system.

Some typical ground systems are discussed in "Antenna Engineering Handbook" by H. Jasik, paragraph 19.4. Specific examples are presented with a discussion of the design considerations and techniques for optimizing particular design features. Additional design and planning factors are presented in "VLF Radio Engineering" by A.D. Watts, paragraph 7.4.1.

Another ground system consideration is the effect of corrosion. Corrosion may be caused by the soil at a particular site acting on the buried wire, or it may be caused by RF and direct currents flowing through the system. Originally, it was thought that rectified RF currents would cause electromechanical corrosion. Subsequent studies conducted at North West Cape concluded that RF or AC entering or leaving the ground system would have relatively little affect on the corrosion rate. Direct current will flow due to a difference in potential resulting from galvanic couples between dissimilar metals, concentrations cells between dissimilar ionic solutions and electrolysis between a metal and an ionic solution. The latter may be considered to account for chemical corrosion.

Further analysis at North West Cape showed that four primary types of corrosion may be involved in degrading the ground system: chemical, rectification, galvanic couples, and concentration cells. It was concluded that the rate of corrosion was dependent on

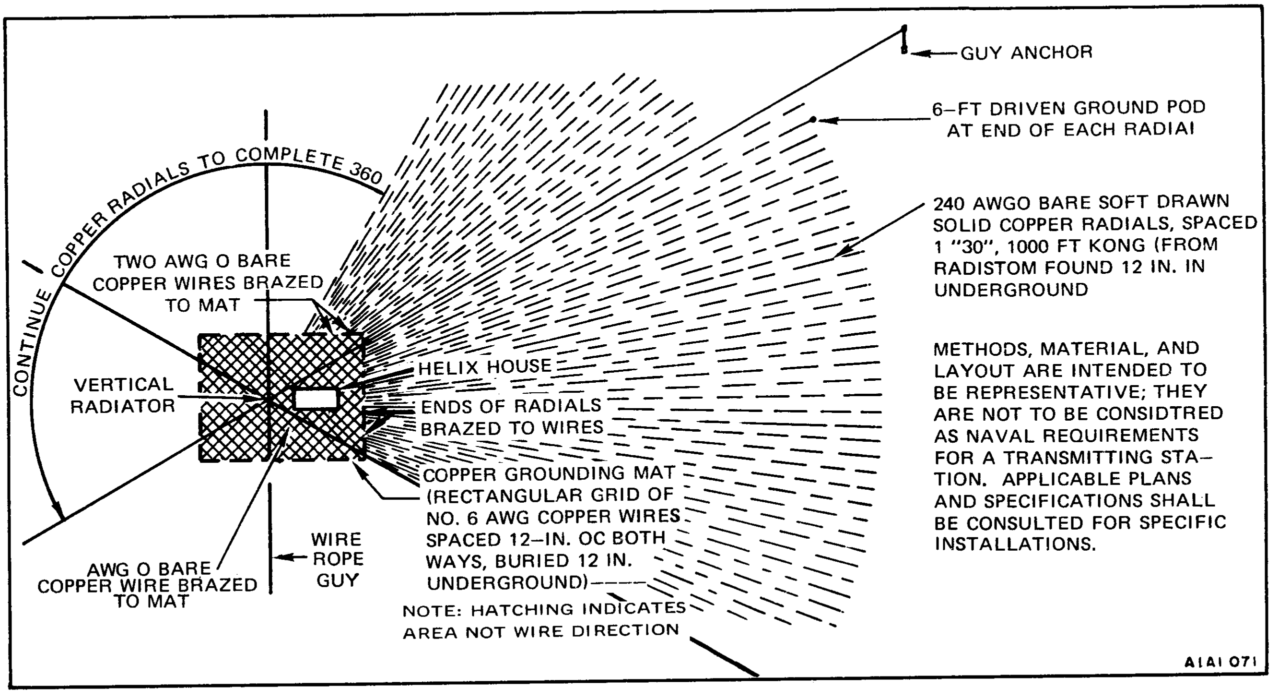


Figure 3-26. Ground-System Elements (Typical for LF Systems)

the DC current component associated with each type of corrosion. A prediction-method was developed for average and maximum penetration of the various types of materials. It was assumed that chemical and rectification attack would be continuous (assuming constant use of the station for the RF effect), thus causing an over-all loss of material or "average" penetration. Superimposed on this constant loss were the affects of galvanic couples and concentration cells which would create further local actions, or pitting, which was identified as "maximum" penetration. Estimates of weight-loss based on these concepts checked reasonably well with measured data.

