AN EVALUATION OF THE EFFECTIVENESS OF INTENTIONAL INTERFERENCE TO eLORAN

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ABSTRACT

Recent studies on the vulnerability of GPS to interference recommend that a backup system be made available to determine own-aircraft position for both navigation and surveillance services in the National Airspace System (NAS). This backup will provide horizontal-only position information during brief, localized GPS outages caused by system, natural or intentional-interference factors. The MITRE Corporation (MITRE) performed an evaluation of the potential candidates for such a backup system.[1] The results of this analysis showed that Loran) is likely the best choice among the alternatives studied. A future, modernized version of Loran is known as enhanced Loran, or eLoran.

This paper concentrates first on three interference scenarios that have been postulated by MITRE, with which an adversary could attempt to intentionally interfere with Loran. The second part of the paper provides a preliminary assessment of Loran coverage degradation under a simplified interference scenario.

PART I. INTENTIONAL INTERFERENCE WITH LORAN

I-1. Properties of Very Low-Frequency (VLF) Antennas

The challenge in Loran antenna design is driven by the very long wavelength (3,000 m) of the Loran signal and the very high peak power being transmitted. Radio antennas all have three components in their equivalent circuit (Figure I-1): reactance (X_a, which at these frequencies is always capacitive); the radiation resistance (R_r), which is the equivalent resistance in which dissipated power represents the power radiated by the antenna; and the "system" resistance (R_s), which is the sum of the resistance in all of the non-radiating components of the antenna (ground system - R_g, matching network - R_m and transmission line - R_t.).

The first two of these parameters are functions of the relationship between the physical height of the antenna radiating element (h) and the wavelength of the signal being transmitted (λ).

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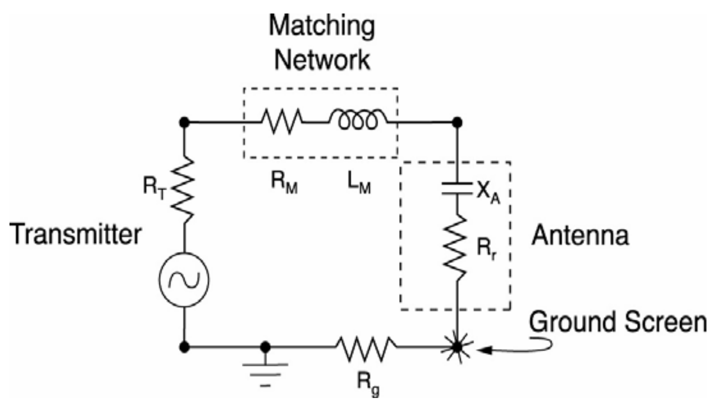

Figure I-1. VLF Antenna Equivalent Circuit

For a vertical monopole antenna tower:[2]

$$Rr = 10.0\ G0(h)^2$$

$$G0 = 2\pi\frac{h}{\lambda}$$

where:

Rr is the radiation resistance (Ω)
h is the antenna height (m)
λ is the wavelength (m)
G0(h) is the electrical antenna height in radians

and [3]

$$Xa = Z0\cot\left(2\pi\frac{h}{\lambda}\right)$$

and [4]

$$Z0 = 138\log\left(12\sqrt{h}\right)$$

where:

Xa(h) is the antenna reactance (-jΩ)
Z0(h) is the antenna characteristic impedance, ohms (Ω)

As the ratio h/λ is reduced, the radiation resistance becomes smaller and the reactance grows (in magnitude), as shown in Figure I-2. This combination requires that efficient VLF antennas be very tall structures. As will be assessed later in this report, it also means that attempts to use short antennas to transmit signals at 100 kHz will face significant barriers.

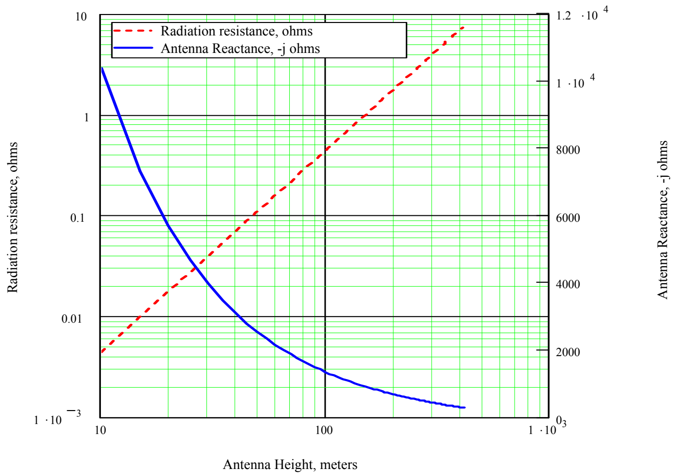

Figure I-2. VLF Antenna Parameters at 100 kHz for a Vertical Tower with No Top Loading

