THE BIGGEST LITTLE ANTENNA IN THE WORLD

The Navy's VLF antenna at Cutler Maine

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A small SMALL ANTENNA
CUTLER VLF (3-30 KHz) ANTENNA

• Why A VLF Antenna?
• Types Of Antennas
• Trideco Design At Cutler, Me.
• Towers and Top Load
• Tuning Network
• Ground System
• Deicing
• Modulation and Reception
HISTORICAL VLF ANTENNAS

• Marconi transmitter at Poldhu, UK
  • Height: 200 ft.
  • Built 1900
  • Destroyed by Storm 1901
  • 24 KW
  • 80 KHz

• Telefunken Transmitter at Sayville
  • Height: 477 ft.
  • Built 1912
  • 200 KW
  • 32 KHz

• German WW II VLF Antenna (Goliath)
  • Height: 673 ft.
  • Removed by Soviets After the War
  • 1800 KW
  • 16 KHz
“ka” MEASURE OF ANTENNA ELECTRICAL SIZE

Wave Number = \( k = \frac{2\pi}{\lambda} \)
Wavelength = \( \lambda \)
Radianlength = \( \frac{\lambda}{2\pi} = \frac{1}{k} \)
a = radius of sphere (Chu Sphere) that circumscribes antenna
\( ka = \frac{1}{2} \) largest antenna dimension in Radianlengths
Electrically small antenna = \( ka < 0.5 \)

FOR CUTLER ANTENNA

Frequency = 15 KHz  \( \frac{H}{\lambda} = \frac{140}{20,000} = 0.007 \)
\( \lambda = 20 \text{ Km} \)
Effective Height = \( H = 140 \text{ m} \)
\( \frac{a}{\lambda} = \frac{640}{20000} = 0.032 \)
Physical Radius = \( R_p = 625 \text{ m} \)
a = \( \sqrt{R_p^2 + H^2} = 640 \text{ m} \)
\( ka = \frac{2\pi a}{\lambda} = 0.20 \)
Q LIMITS FOR SMALL ANTENNAS

Cutler

\[ f = 24 \text{ KHz} \]
\[ ka = 0.32 \]
No Loss, \( Q = 259 \)
74.9\% Rad Eff, \( Q = 194 \)

Chu-Hansen Limit
Single Spherical Mode

\[ ka \leq \pi/2, \ 2a \leq \lambda/2\pi \]

Wheeler Limit
Lumped Element

\[ ka \leq 1/2, \ 2a \leq \lambda/2 \]

Chu-Lower Bound for \( Q \)

\[ Q_{\text{LB}} = \frac{1}{(ka)^3} \]

Wheeler Lower Bound for \( Q \)

\[ Q_{\text{LB}} = \frac{1 + (ka)^2}{(ka)^3} \]

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WHY A VLF SYSTEM?

• With the creation of ballistic missile submarines it became essential to maintain communications
• To avoid detection, nuclear submarines must remain submerged
• VLF provided penetration of seawater 30 to 100 feet because of the very long wavelength
• Very low loss propagation (2 dB/1000 Km)
BALLISTIC MISSILE SUBMARINES

- USS NAUTILUS
  - FIRST NUCLEAR-POWERED SUB
  - COMMISSIONED 1954
  - OPERATE SUBMERGED FOR MONTHS

- USS GEORGE WASHINGTON
  - FIRST BALLISTIC MISSILE SUB
  - 16 POLARIS MISSILES
  - COMMISSIONED DEC 1959
SKIN DEPTH

Attenuation of RF Passing Through Conductive Media

frequency (MHz)

0.01  0.1  1   10  100  1000

Sea Water (4 Siemens)
1E-4 Siemens
Ionosphere
1E-7 Siemens

attenuation (dB/ft)

0.00001  0.001  0.1  1  10  100  1000
US NAVY VLF COMMUNICATION SYSTEM (1990s)

Very Low Frequency/Low Frequency Site Locations
VLF ANTENNA SYSTEM REQUIREMENTS (1959)

