Performance Analysis of Large Electrically Small Transmit Antennas

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***Abstract*—This paper discuses the design/analysis techniques used to analyze the performance of high power electrically small transmitting antennas. In this case they are applied to conversion of a 100 kHz antenna to operate at lower frequencies.**

(Electrically Small Antennas, high power, transmitting antennas, Radiation Q)

I. Introduction

The U.S. LORAN-C 100 kHz pulse navigation system was shut down on Feb. 8, 2010. There were 26 sites in CONUS with various sizes and types of antennas. The majority of them were umbrella top-loaded monopoles. There were five Sectionalized Loran Transmitting (SLT) antennas and one Top-Loaded Inverted Pyramid (TIP). The peak radiated power levels were typically 500 kW but the SLT and TIP antennas radiate considerably more. The Coast Guard is making plans for disposal of the sites and demolition of the towers; however, at this time they are still available to other agencies.

The U.S. Navy has completed a study to determine the cost of developing two new CONUS LF (30 – 75 kHz) transmitters, one east coast and west coast for the submarine broadcast. The U.S. Air Force is also interested in terrestrial VLF transmitters (3 – 10 kHz) to support an experimental VLF satellite mission DSx scheduled for 2014. The Loran-C stations with the SLT and TIP antennas are candidates for both of these applications. These antennas are all similar and capable of radiating large amounts of power at 100 kHz. This paper covers analysis of the capability of these antennas converted to these lower frequency missions.

II. SLT Antenna

The SLT was developed by the Coast Guard for use as a high power electrically small transmitting antenna about 1970 [1]. It is quite different than most other electrically small high power transmitting antennas. It was one of the first practical antennas to which numerical modeling was applied for analysis and optimization, including the effect of ground losses [2]. The Loran SLT antennas consist of 4-700' tall grounded towers laid out in a square 1450' on a side (Fig. 1). The radius of a sphere containing the antenna and its image corresponds to 0.1025 wavelengths at 100 kHz so that even though the antenna is physically large it is approaching being Electrically Small (ka < 0.1) at that frequency [3]. It is well known that ESA have inherently large values of radiation Q which results in (1) narrow bandwidth, (2) reduced efficiency and (3) limited radiated power. Nevertheless, the SLT is a very capable antenna able to radiate peak power of more than 1.45 MW at 100 kHz. A plan view of the SLT at Caribou ME is shown in Fig. 2.

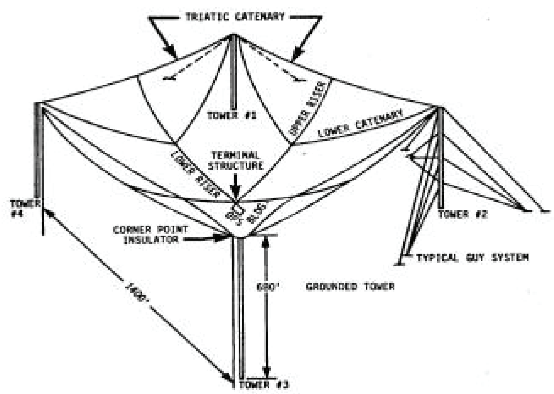

Figure 1. SLT Antenna.

Figure 2. Plan view of Caribou SLT antenna.

The antenna consists of 4 separate panels suspended between the perimeter tower pairs. Each panel is a Tee consisting of an upper catenary suspended between towers and a second (lower) centenary beneath it. The ends of these catenaries are held up by halyards (back stays) that go through a block on the tower top. A single large insulator holds the ends the catenaries. The vertical part of the Tee is called the riser. Fig. 3 shows the layout of a single panel and Fig. 4 shows a scale model with a single panel in place. Each riser is pulled in to the center of the array near the ground and they are connected together to form the feed point (Fig. 5).

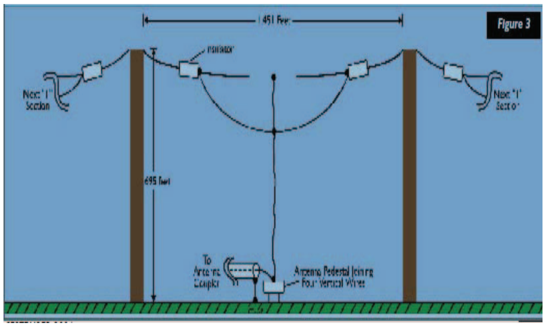

Figure 3. SLT panel layout.