For Loran antennas, typical values for Rr fall in the range between 2 and 20 Ω, with 4 Ω being typical for the commonly used 213m antenna.[5] The reactance ranges from -j23 Ω to -j37 Ω. For the 213m antenna, it is –j23 Ω.

The antenna radiation efficiency is defined as:

$\eta = [Rr/(Rr + Rs)] \times 100$, percent

Thus, it is evident that the "system resistance" (R_s) of the antenna must be as small as possible. The radiation efficiency of typical unloaded LF antennas as a function of height is shown in Figure I-3.

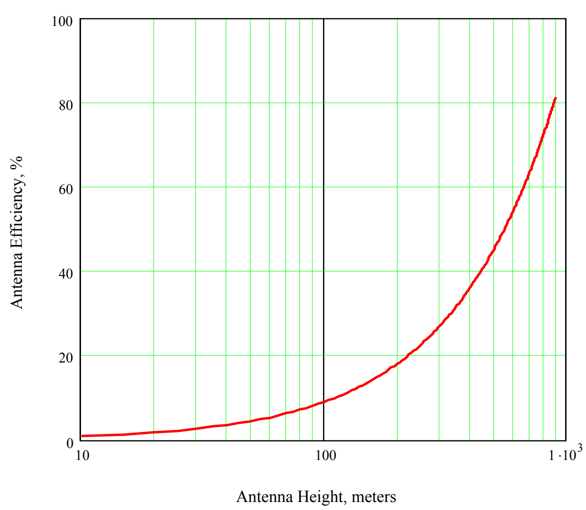

Figure I-3. Radiation Efficiency of an <u>Unloaded</u> Antenna, with λ/2 Ground Screen, as a Function of Antenna Height, Operating at 100 kHz (*After LaPort*)

Normally, the most significant component of R_s is the ground resistance, R_g. The *resistivity* of soil is in the range from 0.2 Ω●m for seawater to as much as 500 Ω●m for very dry soil. The actual ground *resistance* is far less, since the antenna ground current is integrated along many parallel paths. Still, left unaltered, these ground resistance values would substantially reduce the radiation efficiency, even over seawater.

We now turn to the assessment of three scenarios under which intentional interference to Loran might be attempted.

I-2. Intentional Interference Scenarios

A group of senior MITRE engineers defined three scenarios to be assessed for the impact they might have on the reception of Loran signals in aircraft. These three scenarios are discussed below.

I-2-1. Takeover of an AM Broadcasting Station

In this scenario, it has been assumed that a group with ill intent takes over the facilities of an AM broadcasting station. They then bring a 5 kW, 100 kHz transmitter to the site in a truck. The transmitter is connected to the AM station's antenna tower and commercial power, and an attempt is made to broadcast a 100 kHz signal that would interfere with Loranoperations over some geographical area. It is also assumed that the group has caused a GPS outage in the same area so that Loran is being used as a backup navigation source as well as a positioning data source for ADS-B.

There are several substantial barriers to this approach. First, the antenna will be electrically short with a small ground screen system at 100 kHz, and thus will have a low radiation efficiency.

The broadcast-station database maintained by the Federal Communications Commission (FCC) was accessed, and parameters for the population of stations by frequency and antenna height were extracted.[6]

The population of broadcasting antennas whose height would be large enough (i.e., h > 100 m) to have reasonable radiation properties at 100 kHz is relatively small (288 out of 4780)--about 6% of the stations. Because their revenue depends *entirely* on being on the air, broadcasting stations closely monitor their transmitter's status and any interruption would be quickly investigated, even at an unmanned transmitter site. This narrows the population of "candidate" stations to those that are daytime-only operations.