The studies clearly demonstrated that certain thin metallic coatings over a base material were inadequate in significantly changing corrosion resistance under the indicated site environment. Specific recommendations to be implemented relative to the ground systems resulted from this study.

(1) Bare copper is recommended for all conductors in contact with the earth.

(2) Oxygen-free, soft or annealed copper has been specified before because of its superior tinning qualities and flexibility; other commercial grades may be considered on the basis of economy. Such alternate material should have a minimum of zinc and phosphorus. The apparent variance in corrosion-resistance of zinc- and phosphorus-free annealed or medium hard commercial grades is so marginal that economy and flexibility should be the major consideration. Arsenical copper

(0.5% As) could also be considered on the same basis. Electrical conductivity could be sacrificed to as low as 60% that of pure copper for better corrosion performance.

(3) There appears to be no justification for cleaning and protective coating copper-copper exothermic welds. Requirements to remove slag, however, should be retained, mainly for the purpose of inspection to assure that proper weldment had been made.

(4) All aluminum-to-copper connections in contact with the earth or the atmosphere must be cleaned and protective-coated.

(5) A protective coating must be provided locally where wires traverse the air-ground interface. A minimum of six inches above and below finished grade is considered adequate.

(6) It has been demonstrated that buried conductors will be subject to severe local attack and that dissimilar metals in contact with this environment should be avoided. Since steel is sacrificial to copper, the performance of copper-coated steel rods appears to be marginal based on these analyses. It is recommended that 3/4-inch solid copper be used in lieu of all 3/4-inch copper-coated steel ground rods. The additional cost of solid copper as compared to standard copper pipe and copper-coated steel rod appears to be well justified. Pipe, of course, would have to be filled to prevent double corrosion rate.

(7) Since the majority of ground rods may not be driven in, the requirement for predrilling and backfilling should not be altered. There are air or hydraulic injection methods which may be acceptable. Manual or pneumatic driving should be avoided mainly for the purpose of quality control, inspection, and possible deformations where weldments must be made.

(8) The discarding or otherwise placing of dissimilar (particularly ferrous) metals, carbon, and graphite in the vicinity of the ground system should be avoided.

d. Miscellaneous Antenna Considerations. The large physical size and the electrical smallness of VLF antennas create miscellaneous problems that must be considered and evaluated during the design stage.

(1) Corona. This is an important design consideration because of the extremely high voltages used. At VLF, corona occurs before pluming or flashover, with consequent increase in system-losses due to corona.

As the frequency becomes higher, ionization of the air, which involves a time factor, does not occur as visible corona. The first sign of voltage overstress is a standing arc, or plume. The intense heat of a plume can be very destructive, though in some cases it serves to smooth off, by fusion, any small projection in the metallic conductors that produces an excessive gradient. When a system is operated at potentials close to critical pluming or flashover, care must be exercised in splicing wires, removing projecting ends, nicks on the wires, sharp points and corners on the insulator and assembly hardware, binding wires, etc. to prevent corona formation. The potential-rating of a system decreases with increased altitude, also. High-altitude installations require special precautions, and the system design is such that the installation would be suitable for much higher power if installed at sea level.

Corona and flashover, especially self-propagating arcs or streamers extending to ground or to other wires of the system, depend on the energy of the system as well as the voltage. This is familiar qualitatively to radio engineers, who use different space factors for the same potentials in small transmitters, for instance, as compared with high-power transmitters. As soon as an arc starts, current flows into the capacitance of the arc, which lowers its resistance and changes the electric field configuration in such a way as to reduce the gradients near its base. These reduced gradients move the regions of critical gradient outward, increasing the capacitance and the entering current at the base, with great heat developing in the plume. This continues until a condition of electric and thermal stability is reached, which determines the size of the plume. The current required to sustain a plume of a given size increases with the frequency because the size of the plume determines its capacitance. In high-power systems, a plume can eventually extend itself to the point where it will bridge the line and cause flashover. At flashover the arc reduces the potential between the line or arcing points to extremely low values (approximately 50 volts). Actual flashover is seldom experienced except in rather high power systems, where the size of a plume is not limited by the energy of the system to distances small with respect to wire spacings.