- Tunable 14.3-30 KHz
- Radiated power: 1 MW
- Max voltage: 200KV; Max E-field: 0.65 KV/mm
- Efficiency: >50% ($500K penalty)
- Bandwidth: at least 30 Hz
- Operational conditions include 1 1/2-inch ice and 175-MPH winds
- Redundant for reliability and maintenance- two antennas
ANTENNA CONFIGURATIONS

- TRIATIC TOP LOAD
- UMBRELLA TOP LOAD
- TRIDECO TOP LOAD
EXAMPLE OF TRIATIC

RCA’s Radio Central at Rocky Point Used A Set Of Triatic Antennas
Assumptions

\[ f = 15 \text{ KHz} \quad \lambda = 20,000 \text{ m} \]
\[ p = \text{power factor} = .002 \]
\[ P = 1 \text{ Megawatt} \]
\[ A = \text{effective area} \]
\[ h = \text{effective height} \]
\[ Ah = \text{effective volume} \]
\[ V = \text{max. topload voltage} = 200 \text{ KV} \]
\[ E_a = \text{maximum E-field gradient on topload} = .65 \text{ KV/mm} \]
\[ A_a = \text{conductor area} \]

1. Bandwidth defines effective volume
\[ Ah = \frac{3p\lambda^3}{8\pi^2} = .608 \text{ K}m^3 \]

2. Max. Voltage defines Topload effective area
\[ AV = \left( \frac{3\lambda^2}{2\pi} \right) \sqrt{10P} = 604 \text{ m}^2 \text{KV} \]
   for \( V = 200 \text{ KV} \quad A = 3.02 \text{ K}m^2 \quad (2.75 \text{ K}m^2) \]

3. Effective height = \( .608/3.02 = 200 \text{ m} \quad (140\text{m}) \)

4. Max. voltage defines topload area
\[ A_a = \pi \left( \frac{\lambda}{2\pi} \right)^2 \left( \frac{3}{hE_a} \right) \sqrt{40P} = 4650 \text{ m}^2 \]
   For 1” cable, length = 58 Km \( (47 \text{ Km-}98\text{Km}) \)

Ref 1
WIPL-D Model (Radius = 625 m, Height = 140 m)

- Wire Dia. = 2 m

- Shunt Inductance (29.3 μH)

- Series Inductance (142 μH)

- Generator

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Computed Reflection (Impedance)

Radiation Efficiency = 100%
f = 24 KHz Q = 259
Note: Q computed using Yaghjian-Best Formula:
AP Trans., Apr 2005

\[
Q = \frac{f}{\Delta f} \sqrt{\frac{\Delta R^2 + \left( \frac{X}{f/\Delta f} \right)^2}{2R}}
\]

\(f = \text{Resonant frequency}\)
\(\Delta f = \text{Frequency increment for } \Delta R \text{ and } \Delta X\)
TRIDECO ANTENNA

- Six topload panels
- 13 towers
- Approx. 1000 Acres
- Minimizes Corona
TWO ANTENNAS OCCUPY 2000 ACRES ON A PENNINSULA

• Dual transmitter feeds helix house through 100 ohm coax

• Helix house contains tuner

• Trideco top load uses 6 panels for each monopole

Figure 1. VLF Cutler. Ref 6
OVERVIEW OF ANTENNA CONFIGURATION

Figure 1. General layout, Cutler Peninsula.

Location, location

Ref 7

Google Maps
26 TOWERS- 850 to 1000 FT HIGH
SATELLITE IMAGES

Power Plant 18 MW

Main Tower And Helix House

Bing Maps
EACH ANTENNA CONSISTS OF 13 TOWERS

Exciting Engineering Work

Ref 8
Figure 3. VLF Cutler feed-cage and counterweight configuration.
ANTENNA PERFORMANCE (24 KHz)

Table ES-1. South array antenna measurement results.

