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MODELING AND MEASUREMENT OF ELECTROMAGNETIC FIELDS NEAR LORAN - C AND OMEGA STATIONS

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FINAL REPORT
JULY 15, 1987

PAUL C. GAILEY

Prepared for: Ken Doolan, C.I.H.
Commandant (G-CSP)
United States Coast Guard

575 Oak Ridge Turnpike, Oak Ridge, Tennessee 37830 Phone 615/482-3681

MODELING AND MEASUREMENT OF ELECTROMAGNETIC FIELDS

NEAR LORAN-C AND OMEGA STATIONS

Paul C. Gailey

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Final Report for

LORAN/C OMEGA Radiation Exposure Study
Funded by the United States Coast Guard

Under Contract Number DTCG-23-85-20073

LORAN/OMEGA RADIATION HEALTH RISK STUDY BACKGROUND AND OVERVIEW

For the past few years, there has been a concern about radiation emitting devices and adverse non-thermal health effects. The Coast Guard, as a user of some of those devices, shares this concern and has taken steps to protect our personnel. One important step is the recently completed Loran/Omega Radiation Study. Accordingly, additional studies are planned for Coast Guard cutters/boats. There are other electromagnetic radiation sources in the Coast Guard that should be identified for similar risk assessment.

Commandant (G-CSP) initiated and monitored the study for Commandant (G-N) and in coordination with Commandant (G-T). Of primary concern to the program manager was the lack of radiation exposure and field intensity data necessary to answer health risk questions and to assess the potential operational impact of several proposed Environmental Protection Agency (EPA) radiation exposure standards. The study included a representative sample of Loran units and both Omega units; exposure profiles at other Loran stations were developed by modeling and are included in the report.

It seems unlikely that any of the proposed EPA standards for the general public would, if adopted, adversely affect Loran/Omega operations, since field intensities at station boundaries are well below the most stringent proposal. With few exceptions, Loran/Omega working and living environments contain relatively low radiation field strengths. However, very little non-thermal health effects research has been done for the Loran and Omega frequencies and it is difficult to accurately define personnel health risk. There have been an increasing number of studies attributing a wide range of chronic health effects to low frequency radiation exposures at other frequencies. A finite answer on the chronic exposure issue may be years away. In the interim, it is prudent to apply the "as low as reasonably achievable" concept used for other types of exposures. The discussion and recommendations sections of the report include practical information that commanding officers should use to limit personnel exposures.

Commandant (G-CSP) will continue to monitor the radiation health effects research and studies as they pertain to risk in Coast Guard working/living environments. The exposure assessment data of this study will serve as a baseline to evaluate the impact and significance of new research and epidemiological findings on Coast Guard operations. Questions concerning the study can be addressed to Mr. K. F. Doolan, Commandant (G-CSP-4), at FTS 267-2957.

ACKNOWLEDGEMENT

The author gratefully acknowledges the assistance of Ken Doolan and the many other Coast Guard personnel who made this study possible. Richard Adler, Ric Tell, and Ed Mantiply provided valuable technical assistance. A special thanks also to Pat Carson and Judy Heck for their help in manuscript preparation.

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I. Summary

A study of nine LORAN-C and two OMEGA stations was performed to investigate potential health hazards of the electromagnetic radiation from these stations to Coast Guard personnel and the general public. The study employed prediction methods and measurements to determine near electric and magnetic fields on and around station property. Prediction of the electromagnetic field strengths was accomplished using the Lawrence Livermore National Laboratory Numerical Electromagnetic Code (NEC). Results of the NEC modeling were used to prepare for the measurement phase and explore the feasibility of using prediction methods to replace future on-site measurements. Field strength measurements were performed inside station buildings, on the ground around the transmitting antenna, and on the antenna tower itself. Variations in field strength as a function of distance from the transmitter were examined to test modeling predictions, and distances to which existing and proposed safety standards are exceeded were identified to permit evaluation of compliance. Shock hazards and induced body currents were also investigated.

Results of the study indicate that in most cases the station personnel are exposed to field strength levels far below currently applicable occupational safety standards (ACGIH, 1983 adoption). Outside station property boundaries, the field strength levels are typically a small fraction of even the lowest general population standards now proposed by the U.S. Environmental Protection Agency. Potential problems include exposures to personnel climbing energized towers, high field strengths near tuning coils, and high field strengths near the tower base or feed. In some cases, the public is permitted on station property and may be exposed to field strengths near or greater than the ACGIH occupational standard. Simple safety practices can be employed to reduce most exposures to acceptable levels.

II. Introduction and Overview

LORAN-C and OMEGA stations comprise two major radionavigational systems available to marine vessels and aircraft throughout much of the world. Stations located in the United States are under the jurisdiction of the U.S. Coast Guard which is responsible for manning and operating this portion of the system. These facilities emit relatively intense levels of radio frequency energy in an effort to provide coverage over large geographical areas. This study is an investigation of the electromagnetic field strengths generated in the near vicinity of LORAN-C and OMEGA stations. Its purpose is to evaluate the potential for hazardous exposures to Coast Guard personnel and the general public who live and work near the transmitters.

A preliminary survey of LORAN-C and OMEGA near fields performed in 1980 (1) indicated some high field strength areas and pointed to the need for a more complete study. Significant changes in safety standards have also occurred in the intervening time period. The present study serves as an accurate and thorough assessment of field strengths occurring at each of the unique LORAN-C and OMEGA station configurations. The results are then used to predict field strengths at the stations not visited as a part of this study. Measurement and prediction results are general enough to assess standards compliance now as well as in the future should output power levels or safety standards change.

Evaluation of the electromagnetic environment in the near field requires determination of both electric and magnetic field strengths. In these areas, most of the energy occurs in reactive fields rather than traveling waves. Measurements are complicated by a number of near field effects which require a thorough knowledge of electrostatic theory to anticipate and interpret. Before the on-site measurements were begun, modeling of the electromagnetic fields was performed using the Lawrence Livermore National Laboratory Numerical Electromagnetic Code (2) to predict field levels and study expected field distributions and anomalies. The modeling revealed many generalities about the fields and led to a simplified model that can be used without a computer to predict field levels given a station's output characteristics.

Because of the low frequencies, high field strengths, and pulse modulation of LORAN-C (100 kHz) and OMEGA (10.2-13.6 kHz) signals, no commercial instrumentation was available which would meet all the study requirements. Responsibility for the specification and construction of custom instrumentation was delegated to the Johns Hopkins University Applied Physics Laboratory (JHU/APL) under contract with the Coast Guard. An electric field strength meter and a magnetic field strength meter were built which addressed the numerous measurement problems, and operated successfully throughout the study. Calibration of the instruments was conducted at the U.S. Environmental Protection Agency's Non-ionizing Radiation Laboratory in Las Vegas, NV. Comparison testing of the field strength meters against EPA's instruments at a LORAN-C station further confirmed their accuracy. Both instruments measured peak field strengths to avoid complications of the variable duty cycles between stations. Measurements were performed at nine representative LORAN-C stations and two OMEGA stations. Electric and magnetic field strengths were measured in and around station buildings, along radials extending away from the antennas and on the antenna towers. The data was then converted to rms field strengths using mathematically derived relationships discussed in Appendices A and B. Special emphasis was placed on determining areas in which field strengths exceeded proposed and established safety standards. Shock hazard was evaluated using commercially available instrumentation to measure open-circuit voltages and short-circuit currents induced on ungrounded guy wire segments and other conductive objects.

Field strengths (rms) greater than the ACGIH standard (614 V/m and 1.63 A/m) were found in limited areas surrounding antenna feeds and tuning coils. The daily routines of most station personnel do not require them to enter these areas on a regular basis and typical exposures are far below the ACGIH standard. Tower climbers and personnel working near the feed are sometimes exposed to field strengths above the ACGIH standard indicating a need for review of certain work practices. At some stations, the antenna feed is very close to station buildings and relatively high field strengths exist in parking lots and walkways. It is recommended that the public not be permitted in these areas as lower, general population safety standards have been proposed. Field strengths drop off quickly with distance from the antenna feed and exposures beyond station property boundaries are low with respect to proposed standards.

III. Station Descriptions

LORAN-C and OMEGA stations utilize a number of different antenna configurations to radiate their navigational signals. The choice of antenna plays a major part in determining the electric and magnetic field distribution which is produced near the station. Once the field distribution produced by a given antenna type is known, field strengths around similar antennas can be predicted using the station's power output. Stations representing all the unique antenna configurations used in the United States were visited for this study in order to characterize the field distributions. The major features of these antennas are discussed below along with other station considerations which affect personnel exposures.

The most important fact in understanding LORAN-C and OMEGA stations is that the wavelengths are very long. Radiating a carrier frequency of 100 KHz, LORAN-C wavelengths are 3000 meters (9,843 feet) long. OMEGA wavelengths are 30,000 meters (98,425 feet) long. To radiate energy efficiently, an antenna should be a significant fraction of the wavelength long. A monopole above ground, for example, radiates efficiently when it is one-quarter wavelength high. Meeting this criterion for LORAN-C would result in an antenna nearly 2500 feet high. The difficulties and costs of such large antennas are circumvented by using certain techniques to improve the efficiency of much shorter antennas.

A common configuration for LORAN-C antennas is the 625-foot monopole. This antenna consists of a 625-foot steel tower with ground and top radials and is isolated from ground by a cylindrical ceramic insulator. The LORAN-C signal is driven into the antenna above the insulator and referenced to the ground radial system. An increase in the antenna's electrical length is accomplished by extending twenty-four equally spaced steel cables from the top of the antenna out and away from the tower. This configuration is known as top-loading or top radials and results in a higher antenna capacitance distribution which makes the antenna "appear" longer to the drive signal. The net result is improved radiation efficiency.

The top radials are 600 feet in length and depart from the tower top at about a 54 degree angle (see Figure 11). On the far end, they are connected by an insulator to a guy wire which is anchored to the ground about 850 feet from the tower base. These guy wires, along with the supporting tower guy wires, are broken by insulators at several points to reduce coupling with the tower and top radials. Normally, the lowest insulator is out of reach of a person on the ground so as to prevent shocks from induced voltages on the guy wires. The bottom segment is grounded and presents no shock hazard. In rare cases, the lowest insulator is within reach and can produce a shock as discussed in Chapter IX.

Two similar LORAN-C antenna designs are the 700-foot and 1350-foot monopoles. These antennas are also top loaded. The 700-foot monopole employs 12 top radials 680 feet in length which are anchored 1000 feet from the antenna base by guy wires. Port Clarence, Alaska, is the only 1350-foot monopole in the United States. Six top radials extend 350 feet from the tower and are anchored 1900 feet from the tower base by guy wires. All LORAN-C monopoles in the U. S. belong to one of these three types: 625, 700 or 1350-foot tower heights, with the exception of Baudette, MN, which uses a 730-foot monopole. The remaining LORAN-C antennas consist of four towers supporting an extended antenna system.

There are six of the non-monopole type LORAN-C antennas in the U. S. Five of these are of the SLT (Sectionalized LORAN Tower) type. The remaining extended system is called a TIP antenna and is located in Carolina Beach, North Carolina. These extended antennas consist of a series of catenaries and risers supported by four grounded towers (see Figure 25). The towers are approximately 700 feet high and form a square about 1450 feet on a side. The antenna is insulated from the grounded support towers and fed by a cable extending from the transmitter building at the center of the system to the risers.

All LORAN-C antennas employ a ground radial system to improve radiation efficiency. The radials increase the ground conductivity and provide more stable electrical parameters to the transmitter. Typical ground systems consist of 120-180 buried radials spaced two to three degrees apart. Much of the "return" current is confined to these radials.

Only two OMEGA stations are located in the United States. The station in La Moure, ND, consists of a 1200-foot monopole attached to 16 top radials which are anchored 2400 feet from the tower. The Kaneohe, HI, OMEGA antenna is made up of six catenaries spanning a natural valley formation. A multi-cable feedline carries the signal from the matching transformers up to the spans. Because OMEGA wavelengths are so long, these antennas represent only a small fraction of a wavelength, that is, they are electrically short. The result is that they are inefficient and must be driven by much higher voltages to reach a given power output. Drive voltage is not a measured quantity, but it has been estimated that OMEGA voltages are in the vicinity of 250,000 volts while LORAN voltages are roughly 25,000 volts. Table 1 lists the existing LORAN-C and OMEGA stations in the United States along with their antenna types and power outputs. The power output refers to the peak power developed during a pulse.