(2) Insulators. Throughout the antenna array and structure, insulators are used extensively. In general, individual porcelain insulators have very small losses, but a typical VLF antenna uses enough of them so that an appreciable amount of power may be dissipated in dielectric heating of the insulators. Use of insulators to insulate the guys and masts supporting flat-tops will reduce induced charges and thereby increase the antenna's effective height. Because of their extensive use throughout the antenna, they represent a significant operating weight, and related cost factor.

An insulator study was conducted under U.S. Navy Contracts N 62477-67-C-1096 NBy 84708 and N 62477-67-C-1097, NBy 84709 by Holmes and Narver, Inc. which resulted in a final report issued May, 1968. The basic objective of the report is to provide technical and economic guidance in the selection of insulators for new antenna configurations. The background information, analysis of available insulation products, and various considerations related to insulator-selection are generally applicable to design of any large radiating structure. Each insulator type is discussed in terms of weight, cost, reliability, performance history, and pertinent design features.

(3) Structural Factors. For antennas over flat terrain, self-supporting towers or guyed masts are used.

The support structures must be designed to withstand wind and, in some cases, ice loading. At VLF, most support structures are required to withstand a rather heavy horizontal pull-off at the top of the support from the top-hat structure. Top loading is generally used to raise the capacitance of the radiating structure and obtain an increase in effective height, and is essential if appreciable power is to be radiated.

Wind and ice loading can be considered as composed of the sum of the pressure drag and viscous drag. Pressure drag is in essence caused by the impinging air particles producing higher pressure on the windward side of the object as compared to the leeward side. Viscous drag important only for very low speeds and small objects, is proportional to the product of speed, viscosity, and size. Wind loading can produce dynamic effects which must be considered in any detailed design (Aeolian Guy Vibrations).

Wires and cables of various types are used throughout the antenna. Steel bridge-cable is normally used for guys where electrical conductivity and potential-gradient is not a problem. For applications requiring large wire diameters to control corona, hollow aluminum cables are also available and have the advantage of low weight for a given size. Aluminum-coated steel provides good conductivity with high strength and stranded cables combining steel and aluminum strands or aluminum strands over aluminum and steel strands are utilized for antenna top loading and tower RF conductor applications. Three standard ice loading conditions are normally considered for cables and towers:

- Heavy loading = 1/2-inch radial ice
- Medium loading = 1/4-inch radial ice
- Light loading = no ice
  (Ice is assumed to weigh 57 pounds per cubic foot.)

A minimum wind velocity of 80 MPH is normally considered when designing for loads due to wind alone. Larger values of wind velocity and combined loadings of wind with ice are determined as required for the location under consideration.

Cables and wires in the antenna are subject to loading due to their own weight, weight of ice (in some locations), and windage. Ice loading and windage are especially severe in the far north, and windage is high in hurricane belts. Stresses in antenna wires and halyards are dependent on allowable antenna sag and shift, which may be limited by electrical considerations. In order to limit stresses in the antenna and loads on the towers, halyards are sometimes provided with counterweight assemblies or friction drums. Provisions are sometimes made to melt sleet and ice off the antenna flat-top by means of 60-Hz power. Protection devices may be added to release mechanical stress on the flat-top when ice formation becomes especially heavy.

(4) Transmission Matching Components. These components are utilized to optimize the coupling between the transmitter and the antenna.

The basic methods for matching VLF communications transmitters to the associated antennas include:

- Link or loop coupling to the PA output and series variometer or variometer/helix antenna tuning (or modification of same)

- Loop coupling to the PA output, Tee network impedance matching, and shunt variometer-series variometer (or variometer/helix) antenna tuning

- Loop coupling to the PA output, PI network impedance matching, and shunt variometer-series variometer (or variometer/helix) antenna tuning.

These components provide coarse and fine tuning to match the transmitter to the antenna. The Tee or PI network provides an impedance match between the PA output and the transmission line. Feed-through bushings generally couple the "helix house" outputs to the antenna downleads. The bushings are usually gas filled to reduce the size of the insulator for a given flashover rating. Sulphur hexifluoride is the gas generally used (due to its superior dielectric properties) at approximately 30 pounds per square inch pressure to increase the breakdown voltage of the gap inside the bushing. The gas feed-line through the bushing should be 1/2 inch or greater in diameter. The tuning systems used at VLF radio transmitting stations are generally designed to operate at any frequency between 14 and 30 kHz.