Figure 4. Scale model SLT with one panel in place.

Figure 5. SLT Feedpoint at George, WA.

The SLT antenna at the Loran station at George, WA is the same as the one at Caribou. Table 1 gives the operating parameters for these antennas when they were in service.

Table 1. LORAN SLT operating parameters at 100 kHz.

Station	Peak Power (kW)	Peak Current (Amps)	Impedance	Feed Voltage (kV)
George	1450	1125	15.36	17.28
Caribou	780	825	15.36	12.67

These antennas have an extensive buried ground system consisting of 120 #8 copper wires radial from the feed point buried 1 foot deep. They have 8-foot ground rods at the end of the radials and there is a perimeter bus that connects the ends of all the ground radials.

III. Design Considerations and Analysis Technique

In order to operate the SLT at frequencies significantly below 100 kHz it is necessary to tune the antenna with an inductor. The critical parameters that limit radiated power are: (1) voltage and current on the tuning elements (2) corona on the antenna wires (3) voltage on the antenna insulators and (4) currents on the antenna conductors.

For a fixed transmitter power; radiation efficiency also limits the available radiated power. The resistive losses that reduce radiation efficiency are located (1) in the antenna structure (2) in the ground system and (3) in the tuning and matching circuit elements. In this type of analysis, the limitation on radiated power is determined for each antenna component and the lowest one at each frequency selected as the overall limit.

The SLT antenna was modeled physically using scale models and numerically with both NEC and MININEC and the results compared. The antenna is resonant at a frequency slightly above 100 kHz (Fig. 6.) Near resonance the voltage at the extremities are be much greater than at the feed and become the limiting parameter. However, as frequency is reduced below self resonance the voltage at the extremities and the feed point start to approach the same value so the feed voltage may become the limit.

The power limitation due to corona was determined by using MININEC to calculate charge density on the wires, which is converted to the surface electric field (E_s). The input current was adjusted to keep E_s below the critical level for corona onset (Fig. 6.) [4]. Power transmission lines are often designed to operate in corona, especially during inclement weather. However, since the energy dissipated in corona is proportional to the frequency it is not practical to operate in corona at VLF and higher frequencies [4].

The insulator voltages were determined using MININEC by placing high-impedance loads at the insulator locations [5]. The input current was adjusted to keep these voltages below the insulator limits. When new insulators are to be used, this approach is used to determine the required insulator voltage ratings.

The antenna structure losses were calculated using MININEC by loading on the antenna wires, in this case the antenna has aluminum conductors. The tuning and matching network losses are calculated by assuming a Q of 1500.

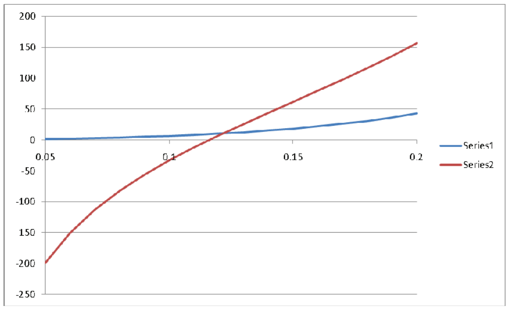

Figure 6. SLT input impedance.

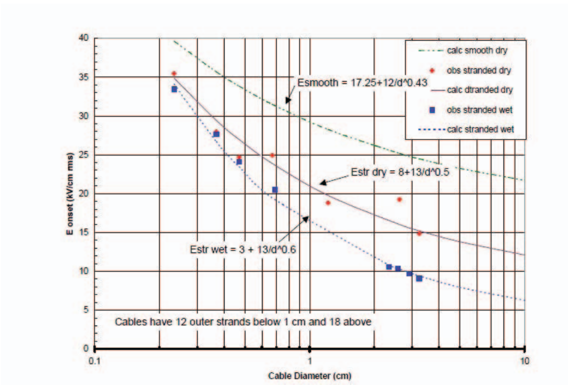

Figure 7. Critical E_s for corona onset at 40 kHz.