There are four major areas involved in transmitting LORAN-C and OMEGA signals which are pertinent to this study. First the signal is generated and synchronized with a time standard in a shielded signal room or building. Next, the signal is amplified by high power transmitters before injection into the tuning or matching system as a third step. Finally, the signal is fed to the antenna for broadcast. Signal generation, amplification, and tuning may occur within a single building or may occupy separate structures. The antenna or feed point is often located next to the transmitters, but may be separated by several hundred feet.

The impact of these considerations to Coast Guard personnel is that the highest field strengths occur in two locations: (1) near the tower base or feed point and (2) near the tuning coils. At stations in which these two areas are physically isolated from other activity areas, exposures are greatly reduced. A common situation, however, is that the antenna or feed is located next to one or two buildings in which nearly all station activities take place. Such configurations require a more careful scrutiny than isolated antennas. Often parking lots and walkways are within 20 feet of the antenna. Many of the recently built and reconditioned LORAN-C stations consist of one or two buildings with adjacent antennas, probably for the purpose of minimizing feedline losses. Field strengths occurring in these areas will be considered in the following chapters.

Another important consequence of station layout is exposure to the public. The extent of station property boundaries determines how close the public can approach the antenna. Generally, the Coast Guard owns or controls property beyond the top radial and guy wire anchor points. This means that the public cannot approach closer than several hundred feet from the antenna without entering station property. As discussed later, field strengths drop off quickly with distance and are very low at the property boundaries. A more important consideration may be cases where the station property is open to the public. Most stations are located in remote areas but the boundaries are not usually fenced, and unauthorized entry is also a consideration.

Housing for Coast Guard personnel is provided at some of the stations and a few include accommodations for families. Normally, the housing units are located outside the antenna system but some exceptions do exist. Exposures occurring in and around housing units must be evaluated as general population rather than occupational exposures, especially in cases where families are included.

Table 1. LORAN-C and OMEGA Antenna Configurations

Station	Antenna Configuration	Power Output (kw)
Attu, AK	625' Monopole	325
Baudette, MN	730' Monopole	500
Caribou, ME	SLT	350
Carolina Beach, NC	TIP	550
Dana, IN	625' Monopole	400
Fallon, NV	625' Monopole	400
George, WA	SLT	1600
Grangeville, LA	700' Monopole	800
Johnston, I., HI	625' Monopole	325
Jupiter, FL	625' Monopole	325
Kaneohe, HI	Valley Span - OMEGA	10
Kure I, HI	625 Monopole	325
La Moure, ND	1200' Monopole - OMEGA	10
Malone, FL	700' Monopole	800
Middletown, CA	625' Monopole	400
Nantucket, MA	625' Monopole	325
Narrow Cape, AK	625' Monopole	400
Port Clarence, AK	1350' Monopole	1000
Raymondville, TX	700' Monopole	400
St. Paul Island, AK	625' Monopole	325
Searchlight, NV	SLT	540
Seneca, NY	700' Monopole	800
Shoal Cove, AK	SLT	540
Upolu Point, HI	625' Monopole	325

IV. NEC Modeling

Electromagnetic fields around certain types of antennas can be predicted using mathematical models implemented on high-speed computers. This approach to field strength determination has several advantages and is often used along with measurements in a complementary role. In the present study, fields at only nine of the twenty-three U.S. LORAN-C stations were measured. By using the measurement results to verify and refine the models, field strengths at the remaining stations can be predicted with confidence. Modeling results were also found to be useful in anticipating field strengths before the surveys and developing generalizations which increase the knowledge of exposures near the stations. This broadened understanding of the factors affecting field strengths is important in light of the operational changes which sometimes occur at existing stations and the construction of additional stations. Reliable prediction methods also reduce the need for continuous on-site measurements.

Initial modeling of the LORAN-C and OMEGA antennas was performed using the Lawrence Livermore National Laboratory Numerical Electromagnetic Code (2) referred to simply as NEC. This computer code calculates numerical solutions to integral equations for the currents induced on the antenna and support structures. NEC is computation intensive and memory intensive for complex antennas and runs most efficiently on large, high-speed computers. In this study, NEC was run on a Cray supercomputer for time efficiency and cost effectiveness. Batch jobs were submitted to the Cray through a remote job entry (RJE) station.

The RJE station was configured from an IBM-XT computer with the addition of a Houston Assembler Protocol Card (HASP) and associated software. Batch jobs consisting of the antenna models and appropriate Job Control Language were uploaded to the Cray via a 4800 baud bi-synchronous modem. After processing, the output files were downloaded to the RJE for analysis and plotting. Processing time varied from less than an hour to overnight depending on the size of the model, the number of calculation points, and the assigned priority.

Creation of models for NEC input requires knowledge of the antenna's geometry and feed characteristics. This information was gathered from mechanical drawings provided by the Coast Guard and various publications (3), (4), (5). Study of the above material revealed that LORAN-C antennas can be grouped into four types as shown in Table 2.

Table 2. Major U.S. LORAN-C Antenna Types

Antenna Type	Number of Stations in the U.S.
625' Monopoles	12 (includes 1 experimental station)
700' Monopoles	5 (includes 1 730' monopole)
1350' Monopoles	1
Extended Antennas	6 (5 SLTs and 1 TIP)

A model constructed to simulate one 625 foot monopole will generally apply to other stations with the same antenna configuration. Thus, only a few models were required to estimate fields around all the U.S. LORAN-C stations. A separate model was required to simulate the OMEGA station in La Moure, ND which consists of a 1200 foot top loaded monopole. The remaining U.S. OMEGA station is a valley span antenna located in Kaneohe, HI. This antenna consists of cables suspending over a natural valley formation. Because the NEC is designed for flat ground planes, the Kaneohe OMEGA could not be modeled in the same way as the other antennas. Alternative methods for predicting field strengths under this antenna are described in Appendix D.

A NEC model is constructed by approximating the antenna and support structure as a series of wires. The process begins by establishing a rectangular coordinate system which can be used to determine the xyz coordinates of every wire end point. A 625 foot monopole with 24 top radials could be modeled using 25 wires and a ground plane. Each wire is subdivided into segments over which the current is computed. One NEC requirement is that the segments be less than one-tenth wavelength in length. This constraint is easily satisfied when modeling LORAN-C and OMEGA antennas because of the extremely long wavelengths involved (3,000 - 30,000 meters). Wire radius is specified to approximate the electrical characteristics of the antenna as closely as possible. The choice is straightforward for some conductors such as the top-radials which may have an actual radius of one or two centimeters. Towers, in contrast, typically have triangular cross sections and are not solid. Various formulas are available to calculate a wire radius which will approximate the tower. For this study, the tower radius was modeled as about 0.4S where S is the length of one leg of the triangle.

The antenna drive was modeled as a voltage source across a single segment. One problem with this technique is that the drive voltage is not a measured quantity. Thus, an initial computer run with an arbitrary drive voltage was required to determine the relationship between the drive voltage and the output power. A new drive voltage could then be calculated which would produce the station's rated output power. This approach assumes that NEC calculates the correct antenna impedance which is not always true, but suffices for a first approximation. Another problem is the size of the drive segment. It is clear when observing an actual LORAN-C or OMEGA antenna that the drive voltage develops across the base insulator which is usually about a meter or less in length. The problem arises from the NEC requirement that adjacent segments have no more than about a 2:1 length ratio. A one meter drive segment requires that an adjacent segment be no more than two meters and so on. The normal method of subdividing the wire (tower) into equal segments would result in excessive computation time because of the resulting number of segments. Instead, a variable segmentation scheme was used which scales adjacent segment lengths according to a specified ratio.

Models of each of the major antenna types were created using the above techniques and various trigonometric relationships to determine end point coordinates. In some cases, simple computer codes were written to assist in calculating coordinates, especially for the SLT antennas which employ catenary wires. Completed models were then typed into NEC input format and submitted to the Cray for computation. Application of the results to other stations of the same antenna type simply requires scaling to the new output power.

Two software utilities were used to simplify the modeling procedure. The first is titled Interactive Graphics Utility for Army NEC Automation (IGUANA) and is used to provide graphic displays of the NEC input data set (6). These displays provide a quick visual check revealing any errors that may have occurred during data entry and can save hours of checking by recalculation. Figure 1 shows a side view of the La Moure, OMEGA model with no guy wires. The IGUANA software is also capable of rotating the model for other perspective views. Another useful software package called Graphical Plotting System (GRAPS) facilitates plotting of the NEC output (7). Examples of the GRAPS output appear throughout the text.

The La Moure, ND OMEGA was the first station modeled because its structural data was available early in the study and because measurement data had been reported by McEnroe (1) which could be used for comparisons. Initially, the antenna was modeled as a 1200 foot tower with 12 top radials above a perfect ground plane. Mininec 3, a personal computer scale code similar to NEC, was used to examine the model response before the RJE station was completed. Results of the Mininec 3 modeling compared favorably with the 1980 electric field measurements, but the execution was found to be too slow for extensive modeling.

Electric field strengths predicted by NEC for the North Dakota OMEGA stations are shown in Figure 2. The model included only the antenna as shown in Figure 1 with no guy wires attached. Results of both the NEC and Mininec 3 modeling show good agreement with McEnroe's measurements. Model complexity was increased in two steps beginning with the top radial support guys and finally including all support guys. Figure 3 shows the model with top radial guys included. These guy wires are connected to the top radials through insulators and extend to the ground. Additional insulators are inserted at several locations along the guys to limit induced currents and resulting interference problems. The insulators were modeled as breaks in the guy wires but are too small to be resolved on most of the IGUANA plots. Figure 4 shows a perspective view of the antenna with the individual wires numbered. Inclusion of the top radial guys produced a slight change in antenna impedance but had little effect on predicted field strengths (Figure 5).

The tower support guys were added to the NEC model as a final increase in model complexity. Figure 6 shows the completed model and Figure 7 provides a 16 times magnification of a portion of the antenna to permit resolution of the guy wire insulators. Note that the support guys do not contact the tower. A small increase in predicted electric field strengths resulted as can be seen in Figure 8. Field strengths directly under the support guys are more variable as shown in Figure 9. The