<table>
<thead>
<tr>
<th></th>
<th>Six-Panel Mode</th>
<th>Four-Panel Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antenna effective height (m)</td>
<td>140.1 ± 2.8</td>
<td>130.4 ± 2.6</td>
</tr>
<tr>
<td>Antenna self resonance (kHz)</td>
<td>40.2</td>
<td>40.0</td>
</tr>
<tr>
<td>Antenna static capacitance (nF)</td>
<td>123.9</td>
<td>90.1</td>
</tr>
<tr>
<td>Gross resistance (ohms)</td>
<td>0.2649</td>
<td>0.2675</td>
</tr>
<tr>
<td>measured at full power</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radiation resistance (ohms)</td>
<td>0.1984 ± 0.0077</td>
<td>0.1719 ± 0.0068</td>
</tr>
<tr>
<td>Antenna base reactance (ohms)</td>
<td>-j 35.4</td>
<td>-j 50.2</td>
</tr>
<tr>
<td>measured at low power</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Antenna bandwidth (Hz)</td>
<td>137.5</td>
<td>100</td>
</tr>
<tr>
<td>Antenna radiation efficiency (%)</td>
<td>74.9 %</td>
<td>64.3 %</td>
</tr>
<tr>
<td>Base voltage (kV)</td>
<td>65.5</td>
<td>99.7</td>
</tr>
<tr>
<td>Base current (A)</td>
<td>1850</td>
<td>1987</td>
</tr>
<tr>
<td>Radiated power (kW)</td>
<td>679</td>
<td>679</td>
</tr>
</tbody>
</table>

Ref 7
CUTLER PERFORMANCE VS FREQUENCY

Fig. 2.8.14. Reactance and bandwidth vs. frequency, Cutler.

Fig. 2.8.15. Radiation efficiencies vs. frequency, Cutler.

Ref 2
DESIGN ISSUES

- Corona/Lightning
- Mechanical Design
- Ice Load
- Antenna Impedance and Efficiency
- Ground system
- Transmitter
DESIGN ISSUE: CORONA

- Actual Antenna Voltages 250 KV Plus Lightning
- Electrical Breakdown of the Air
- Depends on Field Strength, Geometry and Air Pressure
- Designed in 1959 for Cutler Antenna using model and 50 KV
- Special hollow 1.5in cable used in critical areas
• 24,000 feet of cable – 120,000 pounds
• Wire spacing optimized for equal charge
• Wire diameter selected to meet specified electric field (0.65-0.8 KV/mm)
FEED LINES AND INSULATORS
EACH INSULATOR IS 57 FT LONG TO WITHSTAND 250 KV

13,000 lbs.
TOPLOAD COUNTERWEIGHT SYSTEM
TOPLOAD COUNTERWEIGHT SYSTEM

- Counterweights weight 220 Tons
- Panels can move with wind and ice load
- Panels can be lowered for maintenance
- Pulley system reduces weight movement

Ref 5
TOPLOAD COUNTERWEIGHT SYSTEM

Concrete filled wheel

Ref R. Mohn
TOPLOAD DEICING

DEICING POWER

- Deice one antenna at a time
- Topload designed to be lossy at 60 Hz
- 1.6 W/Sq. In = 7.5 Megawatts to Deice
- Diesel generators provide 18 Mw

Figure 7. Simplified schematic diagram of one division in deicing mode.

Ref 7
TUNING NETWORK-HELIX HOUSE
TUNING NETWORK

- Handle 200 KV And 2000 Amps
- Very Low Loss $\ll 0.1$ Ohm
- Tune Antenna Over 14-28 KHz
- Tune Antenna with Modulation
- Antenna Impedance is Capacitive

Figure 8. Simplified schematic diagram of one division in transmit mode.
TUNING NETWORK- HELIX

Ref 8
TUNING NETWORK- HELIX
TUNING NETWORK-VARIOMETER

Wires are 4 inches diameter

(c) 1998 JAMES P. HAWKINS - WAVBV

Ref 5  NAA  Wires are 4 inches diameter  NSS  JP Hawkins
TUNING HELIX - LITZ WIRE

(c) 1998 JAMES P. HAWKINS - W7LTV

JP Hawkins
TUNING HELIX- LITZ WIRE

• Critical to reducing loss in high power tuning inductors
• Skin effect forces most AC current to the surface of a solid conductor, increasing resistance
• Litz wire equalizes current throughout a large conductor
• Thousands of small wires are insulated, braided and packed in large conductor
• Cutler design is a Litz conductor 4 inches in diameter, with 3 parallel conductors

Ref 9
TUNING INDUCTOR IN HELIX HOUSE

Ref 5
TUNING NETWORK- TRANSMITTER OUTPUT TRANSFORMER

OUTPUT TRANSFORMER—twice as tall as a man—typifies over-size equipment. It is new “toroid” type with slanting copper strips corresponding to the coils of an ordinary transformer.