The ground losses were calculated in two ways. One way is to use the surface impedance of the ground in parallel with the impedance of the wire mesh, which was originally used in [1]. There are advantages to this approach in that the losses can be partitioned into parts associated with various locations in the antenna ground system [6]. The other method uses the full wave solution based on the Sommerfeld Integral to account for the effect of lossy ground [7], which is available in NEC [8] and can be applied to buried ground systems. The results of these two techniques are comparable.

IV. Performance

The antenna performance was calculated for two sets of assumptions. First was a 100 kW transmitter with minimal changes to the antenna. The second was a 250 kW transmitter with significant changes to the antenna. The ground system was unchanged for both options.

A. 100 kW Transmitter

For this case the feed point voltages are limited to 50 kV. The feed point must be modified slightly to handle the current and voltage. The maximum voltage on the top insulators is 65 kV rms.

The expected performance for this option is given in the Table 2 and the power radiated versus frequency is shown in Fig. 8. Note that at the lowest frequency the power is reduced, limited by voltage at the feed point.

B. 250 kW Transmitter

The second set of assumptions is a 250 kW transmitter combined with significant antenna modifications, including new insulators and a modified feed point. For this case the maximum base voltage is 75 kV rms and the maximum voltage on the top load insulators is 95 kV rms.

The expected performance for this solution is given in Table 3 and the power radiated versus frequency plotted in Fig. 8. Note that the antenna is current limited at the lower frequencies due to the single riser per panel. Also note that the top load corona limits are well above the other power limits for either set of assumptions.

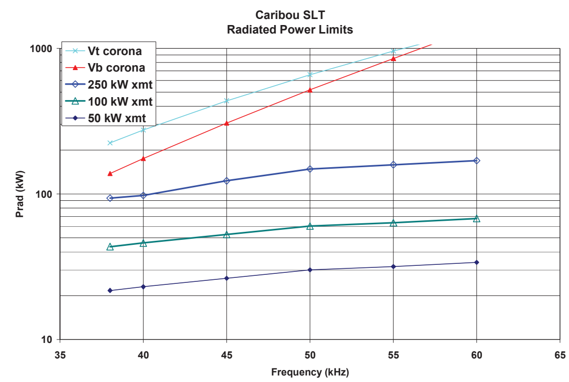

Figure 8. SLT Performance for both options.

References

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[8] EZNEC-5, http://www.eznec.com/

Table 2. SLT Option A. – Minimal Antenna Change 100 kW transmitter									
Freq kHz	Rr Ohms	Rg Ohms	Eff	Xb Ohms	Tuning Ind (mH)	Ibase amps	Vbase kV	Pr kW	Limit
38	0.363	0.835	0.435	-147	0.616	340	50.0	41.9	Vb
40	0.403	0.877	0.460	-138	0.548	338	46.5	46.0	xmt
45	0.515	0.980	0.526	-118	0.415	320	37.5	52.6	xmt
50	0.643	1.069	0.601	-101	0.321	306	30.8	60.1	xmt
55	0.786	1.239	0.635	-86.5	0.250	284	24.6	63.5	xmt
60	0.947	1.397	0.678	-74.1	0.197	268	19.8	67.8	xmt

Table 3. SLT Option B. – Modified feed point, helix house 250 kW transmitter									
Freq kHz	Rr Ohms	Rg Ohms	Eff	Xb Ohms	Tuning Ind (mH)	Ibase amps	Vbase kV	Pr kW	Limit
38	0.363	0.835	0.435	-147	0.616	508	74.8	93.6	Ib
40	0.403	0.877	0.460	-138	0.548	492	67.8	97.7	Ib
45	0.515	0.980	0.526	-118	0.415	488	57.3	122.7	Ib
50	0.643	1.069	0.601	-101	0.321	480	48.4	148.1	Ib
55	0.786	1.239	0.635	-86.5	0.250	449	38.8	158.6	xmt
60	0.947	1.397	0.678	-74.1	0.197	423	31.3	169.5	xmt