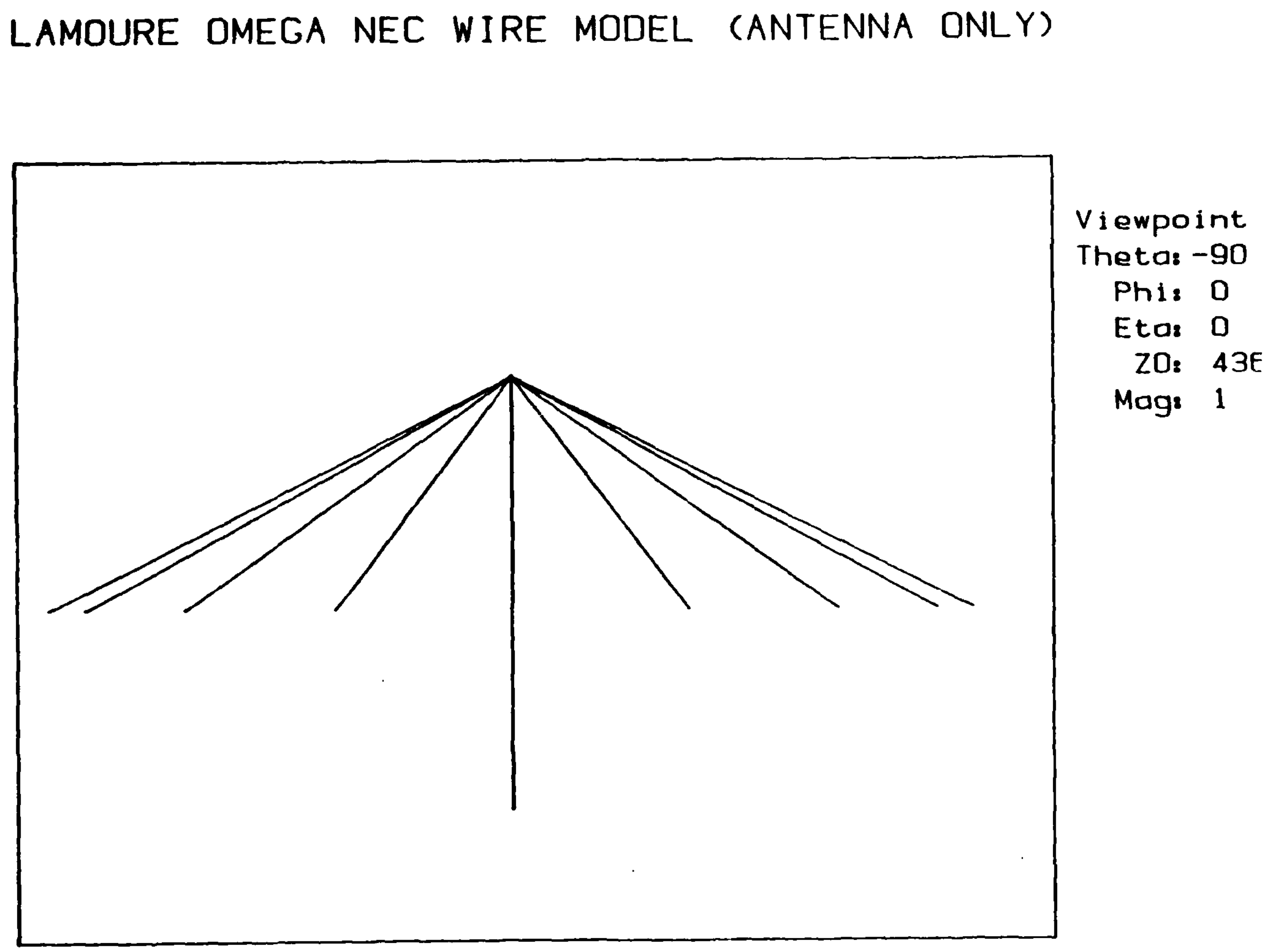


Figure 1. LaMoure OMEGA NEC wire model (antenna only)

