Low Cost Digitally Enhanced Loran for Tactical Applications (LC DELTA)

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Abstract

During the recent spate of hurricanes and tropical storms that punished the state of Florida, navigation aids of all types suffered either directly or indirectly from water and wind damage. During the months of August and September of 2004, Hurricanes Charley, Frances, Ivan, and Jeanne, and Tropical Storms Bonnie and Gaston, tore through the Atlantic and Gulf Coasts of the United States, resulting in damage estimates ranging from $11.8B to $22.8B.

Loran-C Stations Jupiter [7980-Y], Malone [7980-M; 8970-W], and Carolina Beach [7980-Z; 9960-Y] were in the paths of Hurricanes Charley, Frances, Ivan, or Jeanne. Hurricane Charley did no significant damage to any of the stations, and Malone and Carolina Beach suffered minimal damage from Hurricanes Charley and Ivan. However, Loran-C Station Jupiter was unavailable for 60 hours as a result of Hurricane Frances, and six hours as a result of Hurricane Jeanne.

Differential GPS (DGPS) sites were also affected. The Cape Canaveral, FL site was unusable for 113 hours, and the Tampa, FL site was unusable for 54 hours, because of Hurricane Jeanne-related damage. Because of Hurricane Ivan-related damage, the Mobile Point, AL site was unusable for 226 hours, and the Millers Ferry, AL site was unusable for 29 hours.

Loran-C once again demonstrated its robustness under the harshest of environmental conditions. However, this weather "attack" pointed out the need for emergency capability in the event of other types of attacks, for critical infrastructure protection, or simply for rapid deployment of Loran for tactical use.

This paper discusses the concept of, and the need for, a modern Tactical Loran system. We also provide a conceptual framework under which Low Cost Digitally Enhanced Loran for Tactical Applications (LC DELTA) might be developed. We show that the application of 21st century technology to an old problem results in a solution that is both physically and fiscally practical.

1. Introduction

1.1 What is Tactical Loran?

Tactical Loran is not a new idea. Later in this section, we present four historical efforts to deploy versions of Tactical Loran, all of them successful for their designed purposes. However, technology has significantly improved since the last tactical system was retired in the mid 1980s. Recent work in transmitting, timing, receiving, and ancillary equipment technology have not simply postulated, but have proven that Loran is a viable means to provide positioning, timing, navigation, and data channel capability across multiple modes.

Technology has equally transformed Loran's fixed infrastructure, with major improvements to transmitters, antennas, timers, networks and control functionality. The new solid state transmitters replacing tube-based systems are stable, compact and reliable, and can operate unattended. Because they deliver high power—from 250 kilowatts to over 1 megawatt in some cases—only a handful of stations are needed to provide regional coverage. [1]

Loran is not as precise as GPS, but its one-third mile accuracy is better over a much larger area than any of the ground-based alternatives. [2]

Several countries have identified Loran as the best backup for all modes of transportation. ***Enhanced*** Loran-C "can provide a cross-modal radionavigation system backup or complement to GPS for civil aviation, maritime users, emergency services, and timing application." Recent tests have indicated that Enhanced Loran-C meets or exceeds the accuracy, availability, integrity, continuity, and coverage requirements necessary to achieve 8-20 meter maritime Harbor Entrance Approach (HEA) and aviation RNP 0.3 nm Non-Precision Approach (NPA) levels of performance. [3]

For there to be a need for a Tactical Loran capability, we first need to presume that Enhanced Loran-C is approved for long-term operation as part of the U.S. radionavigation system mix. Further, we can presume that Enhanced Loran will operate in the Time-of-Transmission (TOT) mode vice its current, at least in the U.S., Time-of-Arrival (TOA) mode. Although TOT control is not a requirement for Tactical Loran, it provides for more alternative uses of a deployable system than simply as an emergency "spare".

1.2 What are the basic requirements for Tactical Loran?

A Tactical Loran system, depending upon its ultimate use, should be capable of providing fixed, en route, and terminal position, navigation, and timing solutions to government and commercial users at a lower cost than installing a fixed system. Some of the basic requirements for a Tactical Loran system are:

- Rapid installation and de-installation,
- Small Size, Weight, and Power (SWAP) requirement,
- Significantly lower cost than a fixed system,
- Ease of use that supports unmanned operation,
- The capability for autonomous operation,
- Piece-wise equivalent to fixed systems in signal specification and enhanced transmission formats,
- An easily deployable configuration, and
- Equivalent reliability and robustness to fixed systems.

1.3 What has been done in the past?

1.3.1 Loran-D. Loran-D was a short range, high accuracy, low power, tactical system designed for use as a bombing aid by the United States Air Force in the 1960s and 1970s. [4] Its primary objective was to provide a quick reaction capability to establish or extend Loran-C or –D coverage. [5] The TRN-38 version, developed by Sperry Rand's Gyroscope Division in the late 1970s, used 15 "Cycle Generators" as the core of a "portable" transmitter capable of radiating 30kW at rates up to 533 pulses per second into a 400-foot quick erecting TLM antenna. See Figure 1. The tactical antenna could be erected within 12 hours of arrival at a finished site. Otherwise, it took four people 60 hours to erect the tower, including base plate and ground plane installation. [6]

Figure 1: Sperry Technician and Loran-D Transmitter. [7]

1.3.2 Air Transportable Loran System. In the 1960s, the U.S. Department of Defense funded development of the Air Transportable Loran System (ATLS), commonly known as "Atlas". ATLS was a complete, integrated Loran-C station, including everything from power generation through a full-sized (625' TLM) transmitting antenna that could be loaded into a C-130 aircraft for transport worldwide. One "temporary" ATLS installation was at Loran-C Station Lampedusa, Italy. Although the Lampedusa ATLS was supposed to have been temporary, it actually performed as an operational station until 1987, when it was finally replaced with a permanent tube-type transmitting station as part of a NATO project.