Losses in the helix tuning coil and variometer are generally insignificant for well designed systems in comparison with other losses. These losses occur in the coil conductors, in the coil frame, and in the surrounding materials. Losses in the conductor are reduced by using Litz wire and by making the coil physically large. Frame loss is reduced by using low-loss material such as porcelain and/or plastic impregnated laminated wood with an absolute minimum of metal fittings. To reduce the loss in the surrounding materials, the entire inside of the room containing the tuning coil may be lined with copper or aluminum sheet. This non-ferrous shield is bonded to the building ground system. Unshielded ferrous materials are not utilized in the high RF fields present in the helix house.

The presence of high voltages and currents in these matching components and their large size have necessitated a specially designed facility or building which is referred to as the helix house. Entrance to the helix house is restricted during system operation by an interlocked non-magnetic metallic barrier bonded to the grounding system.

The helix house is generally located such that it is adjacent to the transmitter building. Cutler, Maine uses a transmission line between the transmitter building and the two helix houses for tuning its antenna system. For those areas where weather, such as in the torrid or lower temperate zones, does not have detrimental effects, transmission lines may be run above ground in accordance with accepted design practices. However, at facilities where inclement weather prevails, it may be necessary to provide an underground transmission line network. This underground layout at Cutler is large enough to permit access by personnel for the required maintenance and servicing. The transmission line consists of a 9-inch coaxial cable.

3.1.4 Additional Equipment Considerations

There are additional equipments which are an integral part of the VLF radio transmitting station. They perform necessary and specific functions in the overall station equipment operation. Their relationship will be identified in short paragraphs. Reference should be made to each station's technical documentation for specific details.

a. Station Cooling Equipment. During normal routine station operations, the equipment generates heat which must be removed to maintain the proper operational environment. Equipment-generated heat will cause deterioration and degradation of parts and components resulting in inefficient station operation. The station cooling system takes in outside air filters and cools it and circulates it through the equipment. If located in an area of salt air or other corrosive gasses, use high efficiency filters, 85 percent efficiency using NBS atmospheric dust spot test, with prefilters on air supply to building. The equipment-heated air may be routed to an air-to-water heat exchanger to reduce the temperature prior to its re-use with air taken from the outside. This technique of recirculating the inside and new outside air provides a static balance of pressure and temperature in the cooling system. Heat generated in RF components of the IPA's and PA's may be removed by individual heat-exchangers for each unit. Water or air as appropriate is used to cool the RF tubes in operation, the cooling water will be a water-to-water heat exchanger which uses salt or fresh water to cool the distilled water by conduction. Individual heat-exchangers are also used for the dummy load (and the bandwidth resistor if installed).

b. Station Power. Power inputs to the VLF radio transmitting stations are generally commercially supplied and vary with the transmitter rated output and efficiency. For those stations remotely located, power lines may terminate at a main power building located on the outer perimeters of the site. From this building, distribution of the stations power needs are made. A bus provides the 4160 VAC input to the transmitter building for subsequent reduction and routing to the transmitter equipment. The transmitter power distribution network is a complex array of individual circuit breaker panels controlling the routing of AC voltage to the respective equipments.

c. Safety Features. Due to the presence of the high equipment operating voltages and potential radiation hazards, extensive personnel and equipment protective measures are employed throughout the station. For protection of human life, a key interlock system, designed to prevent operating personnel from accidentally contacting any energized circuits having dangerous potentials, is used throughout the system. Equipment access doors cannot be opened while the power circuit breakers are in the 'ON" position. Before entry can be made through these doors, the equipment must be shut down and the high voltage circuit set to "OFF".

In addition there are specific areas within the buildings that are fenced off to prevent access by personnel. Within individual equipments, protective circuitry is included permitting monitoring of equipment status and operating conditions at the main console and at individual cabinet front panels.

d. Oil Filter System. An oil system that stores, filters, and transfers insulating oil for the PA output tuning and/or matching network capacitors is included. A dielectric tester is included in the network to measure the dielectric consistency of the oil.

e. Deicing. At Cutler, Maine, an elaborate deicing system is installed for each antenna array. When ice begins to form on the antennas, one antenna is removed from operation for deicing. Inside the helix house large electrically operated switches apply either the RF output or the 60-Hz power into the antenna system. When the deicing circuit is in use, the RF circuit is shorted to ground. The deicing system is designed to remove ice accumulations on the antennas to a radius of 3 inches.