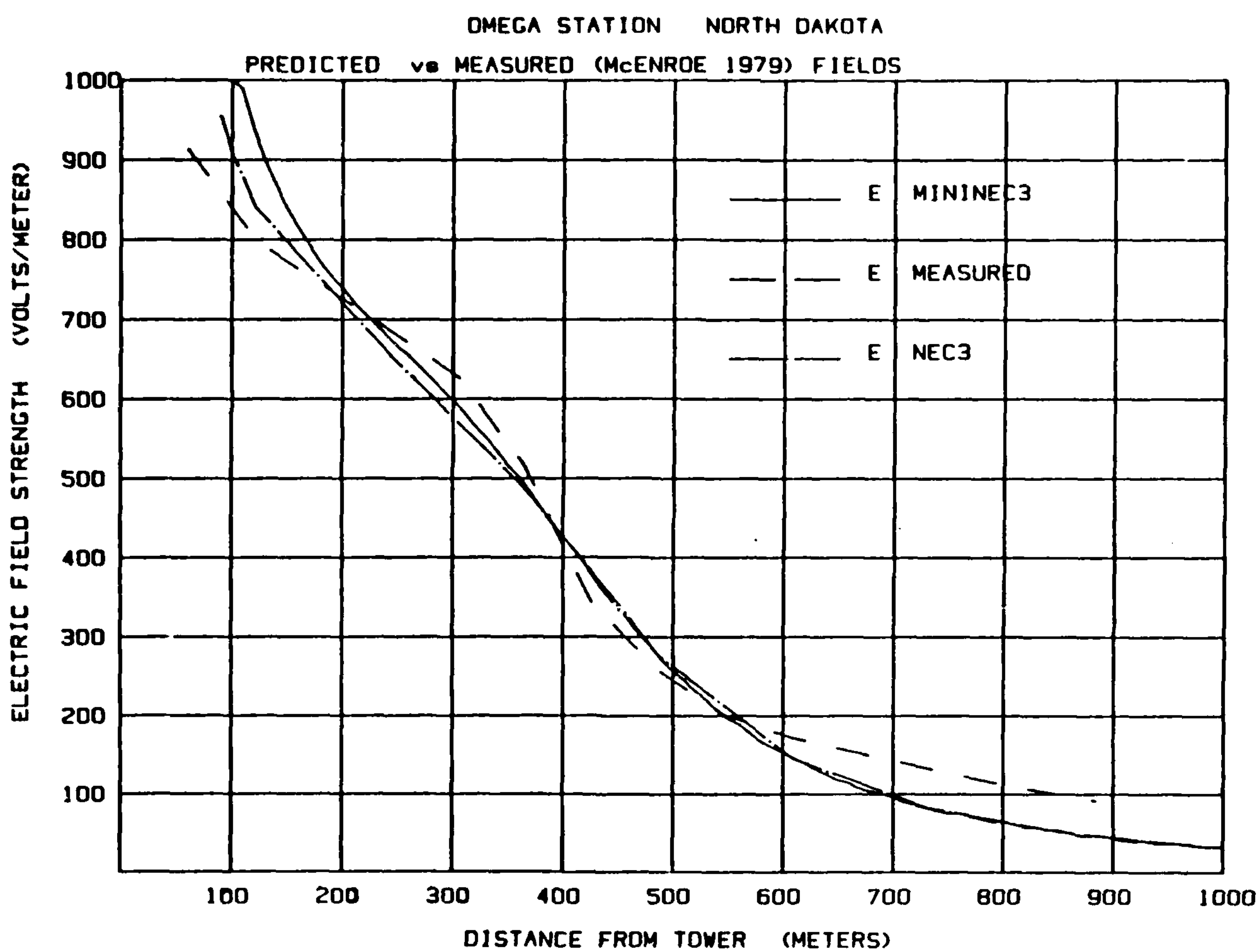


Figure 2. LaMoure OMEGA predicted vs. measured electric fields

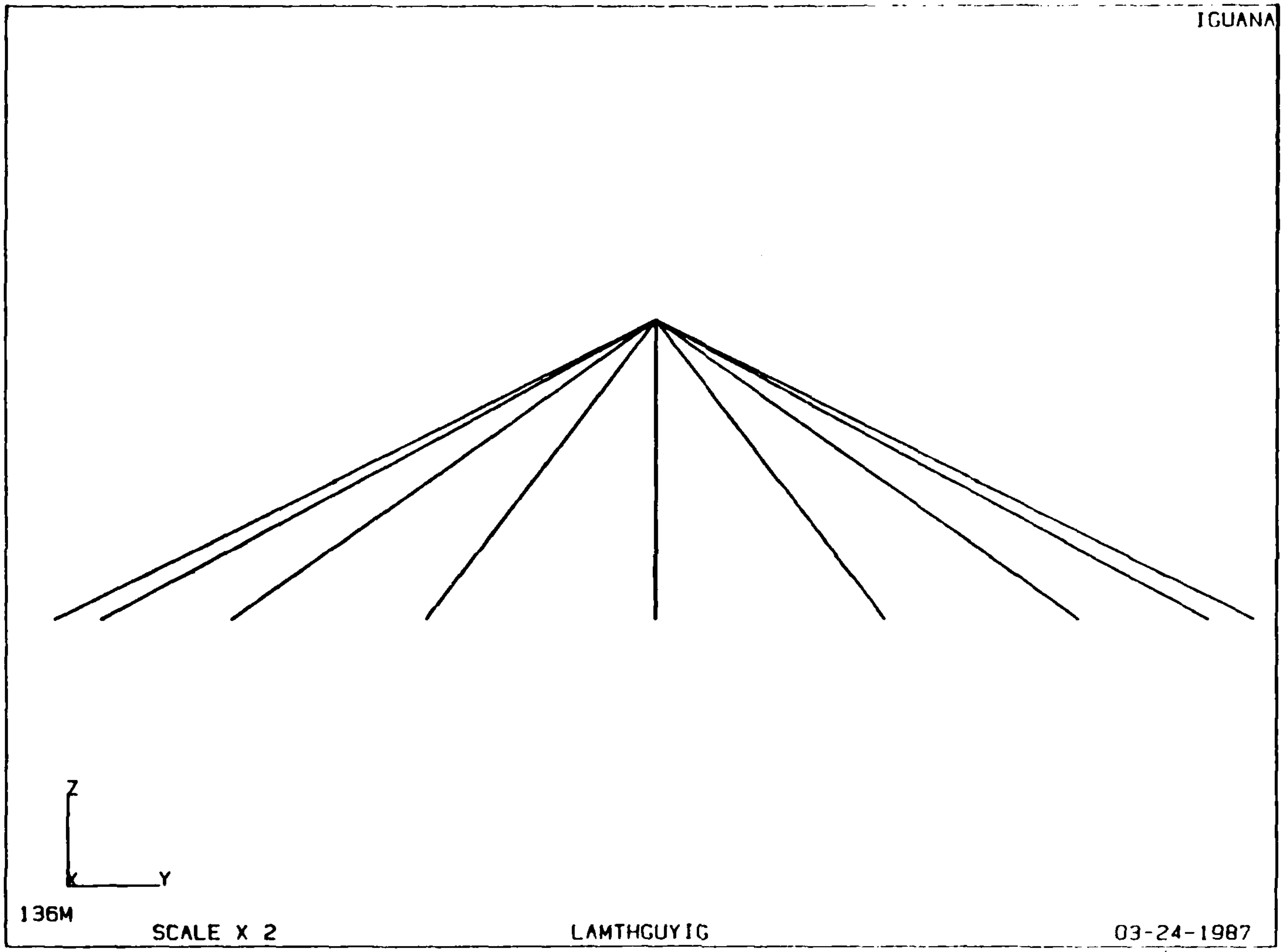


Figure 3. LaMoure OMEGA NEC model with top - radial guys

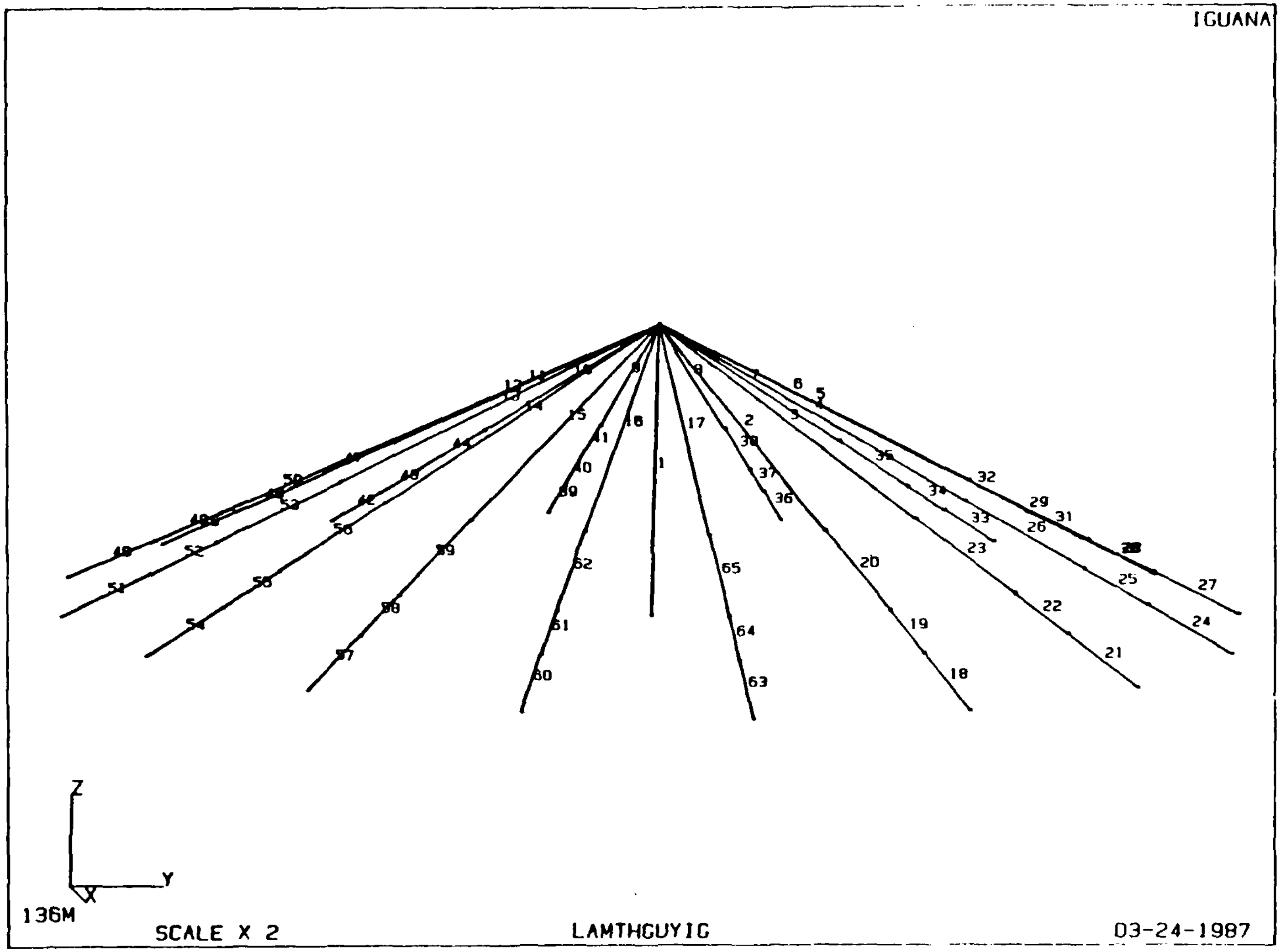


Figure 4. LaMoure OMEGA NEC model showing wire numbers

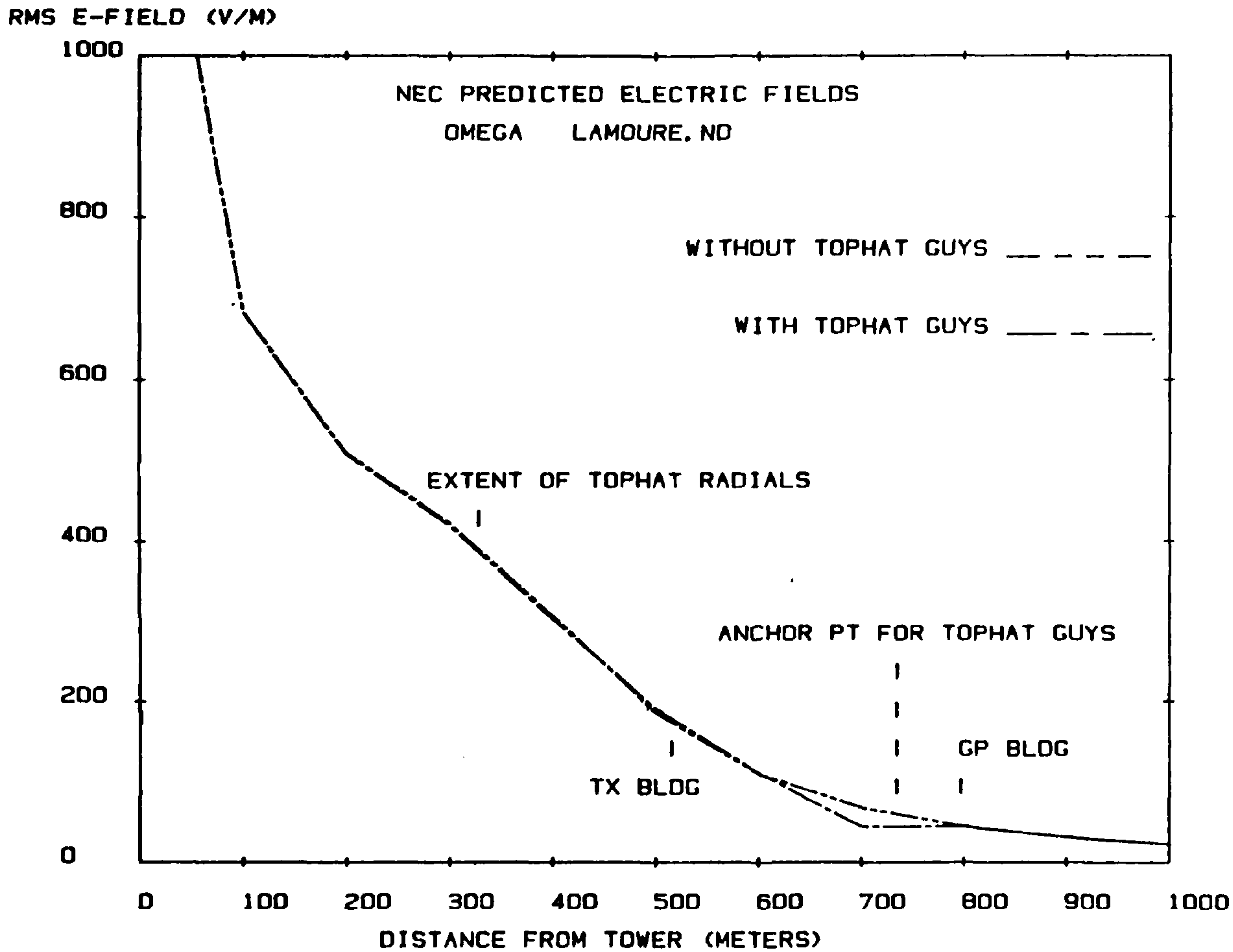


Figure 5. LaMoure OMEGA modeling results showing effect of including top - radial guys

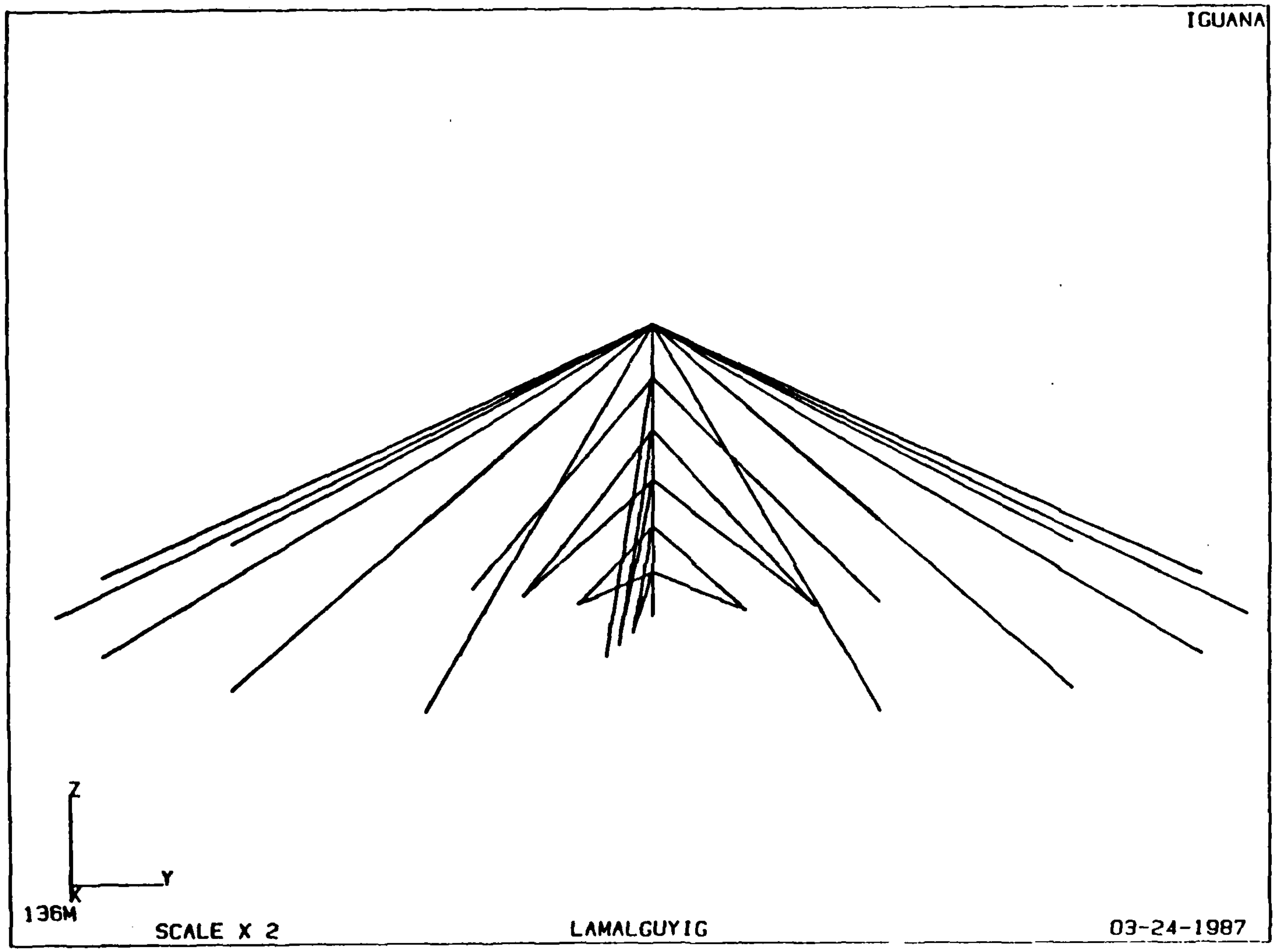


Figure 6. LaMoure OMEGA NEC model with all guy wires

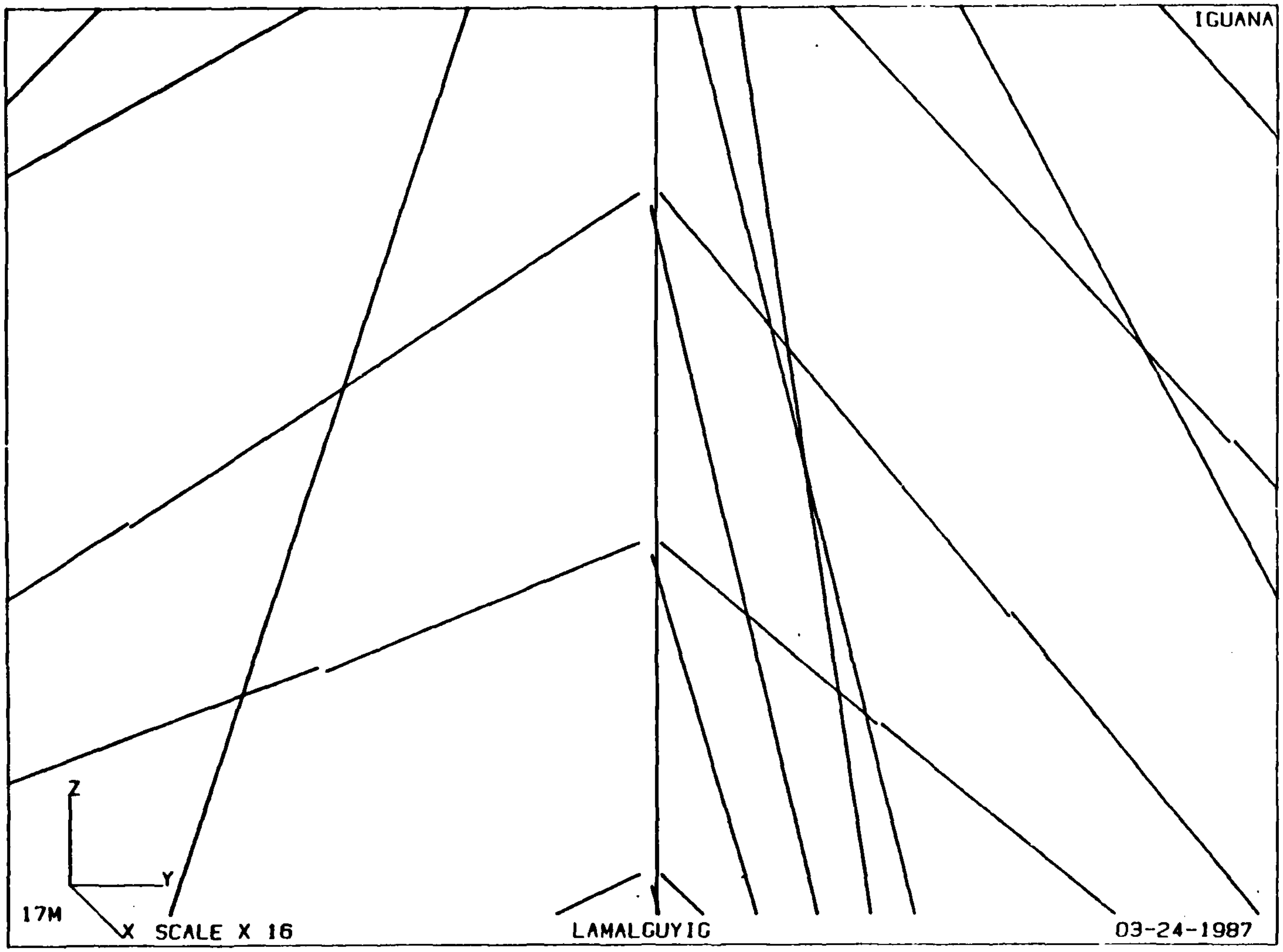


Figure 7. LaMoure OMEGA NEC model expanded to show wire breaks representing insulators