1.3.3 Saint Mary's River Mini-Chain. The Saint Mary's River provides the waterway connection between Lake Superior and Lake Huron on the border of Canada and the United States. The Saint Mary's River was the navigation choke point for bulk cargo vessels, 600 to 1000 feet in length, that connect western Lake Superior product ports with the Lake Huron and Lake Michigan industrial centers. Economics of the steel industry, coupled with winter ice closure of the Saint Mary's River, had driven the construction of iron ore bulk vessels to the maximum length, beam, and draft physically capable of navigation through the narrow locks and rock-cut channels that characterize the waterway. [8]

In the mid-1970s, the U.S. Coast Guard determined the need for, and deployed, an experimental local area navigation system along the Saint Mary's River. The Saint Mary's River Mini-Chain consisted of three stations straddling the border between the United States and Canada. [9] Each unmanned station consisted of a 2-Half-Cycle Generator version of Megapulse' Solid-State Transmitter operated into a Rohn 45G 150-foot guyed antenna. The chain operated successfully from May 1979 through May 1980, and provided "position information to within 20 meters 2DRMS in the critical portions of the river when operated with relatively infrequent differential offsets." [10]

1.3.4 Pulse/8. In 1974, Racal Positioning Systems, Ltd. developed a so-called Mini-Loran variant of Loran-C that used low power solid-state transmitters coupled into 300-foot antennas that radiated peak pulse power of 1kW RMS over baseline lengths of about 350-400 nautical miles. The Pulse/8 systems were installed to aid in the seismic exploration of oil in the North Sea, the Gulf of Mexico, and the Java Sea. There were a total of 10 operational, unmanned Pulse/8 stations in 1986. With Pulse/8, Racal demonstrated that even at a 1kW RMS radiated power (and with 1980's receiver technology), usable signal strengths were achievable at ranges up to 400 nautical miles. Further, these systems were able to achieve repeatable fix accuracies often as good as 15 meters. [11]

2. Scenarios for using Tactical Loran

Loran is inherently complementary to GNSS/GPS. It is terrestrial rather than space-based. It operates in a very different frequency band and has dissimilar failure modes. From a security standpoint, hostile forces would find it hard to disrupt land-based and space-based infrastructures simultaneously. Loran installations can, in most cases, be repaired or replaced repeatedly, whereas the consequences of any successful assault on a satellite infrastructure are likely to be prolonged. GPS signals remain, despite improvements in countermeasures, vulnerable to jamming, whereas Loran, with its strong, dispersed signals, large ground antennas and 90- to 110-kHz medium-wave operation, is thousands of times harder to jam. [1]

The best deterrent to GPS failure (i.e., jamming) is an alternative technology capable of providing equivalent capability. Some questions come to mind. What does a highly regulated industry (telecommunications, gas and electric utilities, etc.) use for backup timing in the event of a GPS outage? We all know how reliable GPS is. The question is what do you do if GPS is not there? Loran-C is the insurance for when that scenario occurs. LC DELTA is the insurance for areas where Loran-C coverage currently does not exist.

Here are some scenarios where tactical Loran might be appropriate. Keep in mind that where Loran-C coverage currently exists, these applications are probably less useful. Therefore, the most probable uses for LC DELTA might be to establish coverage where there is no coverage now, or to establish coverage or improve geometry on the fringes of existing coverage.

Let's note the recent situation in the United States where hurricane-induced damage *could* have necessitated a Tactical Loran capability.

The next Figure 2 shows the paths of Hurricanes Charley, Frances, Ivan, and Jeanne over the East and Gulf Coasts of the United States this past summer. Note that the Loran stations at Jupiter and Carolina Beach are at two of the three points where hurricanes most often make landfall. Just lucky, we guess! Figure 3 shows the damage to Loran-C Station Jupiter's TLM structural guys caused by Hurricane Frances. Other than this twisting together of the structural guys, Loran-C Station Jupiter survived the full brunt of Hurricane Frances' onslaught. Additionally, the station was still safely operable with the structural guys twisted together; however, regaining verticality of the tower necessitated untangling the guys.

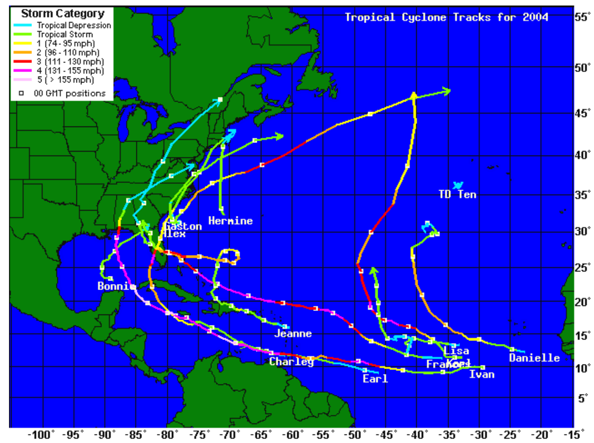

Figure 2: All Hurricanes.

Figure 3: Loran-C Station Jupiter Tower Damage.

2.1 Augmentation to Improve Poor Geometry. Although station location can be optimized for signal characteristics, fiscal and geographic limitations often preclude us from capitalizing on optimum station placement. This sometimes results in less than optimum chain geometry and coverage. There are times when a temporary improvement in geometry might be cost effective. This improvement could be the addition of a single station to address poor coverage for a short term requirement, or the installation of a small network of tactical stations to support a theater of operations.

2.2 Augmentation to Test Station Relocation. In this scenario, LC DELTA provides a low-cost capability to quickly and efficiently test new stations. For example, the U.S. Coast Guard is studying the feasibility of relocating the Port Clarence Loran-C Station to Nome, AK. LC DELTA could, depending on the antenna, be used to provide limited or complete area coverage from Nome during an evaluation or overlap period.

2.3 Additional Stations. Fiscal realities often limit the number of stations in a particular geographic area. A cheaper, smaller footprint alternative might allow for some novel additional stations. For example, would it be beneficial to improve offshore coverage by moving the Xray baseline of the 9940 U.S. West Coast Chain from its current endpoint at Middletown, CA to the Farallon Islands 30 miles west of San Francisco? LC DELTA enables a more cost effective fielding of new stations.

One example where a temporary low power transmitter could be useful is in the area off the southeast coast of Florida. This area is characterized by:

- High Coast Guard operational interest because of illegal immigration and drug traffic,
- Large areas of shallow water (the Little and Great Bahama Banks) at long ranges from land requiring electronic navigation to avoid grounding (See figure 4), and
- The lack of Loran coverage as the most southeast station in the United States is at Jupiter, Florida.

Could an adversary exploit possessing either better local knowledge or having shallower draft gain an advantage by denying the Coast Guard or other authorities the use of GPS? If so, the ability to rapidly establish Loran coverage in the area could allow for safe operations. Figures 5 and 6 illustrate the Loran coverage possible in that area combining a temporary 10 kW transmitter either on land or from a vessel.