3.2 OMEGA VLF RADIO TRANSMITTING STATION EQUIPMENT

Each OMEGA station generates a radio signal to be transmitted for use as a navigational aid. The OMEGA network will consist of eight ground stations providing worldwide coverage. In comparison to the high radiated power of VLF radio communication stations, the OMEGA radiated power requirement is only 10 kW. A simplified configuration block diagram of the station structures and their functional equipment blocks is shown in figure 3-27.

Each station operates from cesium beam standards which provide the measure of frequency stability necessary to produce the desired system accuracies. Timing accuracies have been maintained within ± 2 microseconds. Three frequencies (10.2, 13.6, and 11.33-1/3 kHz) are transmitted in a commutated pattern for navigational positioning. In addition, each station contains additional equipment permitting transmission of one or two other frequencies for use as an accredited standard frequency source.

The transmitting antenna radiated power is about 10 kW using a top-loaded antenna.

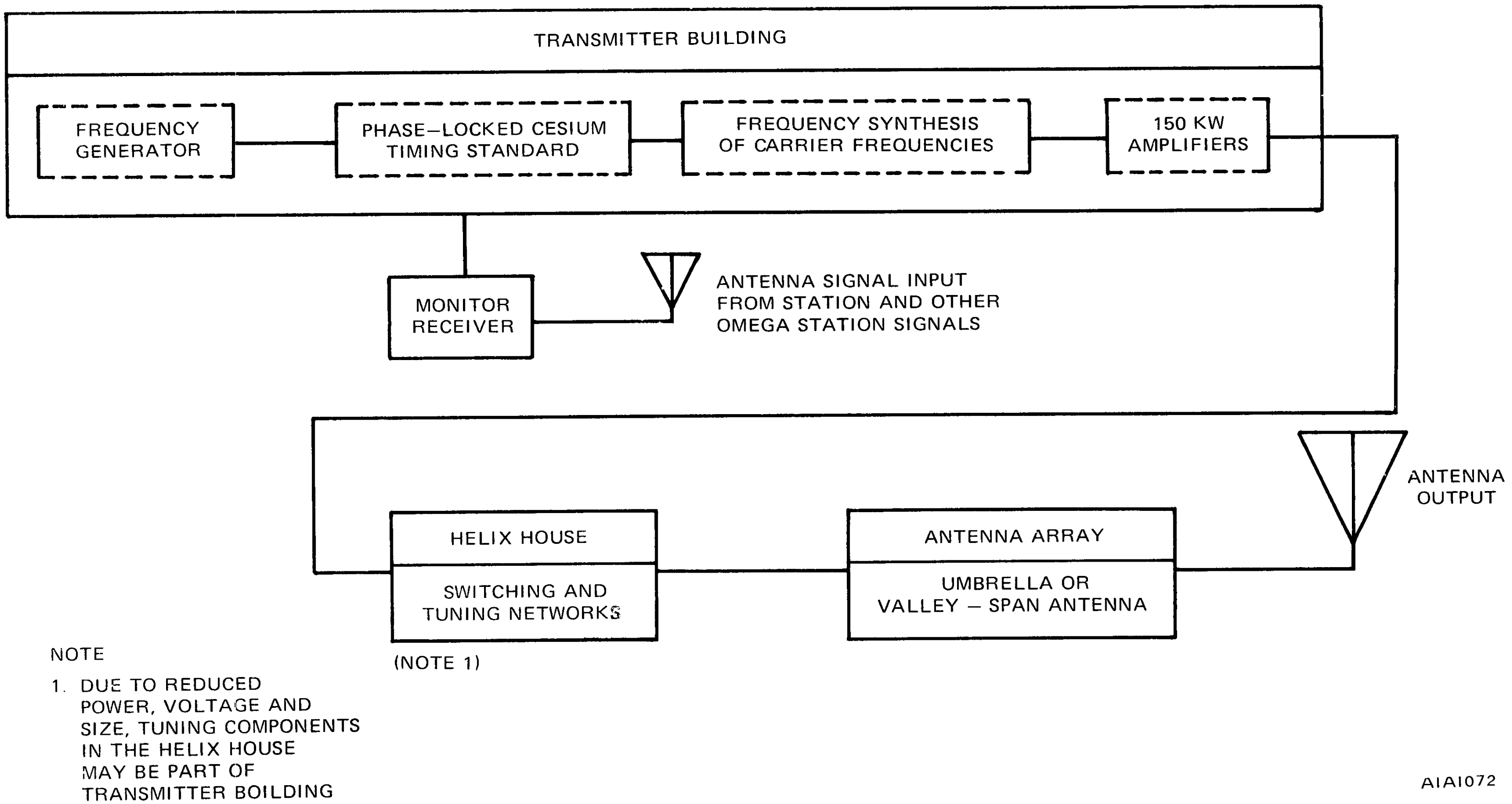
3.3 VLF RADIO RECEIVING EQUIPMENT

The VLF radio receiving set is the important unit in the reception of VLF radio transmissions from a shore station. Shipboard installation requires the receiver be a precision instrument capable of fine tuning over the frequency range of 14 to 30 kHz, have good frequency stability, and good signal