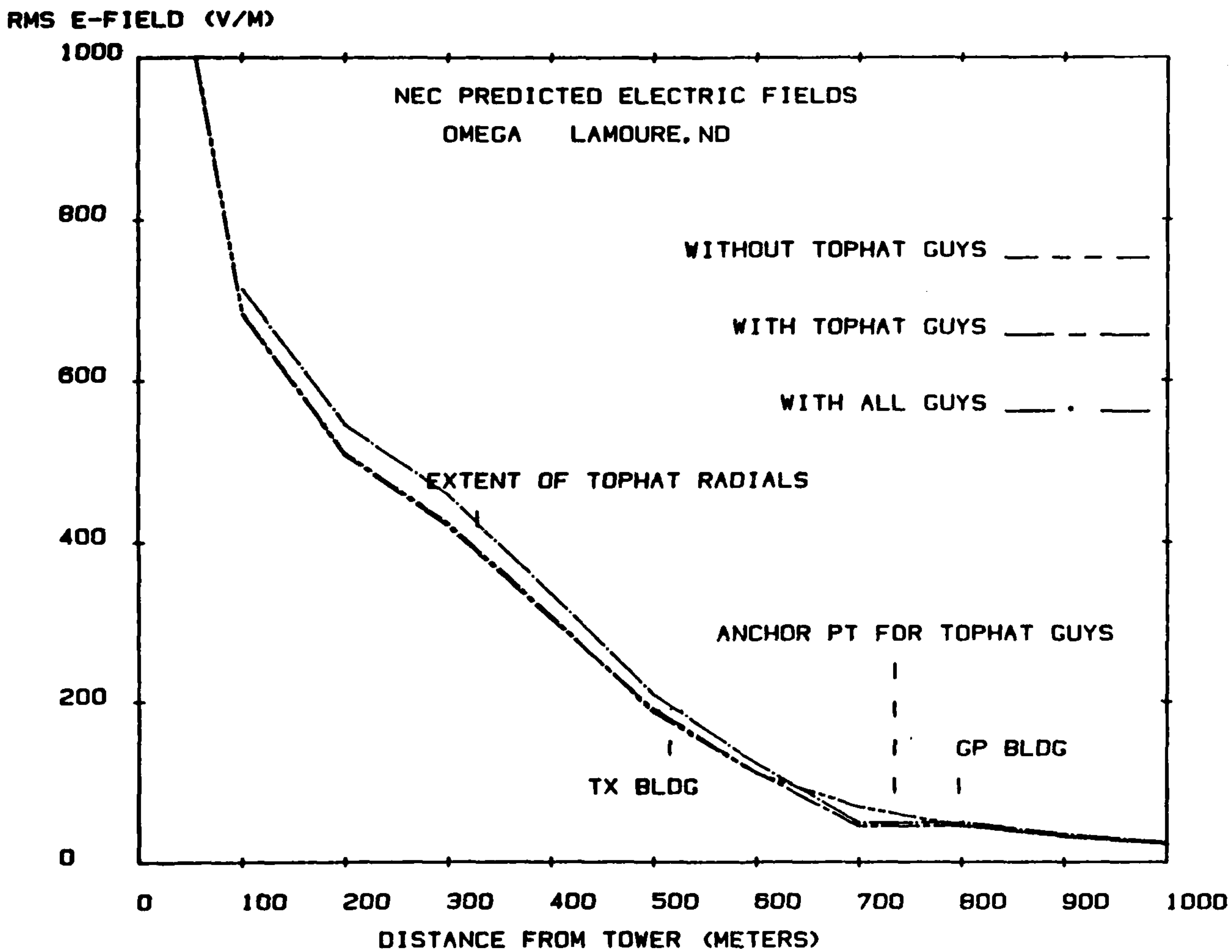


Figure 8. LaMoure OMEGA modeling results showing effect of including all guy wires

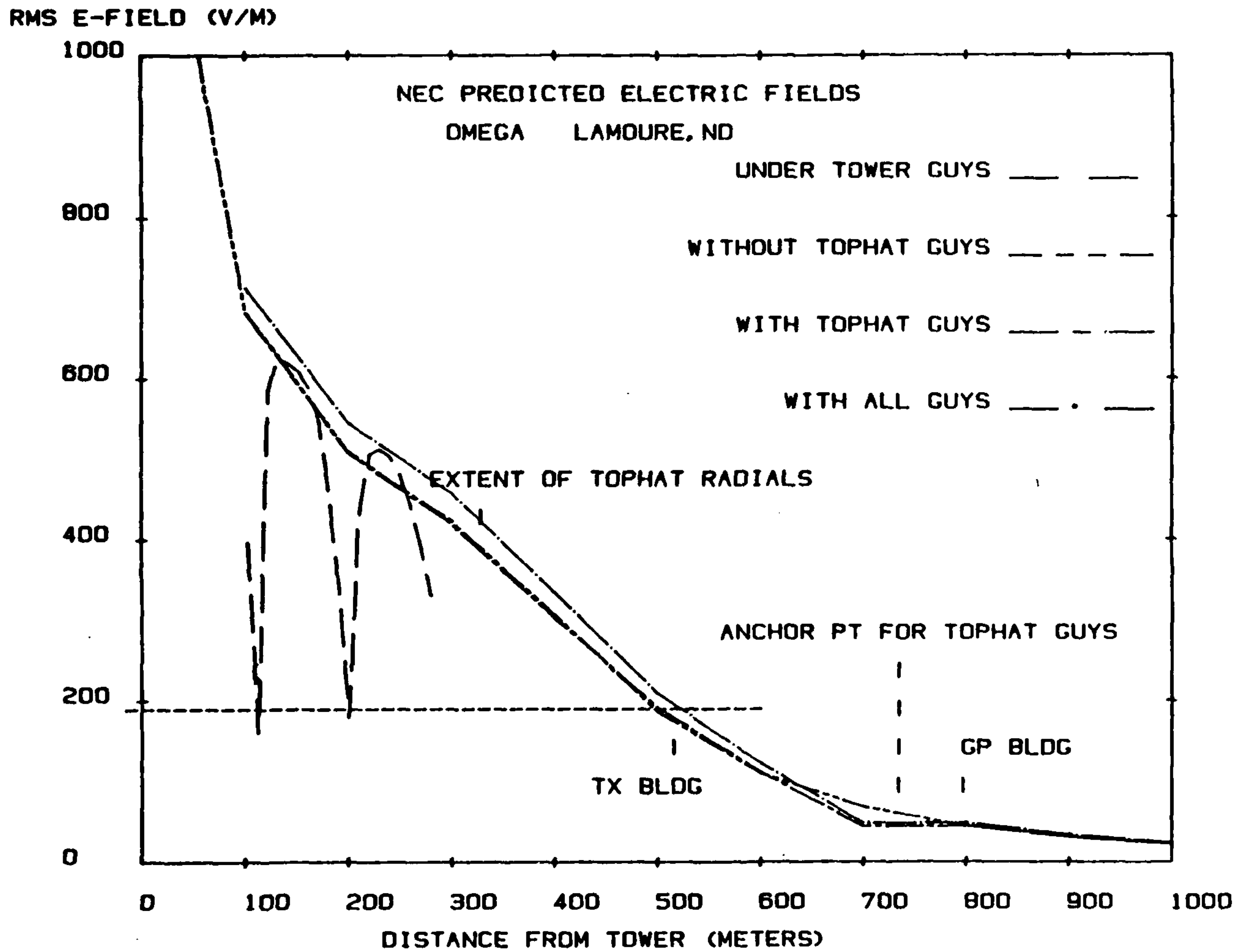


Figure 9. LaMoure OMEGA modeling results showing electric field variations under guy wires

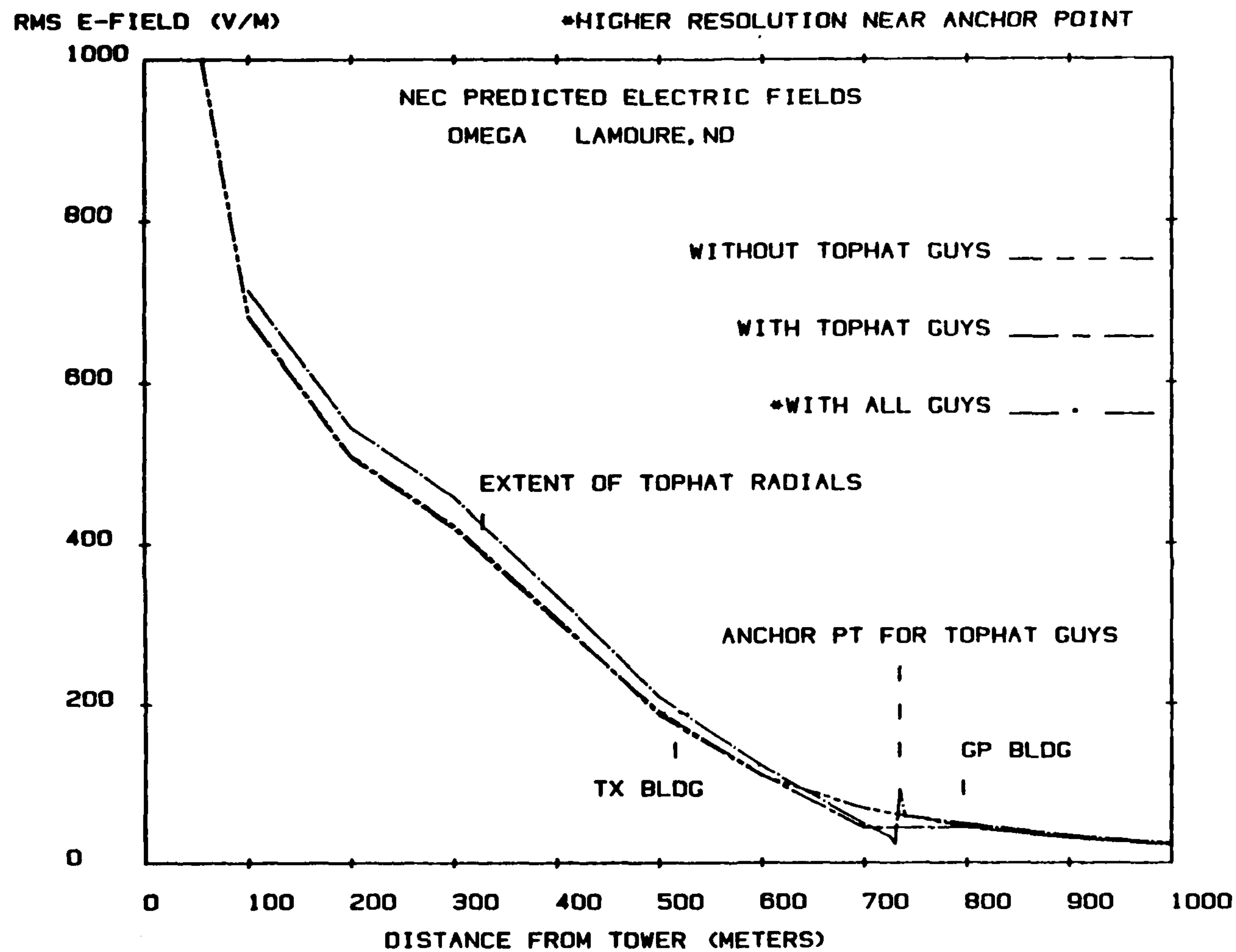


Figure 10. LaMoure OMEGA modeling results showing electric field variations near a top - radial guy anchor point

minimums occur near the guy wire anchor points which are grounded. A significant observation is that the maximums reach only as high as the fields predicted away from the guy wires. This point is important because it means that the guy wires should not increase field strengths. Figure 10 is a plot of field strengths directly under a top radial and associated guy wire with higher resolution near the guy ground anchor. Here, a decrease in field strength is noted as the anchor is approached (walking away from the tower), and an increase is seen as the anchor point is passed. The increase occurs very locally above the grounded guy wire due to the abrupt rise in electrical ground and was observed during the measurement phase.