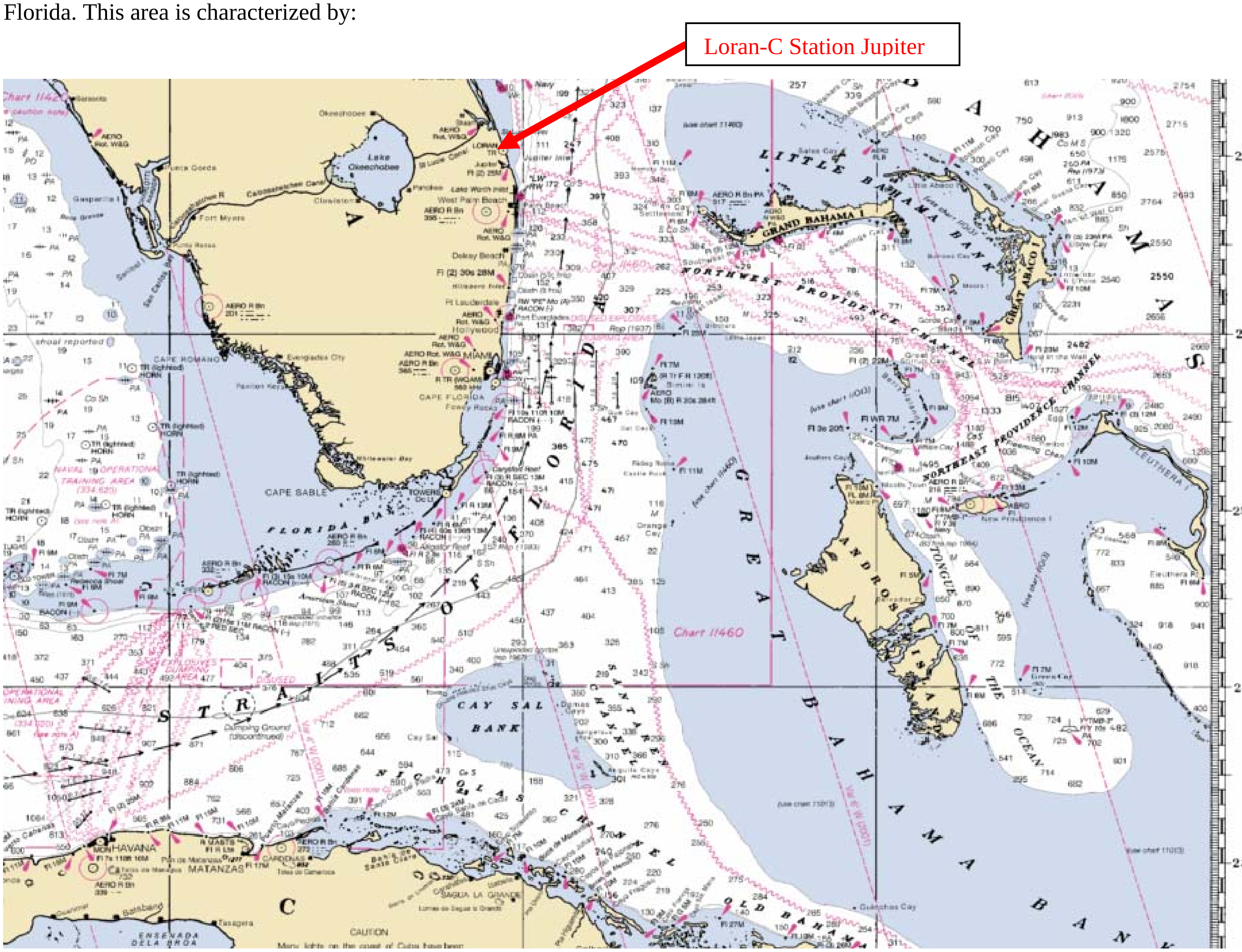

Figure 4: Section of NOAA Chart 411 (Gulf of Mexico).

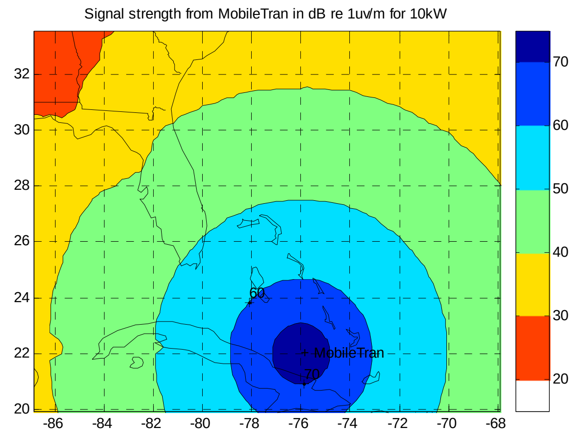

Figure 5

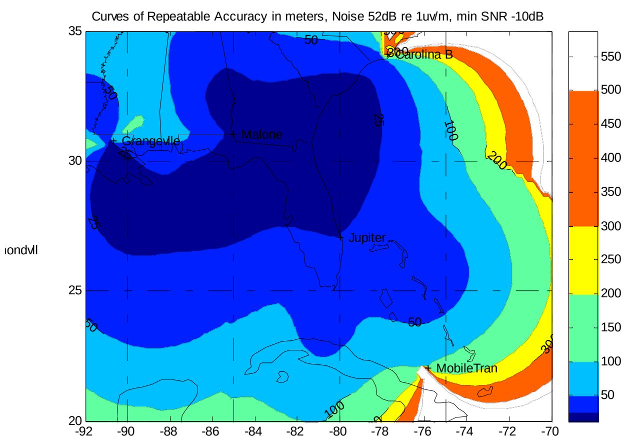

Figure 6

2.4 Portable Locally Positioned Stations. This system would be used by individuals in urban areas where GPS signals might be masked. According to the U.S. Army, this system would fulfill positioning requirements for "first responders (fire, police and other rescuers), transportation tracking and guidance (trucks and delivery), construction, house arrest prisoners, and Alzheimer patients." [12]

2.5 Localized Stratum-1 Timing Sources. In this scenario, LC DELTA would be used to coherentize a network of users who require GPS independence or are operating in an area where GPS reception is marginal. A single Loran-C Station would provide frequency sytonization at the Stratum-1 level and time synchronization at the 100 ns level (assuming differential service).