There are 839 daytime-only AM stations in the United States. These "daytimer" stations transmit from (approximately) sunrise to sunset and then are entirely off the air until the following morning. A period of time might then exist overnight during which a station's antenna could be appropriated with less risk of detection. Figure I-4 is a plot of the antenna height vs frequency relationship for daytime-only stations. Of these, only 18 have an antenna height that is greater than 100 m *and* are sited within 50 km of a major airport. None of the 18 daytime-only stations is within 10 km of a major airport.

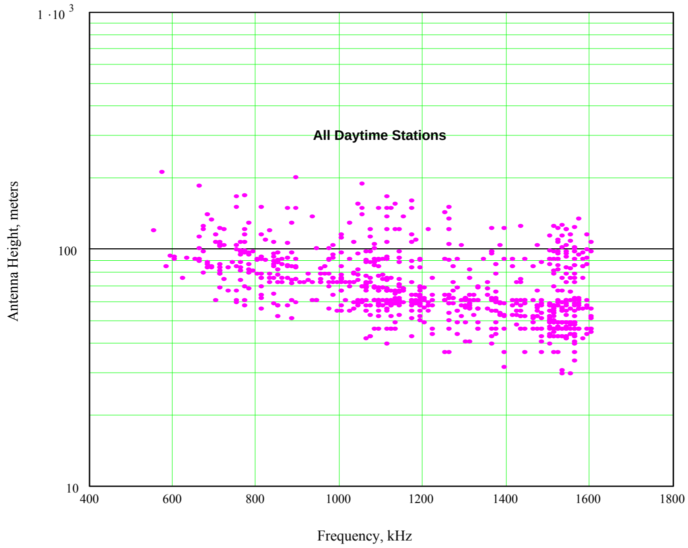

Figure I-4. *Daytime-Only* AM Broadcasting Stations in the United States: Antenna Tower Height vs. Frequency

While daytime-only stations appear to be the only type that could be taken over for illegitimate use, the overnight period when they could be available has a very small air traffic load and thus the impact of Loran interference will likely be minimal to negligible. The risk of discovery and the effort required are large, and the chance of successfully producing harmful interference to aviation is very small.

As we have seen, for short antennas, the capacitive reactance is large, and so reducing it with a matching network helps the situation at first. However, as the antenna reactance is reduced, the impedance approaches the sum of the radiation resistance and the system resistance in magnitude. See Figure I-5. Since this is small for short antennas, the antenna current begins to rise beyond the capacity of the transmitter.

As the antenna impedance falls, it will begin to look more like a short circuit to the transmitter. If the output voltage could be maintained, the current would rapidly reach very high values (Figure I-5, dashed trace increasing to the upper left.) This could provide a large amount of radiated power. But, because of the transmitter's internal impedance, the output voltage will fall until the overload circuits in the power amplifier are tripped or the output amplifier stage burns up.

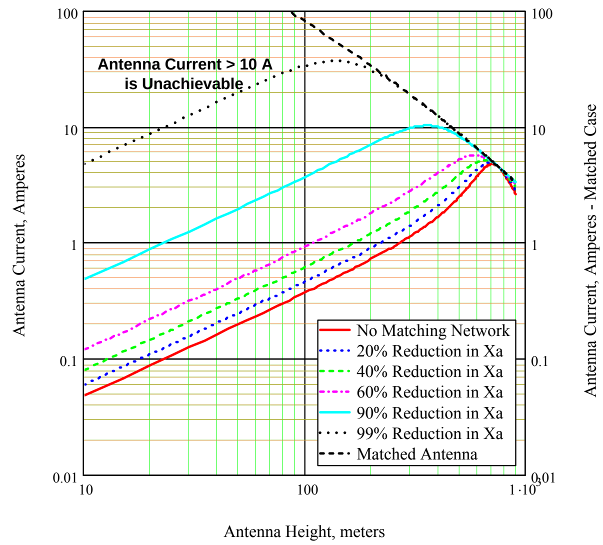

Figure I-5. Antenna Current vs. Antenna Height for Varying Impedance Matching – 5 kW Transmitter Input

The analysis shows that the largest distance at which an interfering signal will result in even a 0 dB Desired-to-Undesired (D/U) ratio is less than 3.5 km. Since Loran can support RNP 0.3 with a D/U ratio of only -10 dB, harmful interference is unlikely for any achievable geometry.

I-2-2. Transmitter in a General Aviation Aircraft

In this case, it has been assumed that a small General Aviation (GA) aircraft has been obtained for the purpose of fitting it out with a 500 W, 100 kHz transmitter and a trailing wire antenna.