This detailed analysis of the La Moure monopole provided useful information concerning the effects of modeling parameters. Most important was the indication that inclusion of guy wires does not have a major impact on modeling results. This lack of effect is probably due to the extensive use of insulators to reduce current flow and re-radiation. The result is significant because guy wire models are time consuming to create and expensive to run. Computer time required to run NEC models varies roughly as the square of the number of segments, so that large models are far more costly than simple ones. The guy wire effects described above are the primary deviation to be expected from the non-guy models used in the rest of the study. Note that field strengths shown in Figures 2, 5, 8, 9 and 10 are single pulse rms values for 10 kHz and are for comparison purposes only. The modeling results are shown in Table 3 in both single pulse rms and overall rms form as described in Appendix B.

The most common LORAN-C antenna configuration is the 625 foot monopole. A NEC model for this antenna was created using the structural data for the Nantucket, MA, LORAN-C station. Figure 11 shows a side view of the model and Figure 12 shows a top view with the individual wires numbered. Electric field strengths for this antenna are predicted to drop off quickly with distance from the tower and then remain relatively constant until the extent of the top-radials is reached (Figure 13). As shown in Figure 14, the magnetic field strength is unaffected by the extent of the top-radials. The electric field effect can be explained as follows. Electric field strengths normally drop off with distance from the base insulator which can be thought of as the voltage source. Field strengths near the insulator approach a maximum value of the drive voltage divided by the length of the insulator. This component of the overall field drops off quickly with distance while fields from the top radials show a slow increase as the radials extend closer to the ground. The two effects compensate to produce a fairly constant electric field strength under the top radials.

Comparison of the predicted field strengths with values measured at Dana, IN, shows good agreement for magnetic fields (Figure 15), but substantial differences for electric fields (Figure 16). Note that the measured electric field strength curve follows the same general shape as the predicted curve even though the values are higher. The implication here is that NEC is not calculating the correct impedance for the antenna thus

Table 3. NEC Predicted Field Strengths for the 1200 Foot LaMoure OMEGA Antenna

	Single Pulse RMS at 10 kHz		Overall RMS for LaMoure, ND	
Distance From Tower (Meters)	Electric Field Strength (Volts/Meter)	Magnetic Field Strength (Amps/Meter)	Electric Field Strength (Volts/Meter)	Magnetic Field Strength (Amps/Meter)
10	5904	5.78	3908	4.45
20	2543	2.89	1683	2.22
30	1677	1.92	1110	1.48
40	1306	1.43	864	1.1
50	1105	1.11	731	0.85
60	983	0.94	651	0.72
70	903	0.82	598	0.63
80	840	0.70	556	0.54
90	774	0.62	512	0.48
100	715	0.56	473	0.43
200	546	0.25	361	0.19
300	458	0.14	303	0.11
400	334	0.09	221	0.07
500	209	0.06	138	0.05
600	123	0.04	81	0.03
700	49	0.03	32	0.02
800	49	0.02	32	0.02
900	34	0.02	23	0.02
1000	25	0.01	17	0.01

Table 4. Power Outputs and RMS-To-Peak Ratios for 625 Foot Monopoles

Station	Rated Power(KW)	GRI 1	GRI 2	RMS-To-Peak Ratio
Nantucket, MA	400	9960 S	5930 S	0.093
Dana, IN	400	8970 M	9960 S	0.085
Upolu Point, HI	250	4990 S	--	0.080
Hobe Sound, FL	325	7980 S	--	0.063
Johnston Island, HI	325	4990 M	--	0.085
Kure Island, HI	325	4990 S	--	0.080
Fallen, NV	400	9940 M	--	0.060
Middletown, CA	400	9940 S	--	0.057
Attu, AK	325	9990 S	--	0.057
Narrow Cape, AK	400	9990 S	7960 S	0.085
St. Paul Island, HI	325	9990 M	--	0.060

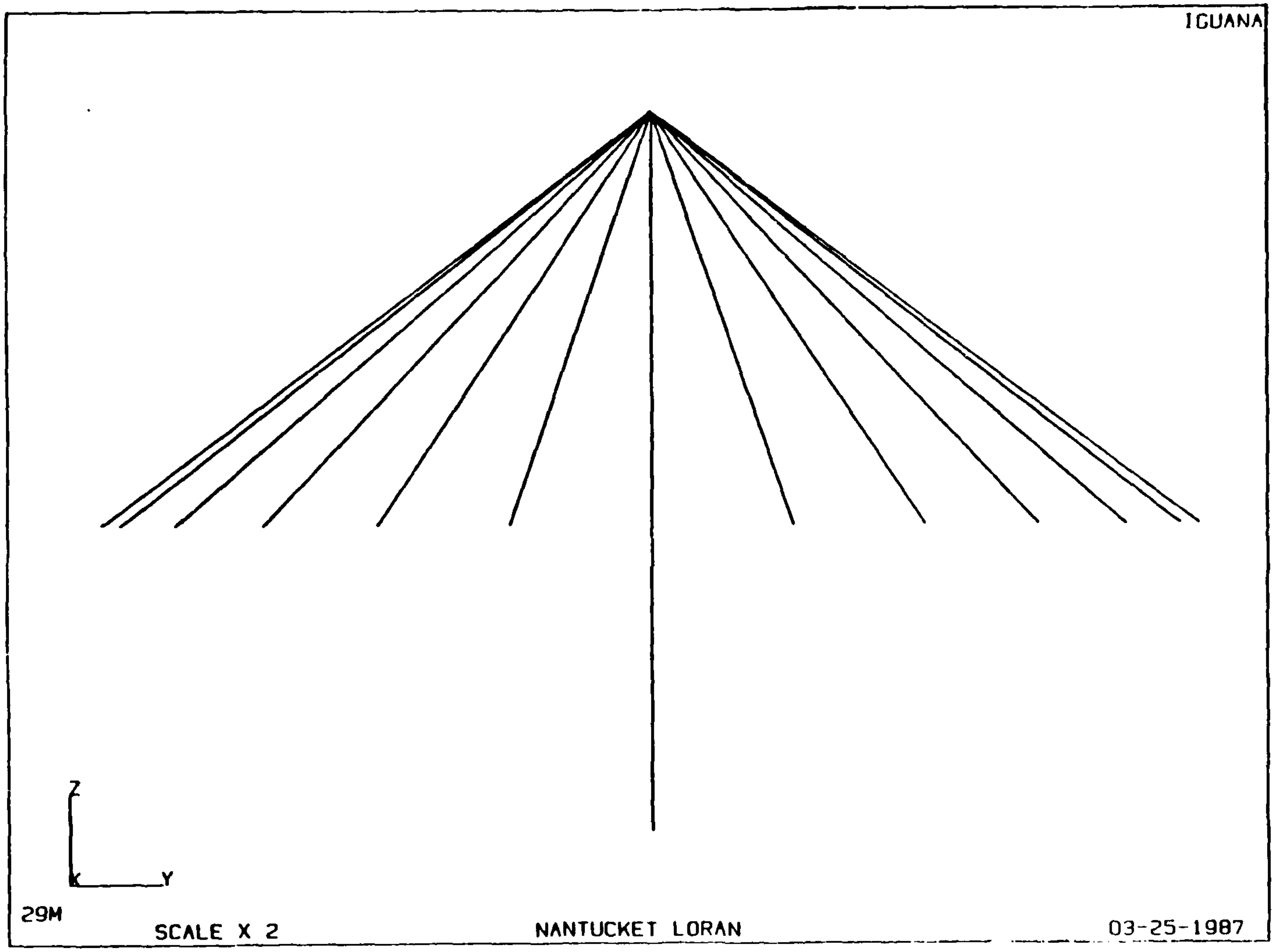


Figure 11. Nantucket LORAN NEC wire model (625' monopole)

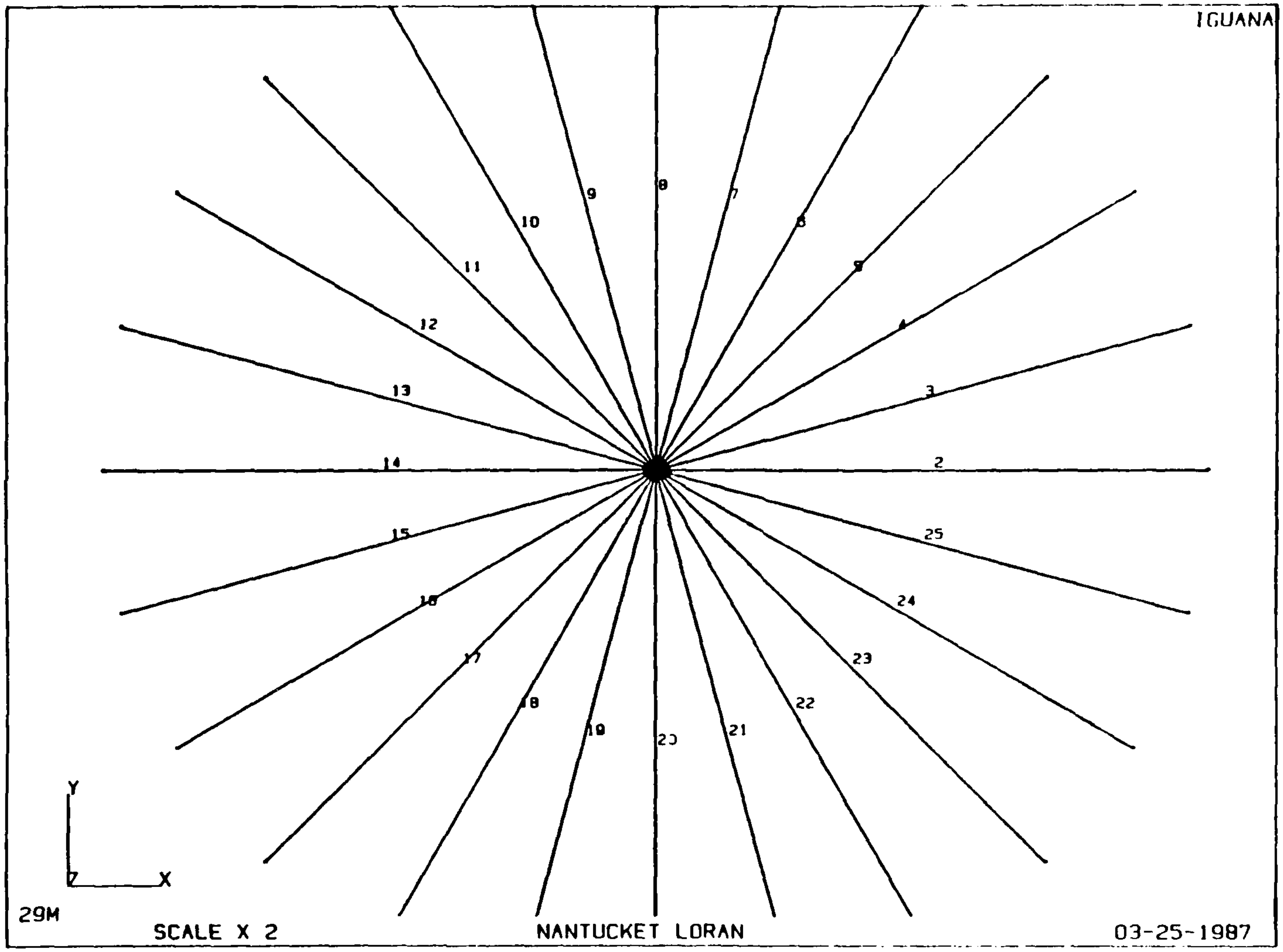


Figure 12. Nantucket LORAN NEC model (top view, numbered)