2.6. Component Solutions. Given the low cost, ease of installation, and small footprint of the conceptual system, it is obvious that it can be disaggregated into its individual components for rapid deployment where needed. We believe a tactical transmitter might be the most necessary component of a Tactical Loran system for North American purposes. For example, a tactical transmitter would be useful under any of the following circumstances:

- Flooding resulting from storm surges either destroying the transmitter, or making it temporarily unusable,
- Fire, earthquake, tornado, or terrorist event destroying the transmitter, and
- Temporary use during changeover from legacy Solid-State Transmitter (SSX) to new SSX (NSX).

Note that some legacy SSX's are mid-1970's vintage, and have actually exceeded their original life expectancy. The changeover from Tube-Type Transmitters (TTX) to SSX has required construction of new buildings to reduce station "down time". A temporary transmitter could easily operate into the existing antenna during the time it takes to remove the existing TTX/SSX and install the new transmitter. A cost-benefit for one tactical transmitter would probably show a payback, depending on the transmitter type and size, after one installation over the cost of constructing a new building, especially in Alaska.

3. Alternative Tactical Deployment Methods

Tactical Loran refers not only to the ability to rapidly deploy position, navigation, timing, and data channel capability on the ground, but also to deploy that capability via alternate means, such as aerostats, airships, fixed wing aircraft, and large navigational buoys. As we will see in the following sections, Tactical Loran capability could easily be fitted on various moving vessels. Obviously, aerostats, airships, and large navigational buoys provide either continuous or near continuous persistence of transmissions, whereas transmissions from fixed-wing aircraft would be less persistent. Finally, existing infrastructure might be used to provide LC DELTA capability. In one example, reuse of the Ground Wave Emergency Network (GWEN) aerostats might be one viable alternative in North America. In another example, an offshore platform could easily support an LC DELTA site.

3.1 Aerostats and Airships. The Department of Defense has a long history of using airships (often called blimps) and aerostats as platforms to meet various operational and support requirements. Probably the most visible and well-known program today is the Tethered Aerostat Radar System (TARS) that has been operating at eight sites along the southern U.S. border and in the Caribbean since the 1980's. The TARS primary mission is surveillance for drug interdiction. Each of the TARS aerostats can lift 2,200 pounds of radar or other sensors up to 12,000 feet, and can stay aloft for months at a time. [13]

Both the land based and sea based aerostat make excellent platforms for LC DELTA. The aerostat simply lofts a wire antenna to an appropriate height and the base station or vessel hosts all the required transmitting, timing, and control equipment. Operations could theoretically continue indefinitely in one location, or the entire "site" could be relocated at a moment's notice.

Figure 7 depicts a representative TCOM, LP land based aerostat moored to a mobile platform. Note that the aerostat would only be necessary when a rapidly deployable, reusable, and relatively cheap antenna is required. Figure 8 depicts a similar configuration using a TCOM, LP sea based aerostat.


Figure 7: TCOM Land Based Aerostat.


Figure 8: TCOM Sea Based Aerostat.

Additionally, airships are capable of inexpensive and fairly rapid deployment of cargo. Tactical Loran capability might be deployed anywhere in the world as an installed package aboard such a vessel, with a trailing wire used as the antenna. Figure 9 depicts a modern airship transiting San Francisco, CA.

Figure 9: TCOM "LC DELTA" Airship?

3.2 Fixed Wing Aircraft. Deployment of a high-powered VLF/LF transmitting capability has existed since the early 1960's. In the United States military, the primary means of communicating with submerged submarines is the TACAMO (Take Charge and Move Out) system which uses a fleet of aircraft. The 16 aircraft are part of the World Wide Airborne Command Post (WWABNCP) providing survivable, reliable, and endurable airborne command, control, and communications between the National Command Authority (NCA) and U.S. strategic and non-strategic forces. Two aircraft are always airborne - one over the Atlantic and one over the Pacific. Other aircraft are stationed on the ground and they are on a 15 minute alert. The aircraft fly 10.5 hour missions, starting at one airfield and ending at another. Random patterns are flown to mislead any unauthorized observers. The TACAMO aircraft can receive and relay signals from a number of different ground command posts. Each aircraft is equipped with a 6.2 mile long trailing wire antenna (wound on a reel) and a 100 kW transmitter operating in the VLF region. When the aircraft has to transmit a message, it banks and proceeds to fly a very tight circle. This causes the trailing wire antenna to hang vertically below. Once the message is transmitted over the VLF downlink the aircraft resumes normal flight. [14]

The TACAMO fleet was initially comprised of the Lockheed Hercules EC130 aircraft, but these were gradually phased out and replaced with the Boeing 747 AWACS type aircraft. These aircraft have the capability to transmit a 200 kW signal using a 2.5 mile trailing antenna.

In 1989, the E-6A, and then in 1998, the E-6B aircraft, which is a modified Boeing 707-320B with CFM-56 engines, began fulfilling the role of the TACAMO platform. Figure 10 depicts one such aircraft. It features a very-low-frequency (VLF) dual trailing wire antenna system to permit one-way, emergency communications to submerged submarines. The VLF system includes an onboard power amplifier-coupler connected to two wire antennas, one about five miles long (28,000 feet) and one slightly less than a mile long (5,000 feet). When deployed, the antennas trail behind and below the aircraft. After deployment of the wires, the aircraft banks sharply and flies a circular orbit that allows the longer wire to hang as vertically as possible to enhance signal transmission. [15]

The transmitter on board the TACAMO aircraft is an AN/ART-54 High-Power Transmitting Set (HPTS), consisting of a Solid State Power Amplifier/Coupler (SSPA/C) OG-187/ART-54 and Dual Trailing Wire Antenna System (DTWA) OE-456/ART-54. This provides increased capabilities (including Low Frequency (LF) transmission spectrum) with significant reliability and operability improvements. It is an integrated hardware/software system designed to provide automatic or manual operation, verify operational status, and provide diagnostic fault isolation. [16]

Figure 10: E-6B TACAMO Aircraft.

3.3 Large Navigational Buoys. The National Data Buoy Center's fleet of moored buoys includes several large diameter models. Typically known as Large Navigational Buoys (LNB), these large seaworthy platforms are available in 6-meter, 10-meter, and 12-meter discus hulls. The choice of hull type used usually depends on its intended deployment location and measurement requirements. To assure optimum performance, a specific mooring design is produced based on hull type, location, and water depth. A large discus buoy deployed in the deep ocean may require a combination of chain, nylon, and buoyant polypropylene materials designed for many years of service. Some deep ocean moorings have operated without failure for over 10 years. [17]

Although a buoy is probably not the first choice, it is possible to use a large navigational buoy as a tactical Loran platform. The reliability of the system would obviously depend upon the roughness of the water. However, the LNB could be used on inland waterways as well as offshore. Deploying LC DELTA using an LNB would require lofting the antenna with an aerostat. Figure 11 is a 12-meter discus hull LNB being used by the FAA.