sensitivity. It must also be capable of transforming received FSK or ICW radio transmissions into the proper format for subsequent processing, and be readily adapted to any one antenna type it may be used with. The set which is currently utilized for VLF operation is designated the AN/BRR-3. Three other radio receiving sets with tuning capabilities over the VLF, LF, and MF frequency range are also used. The AN/FRR-21 and AN/WRR-3 operate at 14 to 600 kHz and are capable of receiving ICW, MCW, and FSK transmissions. The URR/R389 operates at 15 to 1500 kHz and is capable of receiving ICW, MCW, AM, and FSK transmissions.

The antenna configurations that the radio receiving set would operate with include the loop antenna, the buoy antenna, and the ship antenna. The Radio Receiving Set AN/BRR-3 with the three antenna types and ancillary equipment is shown in figure 3-28.

3.3.1 Radio Receiving Set, AN/BRR-3

The receiver is a superheterodyne set made up of relatively wideband RF and variable-bandwidth IF circuits with impulse-noise cancellation and narrowband IF circuits. Any frequency in the 14 to 30 kHz range may be selected with an accuracy of ± 100 Hertz. Finer tuning may be interpolated from the dial indicators. Receiver



NOTE

1. DUE TO REDUCED POWER, VOLTAGE AND SIZE, TUNING COMPONENTS IN THE HELIX HOUSE MAY BE PART OF TRANSMITTER BOILDING

Figure 3-27. OMEGA Radio Transmitting Station Simplified Configuration Block Diagram