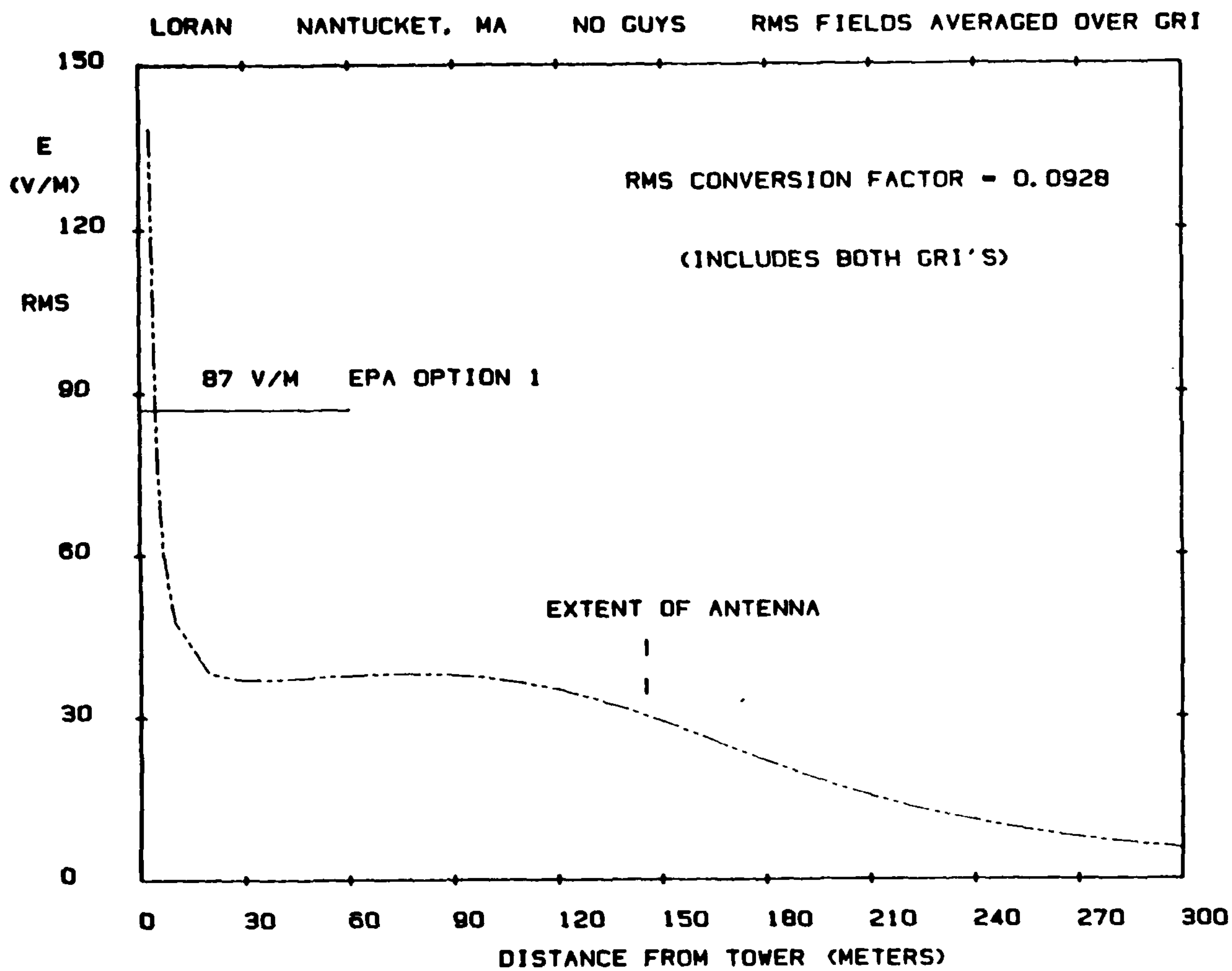


Figure 13. Nantucket LORAN modeling results for electric fields

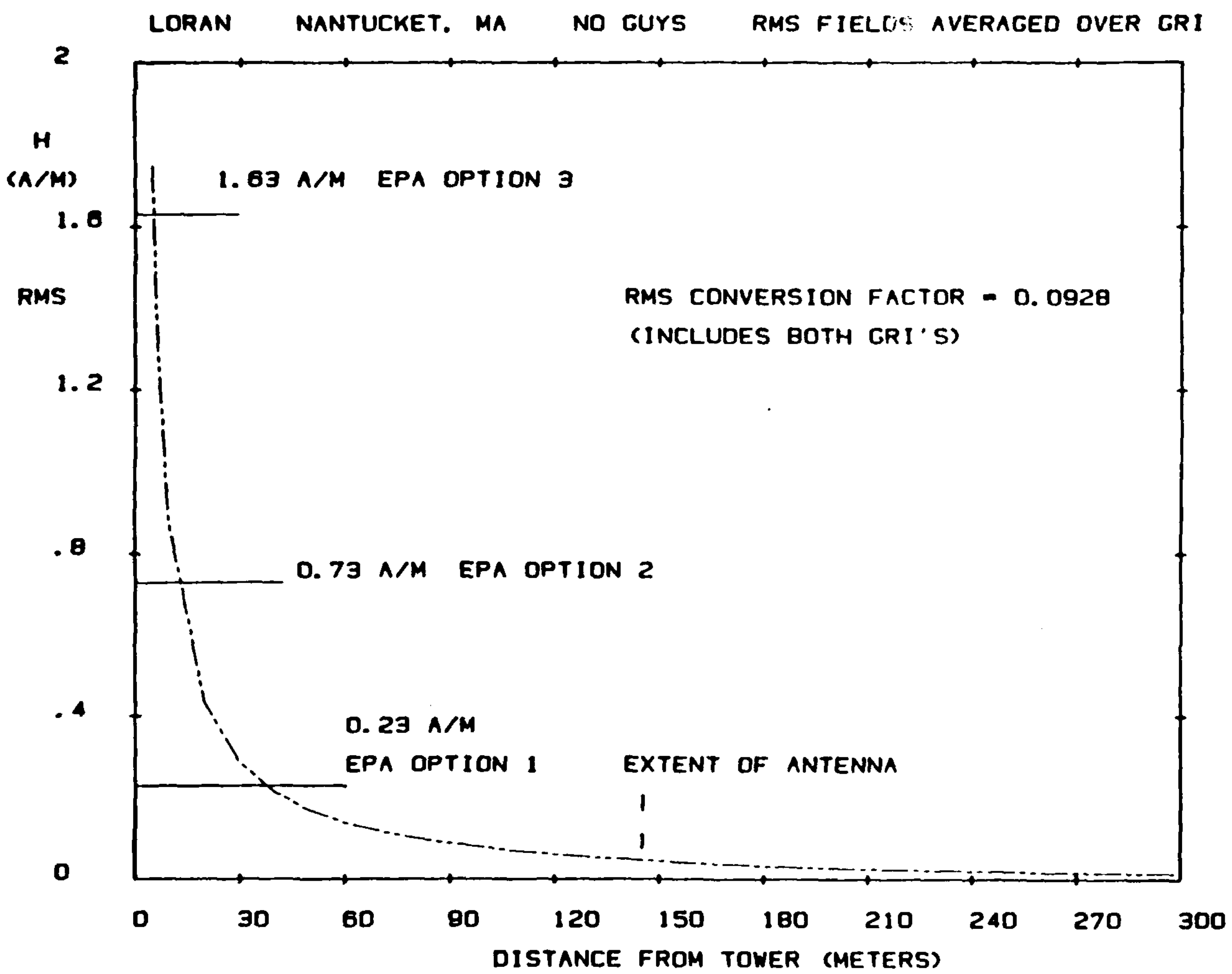


Figure 14. Nantucket LORAN modeling results for magnetic fields

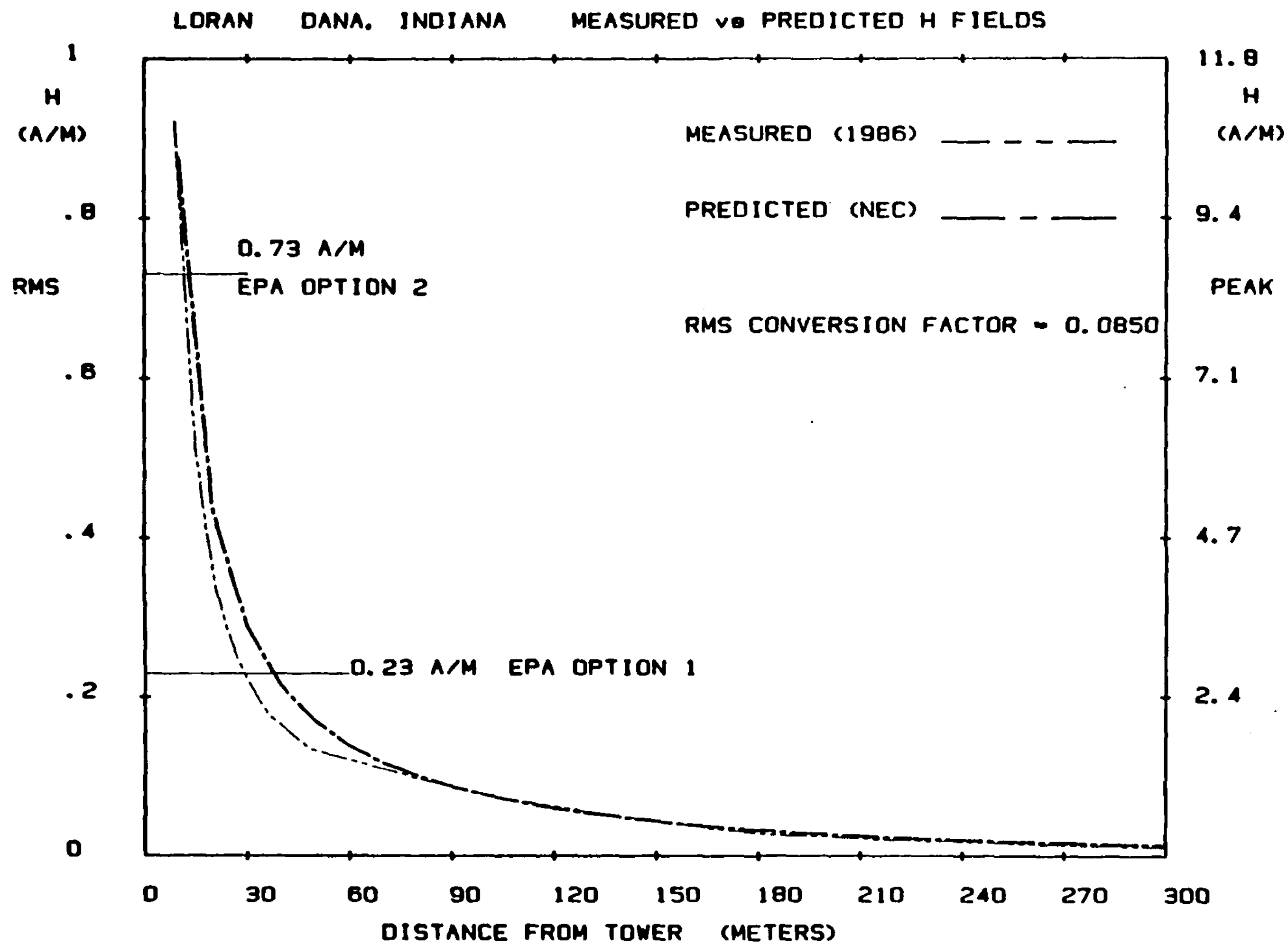


Figure 15. Dana LORAN measured vs. predicted H fields

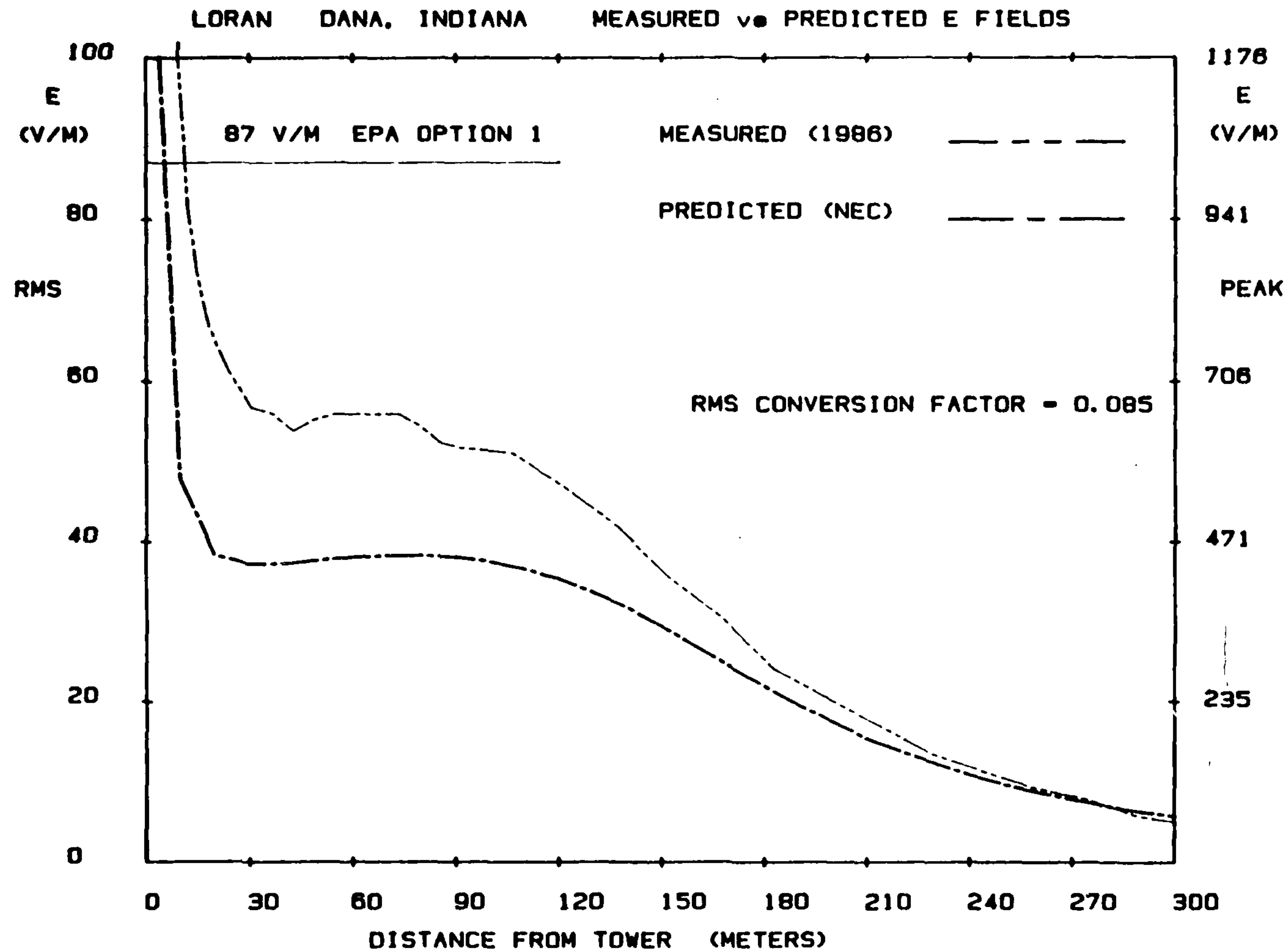


Figure 16. Dana LORAN measured vs. predicted E fields

predicting too low an excitation voltage. This low voltage results in predicted electric fields which are about 40 percent lower than the measured values under the top radials.

The NEC results can be scaled for any existing or future 625 foot LORAN-C antenna given the power output and GRI(s) of the station. Values used for scaling are shown in Table 4 which includes the rms-to-peak ratios as described in Appendix A. Most of these values were taken from the "Radio Navigation Systems" handbook published by the Coast Guard (5). NEC predicted field strengths for currently operational 625 foot monopoles are presented in Tables 5 and 6 for distances of 10 to 300 meters from the tower base, two meters above ground, in any radial direction away from the tower. The second column gives the results scaled as peak field strength for a power output (P) of 1 kW. Peak field strengths for any other power output can be obtained by multiplying the values in this column by the square root of P in kW. Conversion to rms requires subsequent multiplication by the rms-to-peak ratio from Table 4 or Appendix A. Values shown in the following columns are already scaled to the specific station in the column heading. Because of the impedance problem described above, the electric field strengths presented in Table 5 should be multiplied by about 1.7 to prevent underestimation. Magnetic field strengths in Table 6 can be used as they appear for reasonably accurate predictions.

The 700 foot LORAN-C antennas listed in Table 7 are similar to the 625 foot monopoles except that 12 instead of 24 top radials are used (Figures 27 and 18). NEC modeling of this configuration shows good agreement with measurements taken at the Seneca, NY station. Predicted electric fields agree with the measured values to within 20 percent or about 1.6 dB (Figure 19). Magnetic fields (Figure 20) agree so closely that it is difficult to identify the separate curves. Tables 8 and 9 provide the modeling results scaled for peak fields at one kilowatt and for each of the currently operational 700 foot monopoles. Values in the 1 kW column can be used to calculate field strengths at any 700 foot monopole using the power output and GRI as described above.

Port Clarence, AK, operates the only 1350 foot LORAN-C monopole in the United States. This antenna is similar to the other LORAN-C monopoles except that only six top radials are used (Figures 21 and 22). The station radiates 1000 kW peak power using relatively low input voltage and current because the antenna is large enough to represent a significant fraction of a wavelength. This greater radiation efficiency results in low field strengths near the antenna even though it transmits more energy than most other LORAN-C stations. Table 10 shows the NEC predicted peak electric and magnetic field strengths for 1350 foot monopoles and the rms values predicted for Port Clarence, AK. A comparison of measured and predicted field strengths for this station is shown in Figures 23 and 24. In common with the other monopoles, good agreement occurs for magnetic field strengths, but electric field strengths are underpredicted. Figure 23 also illustrates the field enhancement near a guy wire anchor.

Table 5. NEC Predicted Electric Field Strengths for 625 Foot LORAN-C Monopoles

Distance From Tower (Meters)	Peak Electric Fields at 1 kW (Volts/meter)	Nantucket RMS Fields (Volts/meter)	Dana RMS Fields (Volts/meter)	Upolu Point RMS Field (Volts/meter)	Hobe Sound RMS Field (Volts/meter)	Kure Island RMS Fields (Volts/meter)