Figure 11: Large Navigational "FAA" Buoy

3.4 Ground Wave Emergency Network (GWEN). Although this system was shut down in 1997, as part of its inventory several DARPA/Westinghouse 750-6000m tether Aerostat-Augmented balloons were available capable of hoisting an antenna capable of broadcasting the high-powered 150 – 175 kHz GWEN transmissions. [18]

3.5 Offshore Platforms. Offshore platforms have many uses including oil exploration and production, navigation, ship loading and unloading, and to support bridges and causeways. [19] We need only look at the platforms shown in figures 12 and 13 to get some idea of the usefulness of this type of platform to support LC DELTA. With over 3, 200 platforms currently installed in the Gulf of Mexico alone, there is a high probability that platforms would be located proximate to an area requiring Tactical Loran capability.

Figure 12: Offshore Technologies – North Caspian Sea

Figure 13: Offshore Technologies – Nova Scotia

4. Key Components

4.1 Antenna. This is the most difficult piece of a rapidly deployable system. Typical transmitting antennas are invariably massive structures, requiring a large footprint and significant construction times. Most fixed Loran-C stations have Top Loaded Monopole (TLM) antennas ranging in height from 400 feet to 720 feet. A few of the older U.S. stations use Sectionalized Loran Transmitting (SLT) antenna and there is one installed Top Inverted Pyramid (TIP) antenna. Historical Tactical Loran systems, such as those mentioned previously herein, have used 150-, 300-, 350-, or 400-foot antennas, depending on the power requirements.

The analysis below is intended to illustrate the antenna infrastructure necessary to either transmit a tactical Loran signal (or alternatively, to interfere with an existing Loran signal). The numbers chosen for illustration are not magic in any way but are chosen as integer power of 10 typical numbers that together with the functional forms for dependence of antenna impedance parameters allow for easy approximate calculation for other values. Our intent is not to provide a primer on antenna design, but rather to outline the bounding concepts that impact any rapidly deployable transmitting antenna design. Therefore, underlying derivations and calculations are located in the Appendix at the end of this paper.

4.1.1 Transmitter power and radiation resistance. To determine typical power required to either transmit a Tactical Loran signal, consider the signal strength curves in Figure 14 plotted for land conductivity of 3 mmhos/meter and for peak transmitter powers of 1W, 10 kW, and 400 kW. Out to 100 nautical miles (nm), the curves are approximately the -20dB per factor of 10 in range of spherical spreading and beyond 100 nm, they fall off much faster due to the curvature of the earth and the finite ground conductivity.

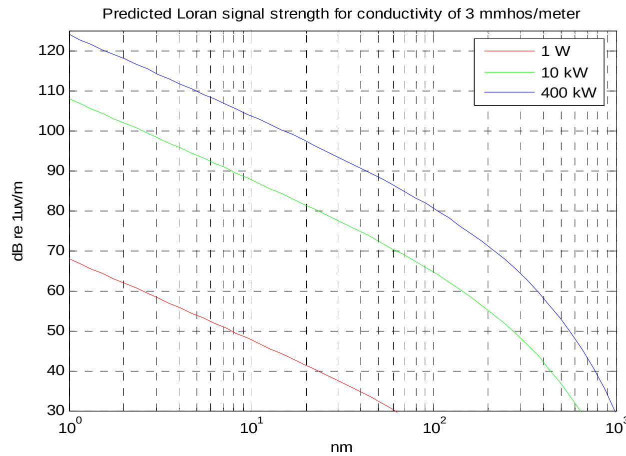

Figure 14

To acquire and track under typical noise conditions requires a signal of approximately 50 dB re 1 uv/m. Because of this extra attenuation due to the curvature of the earth and the finite ground conductivity the range of a 10 kW transmitter is about 50% of that of a 400 kW transmitter or much more than the sqrt(1/40) = 22% that would be expected assuming spherical spreading.

To obtain approximate values for the physical size of antennas to transmit at these peak powers we will assume radiation resistances of one ohm and 0.01 ohms respectively for the tactical and jammer antennas respectively. At these resistances, the peak antenna currents would be 100 amps rms or 141 amps peak for the tactical transmitter and 10 amps rms or 14 amps peak for the jammer.

4.1.2 Loop Antennas. There has been some discussion that a loop might be used as the transmission antenna for a Tactical Loran system. Because a loop antenna might provide a reasonable SWAP tradeoff over a Top Loaded Monopole, we decided to briefly explore whether a loop might in fact work at the required power levels. The detailed analysis is found in the Appendix. The bottom line is that one cannot achieve the desired radiation resistance in a reasonably sized loop by merely increasing the number of turns in the antenna. Effectively what one builds is a huge inductor with huge inductive reactance. The only way it can be done is to make a single loop with a diameter nearly one tenth a wavelength or 1000 feet and at this point it becomes much easier to build a top loaded monopole.

4.1.3 Top Loaded Monopole (TLM) Antennas. There is plenty of historical theoretical and empirical evidence to support using TLM antennas for Loran transmission. Our purpose within this paper is to determine conceptually what might suffice as a low cost, rapid construction/deployment solution.

The radiation resistance in ohms for a monopole antenna of effective length, L_{eff}, is given by [20]:

$$R_{rad} = 80\ \pi^2\ (L_{eff}/\lambda)^2$$

For a short antenna which is top loaded and has a perfect ground plane, the effective length and the physical length are the same. For an antenna with no top loading the effective length is one-half the physical length. In actual practice, the effective height of a TLM may be slightly less than the physical length because of a less than perfect ground plane. For example, the 625-foot Loran TLM antennas have an effective length about 80-90% of their physical length and a radiation resistance somewhat less than the 3.18 ohms predicted by the equation above. Therefore to obtain radiation resistances of 1.0 and 0.01 ohms respectively requires effective heights of 107 meters (350 feet) and 10.7 (35 feet) meters respectively and physical heights slightly more. Without top loading, a conventional whip antenna would need to be 70 feet to obtain a radiation resistance of 0.01 ohms.

A top loaded monopole is capacitive vice inductive as in the case of a loop antenna and while this capacitive reactance is large in comparison to the radiation resistance it is much less than the inductive reactance of a loop of comparable size and radiation resistance. For example in [6], the capacitance was increased to 5,000 pF by retuning the length of the top loading elements on a 350 foot former Decca antenna. 5,000 pF is 318 ohms at 100 kHz and results in a peak antenna voltage of 45 kV for 141 peak amps.