Modern radio transmitters, if used on the design frequency without modification, approach a 75% efficiency. An inverter to convert the aircraft DC power to 120 VAC has a similar efficiency. Thus, the power required from the aircraft alternator system will be about 925 W. This will exceed the alternator capacity of all but the newest single-engine airplanes or light twins.

For a 100 meter antenna constructed from #16 AWG wire (radius = 0.645 mm), the capacitive reactance would be -j3560 Ω. The radiation resistance, $R_{rl}(h)$ for a thin wire antenna in free space (i.e., without a ground plane) is:[7]

$$Rr1 = 20\pi^2\left(\frac{h}{\lambda}\right)^2$$

where:

h is the wire length in meters
λ is the wavelength in meters

The "ground" resistance will be approximately that for free space, 377 Ω, because the airframe is so small compared with the wavelength that it makes a negligible contribution to the reduction of effective ground resistance. The matching coil resistance will be 6.2 Ω, making the system resistance about 383 Ω. This yields a radiation efficiency of:

$\eta = [0.2/(0.2 + 383)] \times 100$, or

$\eta = 0.05\%$,

which is the fraction of the transmitter power that will be radiated by the antenna. For a 500 W transmitter the radiated power will be only 0.25 W (+24 dBm).

Using this interfering signal level at the transmitting antenna, the distance from the aircraft at which the interfering signal would be equal to the *lowest* Loran signal level for any major airport is about 800 m.

I-2-3. "Suitcase" Transmitter

This scenario proposes that a suitcase-sized transmitter with an output power of 5 W is built. Two cases are examined: (1) the transmitter is connected, without matching, to a wire attached to a balloon, and (2) using a short vertical wire antenna that is 1 m long so that it can be concealed. In this latter case, it is assumed that an attempt would be made to take this equipment aboard an aircraft although the chance that it would get through airport security is not good.

From the analyses above, it can be seen that the reactance for an unmatched 100 m tower-type antenna will be -j 1350 Ω. The radiation resistance would be 0.44 Ω. A 5 W transmitter with a standard 50 Ω output impedance will have a carrier voltage of about 16 volts. The antenna current will be 11.8 mA, so the radiated power will be 61.3 μW(-12.1 dBm). This level is below both the noise level and Loran signal level, at the antenna. It will not cause interference to Loran at any distance from the antenna.

The case using the 1 m wire will perform far worse. The radiated power would be about 2 pW (-87 dBm), with the result that it is not an interference threat to Loran at *any* distance from the transmitter, *including* a case where the equipment was somehow carried on the airplane.

Part II. LORAN COVERAGE ANALYSIS UNDER INTERFERENCE

II-1. Scope of Analysis

In this section, theoretical assessment of nominal Loran station (LORSTA) coverage and its degradation by a simplified jamming scenario is discussed. First, a set of nominal LORSTA coverage is assessed subject to mean seasonal and regional CONUS atmospheric noise conditions. Second, the effect of a ground-based 100 W EIRP jammer is assessed under the worst case assumption that the jammer is strategically located at the nominal LORSTA edge of coverage and transmits an identical pulse stream that matches the Loran power spectral density (PSD).

Both desired LORSTA and undesired jamming signals are subject to a complex 100 kHz LF groundwave propagation phenomena where different ground elevation, conductivity, and the dielectric constant alter the propagation distance significantly. Therefore, four empirical ground-propagation data sets are taken from International Radio Consultative Committee (CCIR) recommendations [8] then applied over homogenous, smooth, and spherical paths for both desired and undesired signals. These empirical propagation data sets represent sea water, fresh water, average soil, and dry soil paths in descending order of better-to-worse LF propagation properties. Additional critical assumptions in this paper are as follows.

- Modernized Loran receiver capable of tracking at -10 dB S/N threshold
- Modernized Loran receiver capable of decoding the 9-th pulse communication data link at a -10 dB S/N threshold
- 4 dB receiver peak envelope mismatch loss [9]
- 12 dB receiver nonlinear processing gain against the atmospheric noise [10]
- 100 W EIRP jammer exactly matching the Loran power spectra (for example, a repeater with poor antenna matching efficiency as discussed in Part I)
- No early sky wave, ionospheric noise, envelope-to-cycle identification mismatch
- No additional secondary factor (ASF) other than propagation delay by a homogenous medium
- No receiver-motion Doppler and jerk
- H-field receiver antenna without P-static

II-2. Groundwave Field Strength

The field intensity of a P_t kW transmitter, assuming a realistic short vertical dipole antenna over the surface of a perfectly conducting earth, at a 1 km distance is found as

$$E = \frac{30}{d}\sqrt{\frac{P_t}{10}} \tag{1}$$

= 300.0 mV/m (at 1 km with 1 kW input)
= 109.5 dB/μV/m.