Ref 5

NAA

(c) 1998 JAMES P. HAWKINS, WA4WHV

JP Hawkins

NSS
COAXIAL FEED LINE - TRANSMITTER TO HELIX HOUSE

- 100 Ohm Feed Line From Transmitter To Helix House
- 1MW Power Capacity
- 100 KV
- 2000 Amps

"Ever see a man standing inside a coax matching section? Chief Electronic Technician Swan, who is in charge of all maintenance at NAA, stands inside the copper-lined concrete tunnel mentioned in the text.

Ref 5
DESIGN ISSUE: GROUND SYSTEM LOSS

2000 Miles of #6 Copper Wire Cover the Peninsula and Run Into the Sea

Ref 5
CUTLER GROUND SYSTEM PERFORMANCE

Fig. 7.4.2. Observed and calculated ground system wire length and approximate ground system costs as a function of ground system resistance.

Ref 2
DUAL TRANSMITTERS: 1MW EACH

This is the control console for a two-megawatt transmitter. Driver stages and final amplifiers along the rear walls, with the "guts" of the units well-protected against accidental access.
TRANSMITTERS
DATA/MODULATION

FREQ SHIFT KEYING

MINIMUM SHIFT KEYING
MODULATION

- Narrowband MSK (50-200 bps)

- Continuous Modulation

- Encrypted

- Antenna reactor tunes with modulation
SUBMARINE RADIO RECEIVERS

USS Robert E Lee 1966

USS Nautilus 1970s
MODERN VLF RECEIVER

ENHANCED VERDIN

• UP TO FOUR 50 BPS CHANNELS
• MULTIPLEXED, ENCRYPT AND ENCODE
• MSK MODULATION

TECHNICAL DESCRIPTION

• Requirement: CNO ITR 204D Ser/941D/8U536539 of 18 Oct 89
• Basic Description of System:
  – VERDIN/EVS Provides Shore-to-Sub Communications for Subs at Speed and Moderate Depth.
  – The Equipment is installed in all Submarines and TACAMO Aircraft and the Program is in Post-Production/Operational Phase, Supported by NRaD.
  – Shore System Components Include ISABPS and VERDINs at all FVLF Shore Sites, Off-the-Air Monitor Systems, Trainers, and TACAMO Communication Centers.
  – VERDIN/EVS Systems are Compatible with NATO, MEECN, and Sub BCS GENSER/SE Modes.
  – The VERDIN/EVS Receiver will be Replaced by SLVR.
ACKNOWLEDGEMENTS

My thanks to Al Lopez, Peder Hansen, Nick England and Harold Wheeler for their invaluable contributions.
REFERENCES


   Chapter 6  H. A. Wheeler; Chapter 24 B. G. Hagaman

10. NAVELEX MANUAL 0101,113 “VLF Communication Equipment”

11. navy-radio.com

12. H. A. Wheeler Design Notes ARLAssociates.com
HISTORICAL NOTES: SAYVILLE DESIGN
INFORMATION- 1918

RADIO TELEGRAPH

Sayville #22

Aug 28, 1918

Corona Arrester 6' 16000 Megohms 16000 Volt Effective 8000 Volt Max

Capaciety 0.023 M.F.P. 196000 A

Spoke Wire 7-14 B.F. No. 8 Silver Bronze 30' 1.926 Ohms

Copper Wire 7-16 B.F. Silver Bronze 30' 1.245 Ohms

Antenna Insulators Type SL 948
Fig. 174.—An immense transmitting tuning coil at Radio Central. Note the size, compared with the man standing at its base.
Fig. 173.—An Alexanderson high-frequency Alternator, capable of putting 700 amperes of high-frequency current into the antenna.