4.2 Power. "Whole-station" Uninterrupted Power Supply (UPS) backup of Loran stations is a proven concept. For example, Loran-C Station Jupiter has run with such a system, provided by APC, since April 2000. Depending on the final power requirements of the tactical system, a small generator and/or UPS could easily be sourced.

4.3 Receiver Modifications. It is envisioned that temporary land stations at fixed sites or transmitters on moving platforms would transmit data that would enable receivers to calculate the position of the transmitting antenna and the emission delay. Assuming a positive U.S. decision on Loran, it is expected that the U.S. will adopt a 9th pulse data communications channel on Loran (e.g., Loran Data Channel (LDC)) and the proposed messages below are based on that communications channel. The proposed LDC uses 32 state pulse position modulation on an extra 9th pulse for data only to transmit five bits per Group Repetition Interval (GRI). These messages are 24 words or between 1.42 (GRI 5930) and 2.4 (GRI 9990) seconds duration. Fifteen words of the 24 are Reed Solomon parity and nine words or 45 bits are data. Of these 45 bits, four bits are reserved for message type, and the remaining 41 can be defined as required. At present, two message types are defined (UTC Time and Station Identification, and Differential Loran Corrections) and a third (early skywave warning) has been identified but not defined.

To support mobile, or Tactical, Loran we propose four new messages. Aviation mounted transmitters will transmit two message types on a continuous basis to communicate their position, velocity, and acceleration, one message for north data and a second for east data, and a third occasionally to transmit emission delay. The emission delay message would be the ships reference position message described below and would be transmitted often enough (every 20-30 seconds) to limit time to first fix. User equipment would ignore the other components of the reference position message based on receiving the other aviation message types. The airplane can be flying at speeds of up to 256 m/s or 498 knots. The maximum acceleration before saturation is 3.1 m/s^2 or for a plane flying at 200 knots it can turn at 1.7 degrees per second before saturating the acceleration word. Aviation mounted transmitters would have enough communications bandwidth to keep up with their own position, but probably not have spare bandwidth to support other information such as differential Loran.

Fixed transmitters would use the same two messages as aviation mounted transmitters, except they would set the north acceleration word to a non-valid number which would indicate to user equipment that the north velocity word should be interpreted as the emission delay vice the north velocity. These messages would only be sent often enough to limit time to first fix leaving most of the communications bandwidth to support other information such as differential Loran.

Because ship-borne transmitters could travel at much smaller velocities and remain within a smaller geographic area, after transmitting a message containing their reference position and emission delay, their offset from that reference position and velocity can fit into a single message. The reference position and emission delay message is transmitted often enough to limit time to first fix. The offset position and velocity message would consume approximately one-half of the communications bandwidth leaving some for other information such as differential Loran. Every time the reference position is changed, a single bit reference position counter is flipped. The same bit is transmitted in both the reference position and offset position messages. User equipment checks this bit in both messages to verify that the offsets correspond to its current reference position. If the bit does not match, it knows that it dropped the last reference position message and needs to wait until it successfully decodes the next one before calculating a fix.

The maximum speed before saturation of the velocity word is eight m/s or 15.6 knots. Since no acceleration data is sent, it is assumed the ships maneuvers are modest.

The bit assignments for the four messages and range and resolution of each word are described in Tables 1 through 4 below. The last column converts to meters the resolution in degrees for latitude and longitude. For longitude the resolution in meters is at the equator and would improve accordingly at higher latitudes.

Aircraft Latitude & North Velocity & Acceleration or Fixed Latitude & Emission Delay					
	# bits	range	resolution	units	meters
MSG type	4	0 - 15			
Latitude	24	-90 to 90	1.07E-05	degrees	1.19
North velocity or ED	11	-256 to 256	0.25	m/s	
North acc. or ED flag	6	-3.1 to 3.1	0.1	m/s^2	
total	45				

Table 1

Aircraft Longitude & East Velocity & Acceleration or Fixed Longitude					
	# bits	range	resolution	units	meters
MSG type	4	0 - 15			
Longitude	24	-180 to 180	2.15E-05	degrees	2.38
East velocity	11	-256 to 256	0.25	m/s	
East acceleration	6	-3.1 to 3.1	0.1	m/s^2	
total	45				

Table 2

Ship Reference Position & Emission delay					
	# bits	range	resolution	units	meters
MSG type	4	0 - 15			
Reference Latitude	15	-90 to 90	0.005493	degrees	610
Reference Longitude	15	-180 to 180	0.010986	degrees	1221
Emission Delay	10	0 - 102,300	100	usec	
Ref pos counter	1	0 - 1			
total	45				

Table 3

Ship Offset from reference & Velocity					
	# bits	range	resolution	units	meters
MSG type	4	0 - 15			
North Offset	14	-0.1 to 0.1	1.22E-05	degrees	1.36
North velocity	6	-8 to 8	0.25	m/s	
East Offset	14	-0.1 to 0.1	1.22E-05	degrees	1.36
East velocity	6	-8 to 8	0.25	m/s	
Ref pos counter	1	0 - 1			
total	45				

Table 4

4.4 Time Recovery & Signal Generation. The tactical Loran implementation involves minimizing size, weight, power, and cost while retaining the performance aspects that enable the critical performance set. The technology infusion provided by the Loran recapitalization effort has resulted in a significant reduction in SWAP and cost for Loran timing, signal generation and control. This technology, which has been applied in the Time and Frequency Equipment (TFE) suites used at the U.S. Loran-C transmitting Stations can be re-packaged and applied to the tactical case. This section details the critical components for the timing subsystem for the tactical Loran system, including differences from the standard Loran Station case and options for reducing cost and SWAP.

The significant components of a tactical Loran timing subsystem are seen in Figure 15. The source, front end, Loran signal generation and measurement and control components provide the ability to transmit a Loran pulse that is on-time, in tolerance, and continuously verified for integrity and performance. In addition to power and network connections, the timing subsystem has one output interface (transmitter drive signals) and two input interfaces (transmitter return and antenna for Timing Front End).