The simplified field strength of ground wave propagation with power P in kW and distance d in km over a perfectly conducting flat surface can be derived from (1) as

$$E = 109.5 + 10\log_{10}P_t - 20\log_{10}d \;\; (\mathrm{dB}/\mu\mathrm{V/m}) \;\; (\text{at } d \text{ km with } P_t \text{ in kW}). \quad (2)$$

However, when propagated over a smooth, spherical earth, the empirical effective propagation distance curves are shorter than the 'theoretical' distance in (2). These empirical ground wave propagation distances over various carrier frequencies are available from Annex I to the CCIR recommendation [8]. The Loran 100 kHz carrier ground wave propagation distances are shown in Figure II-1. Note the y-axis indicates the 109.5 dB/μV/m field intensity normalized to a 1 kw transmitter at 1 km distance.

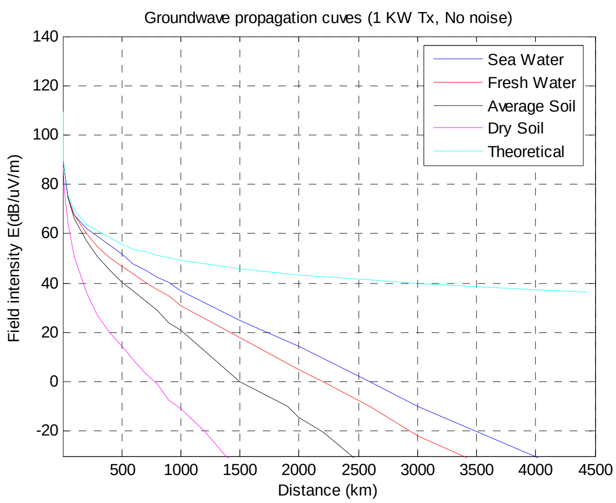

Figure II-1. Groundwave Propagation Distance of 100 kHz Carrier in km vs. Field Intensity

As the LORSTA transmission power level typically ranges between 0.4 Mega-Watt (MW) to 1.6 MW, the ground wave propagation curves can be scaled to estimate single LORSTA nominal coverage. Based on equation (2), the received field strength at a Loran receiver 1 km away from a 0.4 MW and 1.6 MW LORSTA, yields, respectively:

$$E_{0.4\mathrm{MW},\,1\,\mathrm{km}} = 135.5\ \mathrm{dB}/\mu\mathrm{V/m}$$
$$E_{1.6\mathrm{MW},\,1\,\mathrm{km}} = 141.5\ \mathrm{dB}/\mu\mathrm{V/m}.$$

II-3. Atmospheric Noise and Nominal LORAN Coverage

Atmospheric noise is the most significant issue in eLoran signal availability. The field strength of atmospheric noise in the LF spectrum varies hourly, seasonally, and regionally [9, 10, 11]. In CONUS, its root mean square (rms) value can fluctuate by more than 30 dB between winter and summer in the same region. In the summer, different regions can have more than 20 dB differences. The external noise power (F_a) per unit bandwidth received by a short antenna relative to kT, where k is Boltzmann constant 1.38E-23 J/K and T is the reference temperature (K), typically at 288 K is given as:

$$F_a = E_n - 20\log_{10}F_M + 95.5 - 10\log_{10}B. \quad (3)$$

E_n is the incident rms noise field strength (dB/μV/m), F_M is the received frequency (MHz) and B is the bandwidth (Hz). For Loran, the value of the rms noise field strength for a short vertical antenna over a perfectly conducting ground using B = 20 kHz, F_M = 0.1 MHz yields,

$$E_n = F_a - 72.5\ \mathrm{dB}/\mu\mathrm{V/m}. \quad (4)$$

The average atmospheric noise power F_a received by a short dipole antenna can be estimated from the tabulated seasonal, temporal, and worldwide regional variation charts from 1998 ITU.R Rec. Pl.372-6 using a similar statistical interpolation algorithm that was originally developed in MITRE's 1982 airport screening model [9]. In this paper, the minimum, average, and maximum seasonal rms field intensity values in [9] are considered. These are 41, 52, and 65 dB/μV/m, respectively. They are compensated by a 12 dB receiver nonlinear processing gain against the atmospheric noise by the Loran Integrity Performance Panel (LORIPP) recommendation [10]. The envelope peak mismatch loss of 4 dB is also considered, yielding 33, 44, and 57 dB/μV/m noise field intensities across the Loran coverage.