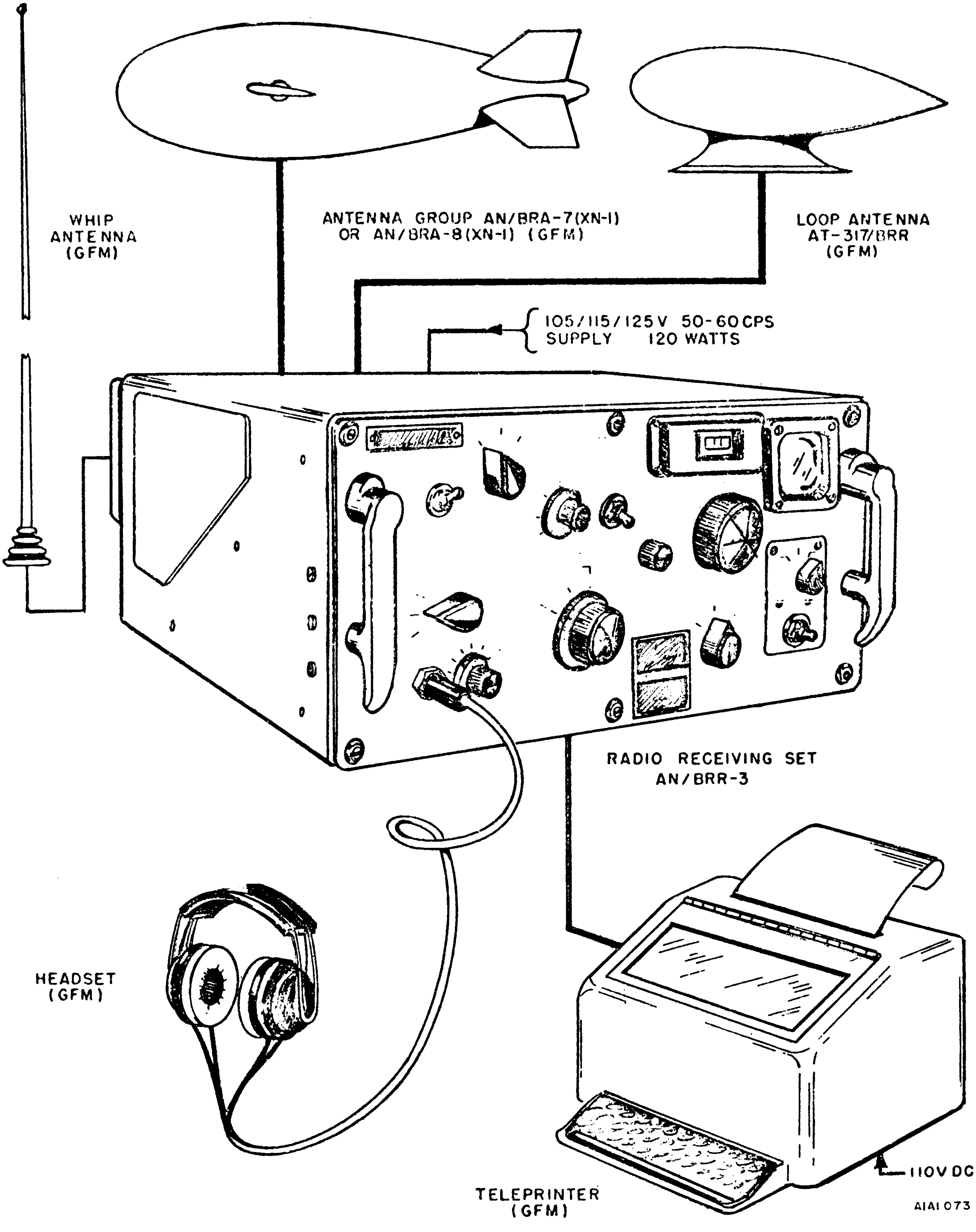


Figure 3-28. Radio Receiving Set AN/BRR-3 and Accessory Equipment (Typical)

sensitivity variations due to using any one of the three antennas is compensated for automatically by a selector switch which matches the correct impedance network with the antenna. A separate input jack for each antenna type is provided on the rear panel of the receiver. Receiver selectivity depends on the selected bandwidth circuit and noise-cancel condition chosen. Audio monitoring of ICW signals is possible with a headset connected to an audio output jack. When receiving FSK signals, it is possible to monitor this signal with a teleprinter connected to another output jack. Detailed equipment information can be found in the Radio Receiving Set AN/BRR-3 (U) Technical Manual, document number 0967-063-6010.

This receiver also is capable of receiving facsimile (FAX) signals when provided with additional terminal equipment.

3.3.2 Receiving Antennas

Three types of antennas may be used with the AN/BRR-3 receiver through the use of an antenna selector switch on the front panel. The different antennas are (refer to figure 3-3); whip or wire antenna with an output capacitance (including cable) greater than 1000 micromicrofarads, any 50-ohm output impedance antenna system, or any antenna in the AN/BRA-7 or AN/BRA-8 Antenna Group, or Loop Antenna AT-317/BRR series.

Details pertaining to equipment interface, cabling, and operational considerations for each antenna type are included in the referenced receiver technical manual.

3.4 OMEGA VLF RADIO RECEIVING EQUIPMENT

Many different kinds of receivers may be designed to work with part or all of the OMEGA spectrum. The OMEGA navigational receivers are required for the following categorical groupings:

o A relatively simple, single-frequency receiver for use aboard small and medium-size surface ships

o A computerized, fully-automatic receiver for use aboard aircraft and submarines.

The AN/SRN-12 is an operational receiver satisfying the applicational requirements of the first group. An airborne receiver designated the AN/ARN-99 provides the basic family of OMEGA navigational receivers identified by the categorical groups.

Antenna coupling units are generally required to provide the correct impedance match between the navigational receiver set and those antennas currently in use.