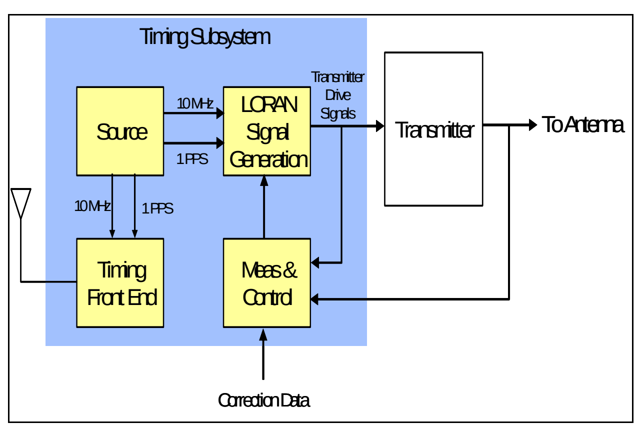

Figure 15: Timing Subsystem.

4.4.1 Source. The choice of clock plays a significant role in the size, weight, performance and cost of a tactical Loran system. Historically, three cesium standards have been used at transmitting U.S. Loran-C stations. Cesiums provide the best performance for a fieldable atomic standard but come at a steep financial (~50k) and SWAP cost. For the tactical case, a rubidium standard provides another option. A rubidium provides the necessary frequency stability ($<1\times10^{-12}$ at an hour averaging time) in a small package at a fraction of the cost of a cesium. The performance cost of going to the smaller and cheaper clock is in holdover performance or the frequency stability to which the clock reverts when it is not being externally steered. This can be mitigated by a high reliability front end which is discussed below.

4.4.2 Timing Front End. The timing front end provides the external reference that allows synchronization of the transmitter with UTC. Historically, a GPS receiver is used as a timing front end as it provides time synchronization at the 10-20 ns level with little effort [21]. A two-way time transfer [22] front end can also provide time synchronization in a method that is totally GPS independent. With a rubidium as a timing source, a dual front end mitigates the trade off in holdover performance (versus a cesium) as the two-way can fail over to GPS or vice versa.

4.4.3 Loran Signal Generation. The signal generation component is responsible for creating the transmitter drive signals from the time and frequency references provided by the source. In the Time and Frequency Equipment (TFE) design used at the U.S. Loran stations, all of the signal generation occurs in a set of Field Programmable Gate Arrays (FPGAs) and a single microcontroller. The frequency reference from the timing source is used to clock a logic chain in an FPGA where the necessary Loran signals are created with strict phase relationships to each other and to the controlling frequency and time references. The signal generator also has the ability to control the pulses (data modulation, blink, cross-rate blank, phase adjust, etc.) based on commands from the measurement and control section.

4.4.4 Measurement and Control. In order to provide the performance and integrity required by Loran systems, the transmitted signal must be continuously verified and strictly controlled. The measurement and control component is responsible making the required measurements to ensure that the transmitted pulses have the proper phase relationship with UTC, consistency within the pulse groups and acceptable short term frequency stability. The measurements are processed in a CPU and control is applied via commands to the Loran signal generation component.

4.5 Transmitter. The transmitter is another difficult item. Most existing Loran transmitters have had large footprints, required significant ancillary equipment (air cooling, air conditioning, and/or water cooling systems), consumed a lot of power, and required significant time to install. Some small footprint transmitters have been developed in the past (St. Mary's River Mini-Chain, Pulse/8). The technology now exists to develop small SWAP digital transmitters that are tremendously efficient, require minimum environmental control, and are highly reliable. For example, Harris Corporation is one of several digital transmitter manufacturers that have equipment that operates near the Loran frequency. [23] Figure 16 depicts a one megawatt digital Long Wave transmitter. This version is several orders of magnitude larger than what might be needed for a Tactical Loran site; however, it provides the conceptual foundation for LC DELTA. Figure 17 shows a representative 10 kW digital AM transmitter.

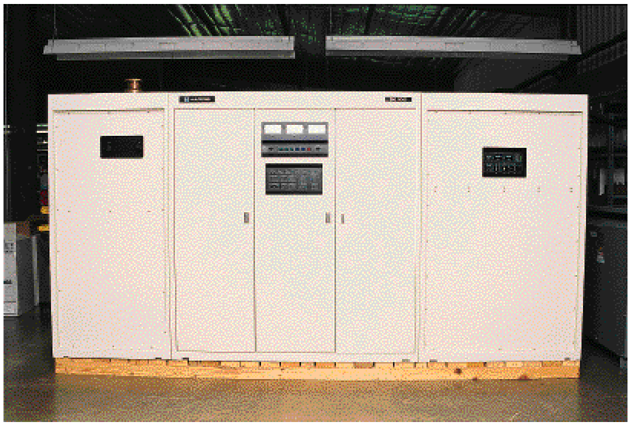

Figure 16: Harris 1 MW DX-LW Digital AM Transmitter.

Figure 17: Harris 10 kW DX Digital AM Transmitter

5. Cost Estimates

What are the costs of our conceptual Tactical Loran system? Obviously, they are scenario and location dependent. However, we can provide a rough order of magnitude based upon the following components of a representative LC DELTA "suite":

- Transmitting antenna,
- Prime, generator, and/or backup power,
- Time Recovery & Signal Generation,
- Remote Command & Control Capability,
- Appropriately sized (10 kW) transmitter,
- Ancillary equipment (i.e., HVAC),
- Any requisite civil engineering,
- Built-in redundancy, and
- Built-in communications capability.

Given these fairly typical baseline requirements, and applying 21st century technology, we expect LC DELTA to be an order of magnitude less costly than a full-scale fixed site.

Because a TACAMO aircraft is already designed to support a 200 kW transmitter, appropriate power, electronic equipment racks, and a trailing wire antenna, we presume that most of the costs for this type of system would involve similar equipment purchases as in the ground-based scenario, determining the appropriate trailing antenna design, and any associated R&D.

Similarly, we presume that the additional costs associated with an aerostat-lifted antenna would relate to the aerostat and its support infrastructure, the antenna, and any associated R&D.

6. Conclusions

We have shown that the application of 21st century technology to an old problem results in a solution that is both physically and fiscally practical. A Low Cost Digitally Enhanced Loran for Tactical Applications could be constructed with minimal R&D investment.

7. Future Plans

This paper was envisioned purely as an exercise in the possible. Other than the Army's SBIR initiative, the authors are unaware of any plans to construct a tactical Loran system. However, it would be relatively easy to implement a proof-of-concept LC DELTA as a demonstration to motivate funding for a permanent capability.

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Appendix

The analysis below is intended to illustrate the antenna infrastructure necessary to either transmit a tactical Loran signal (or alternatively, to interfere with an existing Loran signal). The numbers chosen for illustration are not magic in any way but are chosen as integer power of 10 typical numbers that together with the functional forms for dependence of antenna impedance parameters allow for easy approximate calculation for other values.