Table II-1 summarizes nominal LORSTA coverage estimates over smooth, homogenous, and spherical earth, including the atmospheric noise figure. The coverage is represented by the distance from the LORSTA at which the signal-to-atmospheric noise ratio (S/N_A) decreases to -10dB.

Table II-1. Nominal LORSTA Coverage (Coverage Limit at -10 dB S/N)

Power (MW)	Atm Noise (dB/μV/m)	Sea Water (km)	Fresh Water (km)	Avg. Water (km)	Dry Land (km)
1.6	41	2961.6	2561.6	1862.4	944.0
	52	2518.9	2121.6	1457.7	734.2
	65	1978.1	1616.9	1145.2	491.6
1.2	41	2911.6	2511.6	1813.4	908.3
	52	2467.2	2071.6	1427.6	706.4
	65	1918.6	1568.9	1115.1	468.9
0.8	41	2841.2	2441.2	1744.3	877.4
	52	2394.3	2001.2	1385.3	673.2
	65	1834.8	1501.1	1072.8	436.9
0.4	41	2720.8	2320.8	1626.3	831.0
	52	2269.8	1885.4	1313.0	618.5
	65	1691.4	1385.4	1000.5	386.0

II-4. Effect of 100 W EIRP Jammer to LORSTA Coverage

It is assumed that the jammer is located at the nominal edge of coverage of LORSTA (i.e., at the distances shown in Figure II-1).. The Loran receiver's signal-to-noise plus jamming ratio $S/(N+I)$ is calculated from the signal-to-atmospheric noise ratio (S/N_A) and the signal-to-jammer ratio (S/I) using the following equation in decimal ratio.

$$\left(\frac{S}{N+I}\right)^{-1} = \left(\frac{S}{N_A}\right)^{-1} + \left(\frac{S}{I}\right)^{-1} \qquad (6)$$

Figure II-2 depicts an example effect of a 100W EIRP jammer for the case of a 1.6MW LORSTA over sea water in 41 dB/μV/m atmospheric noise. For this example, the nominal coverage is at a distance of 2961.6 km. The effect of the jammer (located at the edge of the nominal coverage) is to reduce the LORSTA coverage to a distance of 2158.4 km. Table II-2 shows this reduced coverage value in the first row under "sea water." The desired LORSTA S/N_A (blue dotted line) decreases from the maximum at 108.5 dB[1] in the y-axis to -10 dB at the nominal coverage in the x-axis. At this nominal coverage, the jammer maximum field intensity I has its peak that is scaled to 100 W using (2) then decreases toward the origin by the horizontal mirror-image. The signal-to interference ratio S/I(Jammer) in dB is shown in the dotted red line, then the signal-to-noise plus jamming ratio $S/(N+I)$ is obtained in the solid black line based on [6]. At the -10 dB $S/(N+I)$ threshold, the nominal coverage is now reduced by approximately 27% to 2158.4 km.

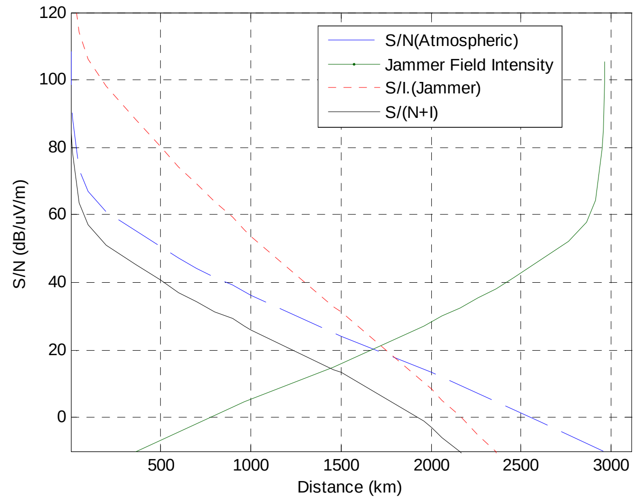

Figure II-2. 1.6 MW LORSTA Nominal Coverage and Its Reduction by 100 W EIRP Jammer over Sea Water in CONUS Minimum Seasonal Mean Atmospheric Noise (41 dB/μV/m)

Table II-2 summarizes the coverage reduction by a strategically located 100W jammer at the nominal coverage in Table II-1, and Table II-3 shows the relative coverage reduction in percentage by using both Table 1 and 2.

Table II-2. Reduced LORSTA Coverage by 100 W EIRP Jammer (Coverage Limit at -10 dB S/(N+I))

Power (MW)	Atm. Noise (dB/μV/m)	Sea Water (km)	Fresh Water (km)	Average Land (km)	Dry Land (km)
1.6	41	2158.4	1850.4	1317.7	699.2
	52	1887.7	1578.5	1094.0	534.0
	65	1460.3	1201.5	857.5	324.9
1.2	41	2107.4	1801.5	1280.5	666.3
	52	1831.7	1530.4	1064.0	508.8
	65	1406.8	1153.4	830.7	308.4
0.8	41	2035.7	1732.4	1228.2	635.7
	52	1752.8	1460.9	1022.5	477.2
	65	1331.4	1085.7	794.2	287.0
0.4	41	1905.8	1614.4	1135.9	586.6
	52	1618.0	1345.1	941.4	421.6
	65	1199.6	979.4	717.7	250.8

[1] Peak S/N(atmosphere) = $E_{1.6\text{MW}, 1\text{ km}}$ - RMS atmospheric noise + Rx. Nonlinear processing gain – Peak envelop mismatch loss: 108.5 dB = 141.5 dB/μV/m – 41 dB/μV/m + 12 dB - 4 dB

Table II-3. Relative LORSTA Coverage Reduction by 100 W EIRP Jammer (Coverage Limit at -10 dB S/(N+I))

Power (MW)	Atm. Noise (dB/μV/m)	Sea Water (%)	Fresh Water (%)	Average Land (%)	Dry Land (%)
1.6	41	27.1	27.8	29.2	25.9
	52	25.1	25.6	25.0	27.3
	65	26.2	25.7	25.1	33.9
1.2	41	27.6	28.3	29.3	26.6
	52	25.8	26.1	25.5	28.0
	65	26.7	26.5	25.5	34.2
0.8	41	28.4	29.0	29.6	27.5
	52	26.8	27.0	26.2	29.1
	65	27.4	27.7	26.0	34.3
0.4	41	30.0	30.4	30.2	29.4
	52	28.7	28.7	28.3	31.8
	65	29.1	29.3	28.3	35.0

When the three most representative CONUS seasonal and regional atmospheric noise average values are considered, the effectiveness of a 100 W EIRP jammer is shown to have between a 25% to 35% reduction of nominal coverage. Note that this reduction estimate is based on a worst case geometrical assumption where a repeater-type jammer is strategically located at the nominal coverage limit of a single LORSTA. Importantly, despite jamming, the LORSTA coverage rarely drops below 1000 km over seawater, fresh water, and average soil conditions except during the summer when atmospheric noise is worst in regions with heavy lightning.

III. SUMMARY CONCLUSIONS

The analysis in Part I of this paper has shown that none of the three postulated deliberate interference scenarios will result in harmful interference to Loran when it is being used as a GPS backup for aviation. The analysis shows a very low probability of successfully producing operationally significant interference (due, in part, to the fact that the most sophisticated attempt could be implemented only late at night), combined with the complex technical challenges, electrical hazards and likelihood of discovery. In the authors' opinion, based on these results, it is unlikely that anyone would attempt this.

The theoretical analysis in Part II of the paper shows that the worst-case coverage reduction is not significant. It likely could be mitigated by the existing multiple chain coverage in CONUS. Thus, the robustness of the Loran system under intentional interference is demonstrated.

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[4] A good rule of thumb for steel towers, based on searches of several tower manufacturer websites, is that the "diameter" (~ width of a side) in meters is:

$$d(h) := \frac{\sqrt{h}}{6}$$

[5] U.S. Coast Guard, *Radionavigation Bulletin*, Spring/Summer 2002, Table 1.

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