Transmitter power and radiation resistance. To determine typical power required to either transmit a Tactical Loran signal, consider the signal strength curves in Figure A1 plotted for land conductivity of 3 mmhos/meter and for peak transmitter powers of 1W, 10 kW, and 400 kW. Out to 100 nautical miles (nm), the curves are approximately the -20dB per factor of 10 in range of spherical spreading and beyond 100 nm, they fall off much faster due to the curvature of the earth and the finite ground conductivity.

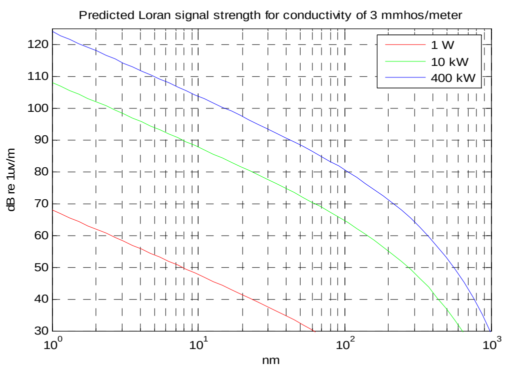

Figure A1

To acquire and track under typical noise conditions requires a signal of approximately 50 dB re 1 uv/m. Because of this extra attenuation due to the curvature of the earth and the finite ground conductivity the range of a 10 kW transmitter is about 50% of that of a 400 kW transmitter or much more than the sqrt(1/40) = 22% that would be expected assuming spherical spreading. At the low power levels of a potential jammer, the propagation is spherical spreading and a four watt jammer would have two times the range of a one watt jammer, etc.

To obtain approximate values for the physical size of antennas to transmit at these peak powers we will assume radiation resistances of one ohm and 0.01 ohms respectively for the tactical and jammer antennas respectively. At these resistances, the peak antenna currents would be 100 amps rms or 141 amps peak for the tactical transmitter and 10 amps rms or 14 amps peak for the jammer.

Loop Antenna Calculations. The radiation resistance in ohms in air for a circular loop of diameter D with N turns of wire is given by [20]:

$R_{rad} = 19{,}000\ N^2\ (D/\lambda)^4$

Therefore for a loop of diameter 3 meters or approximately 10 feet, $D/\lambda = 0.001$ and

$R_{rad} = 1.9\text{ e-}8\ N^2$ ohms

or to get a resistance of one ohm requires 7,255 turns or 68.3 km of wire and to get 0.01 ohm requires 726 turns or 6.83 km of wire.

For a loop of diameter 30 meters $D/\lambda = 0.01$ and

$R_{rad} = 1.9\text{ e-}4\ N^2$ ohms

or to get the same resistances of one and 0.01 ohms requires 73 turns or 6.83 km of wire and seven turns or 680 meters of wire respectively. Therefore, the larger one can make the loop diameter, the less wire is needed to get a given radiation resistance.

The self inductance of this coil of wire where the length one is much more than the diameter D is given by [24]:

$L = \mu_o\ \pi\ N^2\ D^2/l$

Where μ_o is the magnetic permeability of free space or 4π e-7 H/m. For short loops ($l < D$) this formula becomes [25-26]

$L = K\ \mu_o\ \pi\ N^2\ D^2/l$

Where the dimensionless constant K is from series calculations in [26]. A table of values of K is published in [25] and plotted as a function of length over diameter on a log-log plot in figure A2. The asymptotic values of K are one for large values of length over diameter and

$K = 1.392 * (\text{length over diameter})^{0.8}$

For a 30 meter loop with 73 turns, and one = 1.5 meters, K = 0.1236 and L = 1.56 Henries. What this means is that the inductive reactance at 100 kHz is 980 kΩ and the peak antenna voltage for 10 kW peak power and 141 peak amps is 138 MV. Obviously this cannot be done. Even for a one watt jammer, and the same 30 meter loop with one tenth the number of turns and one tenth the peak amperage, the peak voltage is 1000 times less but still 138 kV. The bottom line is that one cannot achieve the desired radiation resistance in a reasonably sized loop by merely increasing the number of turns in the antenna. Effectively what one builds is a huge inductor with huge inductive reactance. The only way it can be done is to make a single loop with a diameter nearly one tenth a wavelength or 1000 feet and at this point it becomes much easier to build a top loaded monopole.

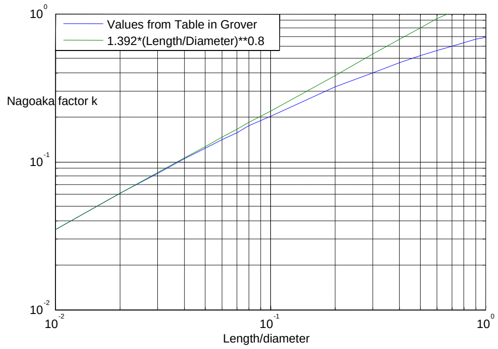

Figure A2

Top Loaded Monopole (TLM) Antenna Calculations. The radiation resistance in ohms for a monopole antenna of effective length, L_{eff}, is given by [27]:

$$R_{rad} = 80\pi^2 (L_{eff}/\lambda)^2$$

For a short antenna which is top loaded and has a perfect ground plane, the effective length and the physical length are the same. For an antenna with no top loading the effective length is one half the physical length. In actual practice the effective height of a top loaded monopole may be slightly less than the physical length due to a less than perfect ground plane. For example, the 625 foot Loran TLM antennas have an effective length about 80-90% of their physical length and a radiation resistance somewhat less than the 3.18 ohms predicted by the equation above. Therefore to obtain radiation resistances of 1.0 and 0.01 ohms respectively requires effective heights of 107 meters (350 feet) and 10.7 (35 feet) meters respectively and physical heights slightly more. Without top loading, a conventional whip antenna would need to be 70 feet to obtain a radiation resistance of 0.01 ohms.

A top loaded monopole is capacitive vice inductive as in the case of a loop antenna and while this capacitive reactance is large in comparison to the radiation resistance it is much less than the inductive reactance of a loop of comparable size and radiation resistance. For example in [28], the capacitance was increased to 5,000 pF by retuning the length of the top loading elements on a 350 foot former Decca antenna. 5,000 pF is 318 ohms at 100 kHz and results in a peak antenna voltage of 45 kV for 141 peak amps.

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