10	25.69	47.7	43.7	32.5	29.2	37.1
20	20.58	38.2	35.0	26.0	23.4	29.7
30	19.96	37.0	33.9	25.2	22.7	28.8
40	20.04	37.2	34.1	25.3	22.8	28.9
50	20.25	37.6	34.4	25.6	23.0	29.2
60	20.44	37.9	34.7	25.9	23.2	29.5
70	20.56	38.2	35.0	26.0	23.4	29.7
80	20.56	38.2	35.0	26.0	23.4	29.7
90	20.43	37.9	34.7	25.8	23.2	29.5
100	20.12	37.3	34.2	25.5	22.9	29.0
110	19.63	36.4	33.4	24.8	22.3	28.3
120	18.95	35.2	32.2	24.0	21.5	27.3
130	18.06	33.5	30.7	22.8	20.5	26.0
140	16.99	31.5	28.9	21.5	19.3	24.5
150	15.78	29.3	26.8	20.0	17.9	22.8
160	14.47	26.9	24.6	18.3	16.4	20.9
170	13.13	24.4	22.3	16.6	14.9	18.9
180	11.8	21.9	20.1	14.9	13.4	17.0
190	10.55	19.6	17.9	13.3	12.0	15.2
200	9.39	17.4	16.0	11.9	10.7	13.5
210	8.34	15.5	14.2	10.5	9.5	12.0
220	7.41	13.8	12.6	9.4	8.4	10.7
230	6.58	12.2	11.2	8.3	7.5	9.5
240	5.85	10.9	9.9	7.4	6.6	8.4
250	5.22	9.7	8.9	6.6	5.9	7.5
260	4.66	8.6	7.9	5.9	5.3	6.7
270	4.18	7.8	7.1	5.3	4.7	6.0
280	3.76	7.0	6.4	4.8	4.3	5.4
290	3.39	6.3	5.8	4.3	3.9	4.9
300	3.07	5.7	5.2	3.9	3.5	4.4

Table 6. NEC Predicted Magnetic Field Strengths for 625 Foot LORAN-C Monopoles

Distance From Tower (Meters)	Peak Magnetic Fields at 1 kW (Amps/meter)	Nantucket RMS Fields (Amps/meter)	Dana RMS Fields (Amps/meter)	Upolu Point RMS Field (Amps/meter)	Hobe Sound RMS Field (Amps/meter)	Kure Island RMS Fields (Amps/meter)
10	0.4700	0.872	0.799	0.595	0.534	0.678
20	0.2341	0.434	0.398	0.296	0.266	0.338
30	0.1552	0.288	0.264	0.196	0.176	0.224
40	0.1154	0.214	0.196	0.146	0.131	0.166
50	0.0913	0.169	0.155	0.115	0.104	0.132
60	0.0750	0.139	0.128	0.095	0.085	0.108
70	0.0633	0.117	0.108	0.080	0.072	0.091
80	0.0543	0.101	0.092	0.069	0.062	0.078
90	0.0472	0.088	0.080	0.060	0.054	0.068
100	0.0414	0.077	0.070	0.052	0.047	0.060
110	0.0366	0.068	0.062	0.046	0.042	0.053
120	0.0325	0.060	0.055	0.041	0.037	0.047
130	0.0290	0.054	0.049	0.037	0.033	0.042
140	0.0260	0.048	0.044	0.033	0.030	0.037
150	0.0234	0.043	0.040	0.030	0.027	0.034
160	0.0211	0.039	0.036	0.027	0.024	0.030
170	0.0191	0.035	0.032	0.024	0.022	0.028
180	0.0173	0.032	0.029	0.022	0.020	0.025
190	0.0159	0.030	0.027	0.020	0.018	0.023
200	0.0145	0.027	0.025	0.018	0.016	0.021
210	0.0134	0.025	0.023	0.017	0.015	0.019
220	0.0123	0.023	0.021	0.016	0.014	0.018
230	0.0114	0.021	0.019	0.014	0.013	0.016
240	0.0106	0.020	0.018	0.013	0.012	0.015
250	0.0099	0.018	0.017	0.013	0.011	0.014
260	0.0092	0.017	0.016	0.012	0.010	0.013
270	0.0086	0.016	0.015	0.011	0.010	0.012
280	0.0081	0.015	0.014	0.010	0.009	0.012
290	0.0077	0.014	0.013	0.010	0.009	0.011
300	0.0072	0.013	0.012	0.009	0.008	0.010

Table 6 (cont'd). NEC Predicted Magnetic Field Strengths for 625 Foot LORAN-C Monopoles

Distance From Tower (Meters)	Johnston Island RMS Fields (Amps/meter)	Fallon RMS Fields (Amps/meter)	Middletown RMS Fields (Amps/meter)	Attu RMS Fields (Amps/meter)	Narrow Cape RMS Fields (Amps/meter)	St. Paul Island RMS Fields (Amps/meter)
10	0.720	0.564	0.536	0.483	0.799	0.508
20	0.359	0.281	0.267	0.241	0.398	0.253
30	0.238	0.186	0.177	0.159	0.264	0.168
40	0.177	0.138	0.132	0.119	0.196	0.125
50	0.140	0.110	0.104	0.094	0.155	0.099
60	0.115	0.090	0.086	0.077	0.128	0.081
70	0.097	0.076	0.072	0.065	0.108	0.068
80	0.083	0.065	0.062	0.056	0.092	0.059
90	0.072	0.057	0.054	0.049	0.080	0.051
100	0.063	0.050	0.047	0.043	0.070	0.045
110	0.056	0.044	0.042	0.038	0.062	0.040
120	0.050	0.039	0.037	0.033	0.055	0.035
130	0.044	0.035	0.033	0.030	0.049	0.031
140	0.040	0.031	0.030	0.027	0.044	0.028
150	0.036	0.028	0.027	0.024	0.040	0.025
160	0.032	0.025	0.024	0.022	0.036	0.023
170	0.029	0.023	0.022	0.020	0.032	0.021
180	0.027	0.021	0.020	0.018	0.029	0.019
190	0.024	0.019	0.018	0.016	0.027	0.017
200	0.022	0.017	0.017	0.015	0.025	0.016
210	0.021	0.016	0.015	0.014	0.023	0.014
220	0.019	0.015	0.014	0.013	0.021	0.013
230	0.017	0.014	0.013	0.012	0.019	0.012
240	0.016	0.013	0.012	0.011	0.018	0.011
250	0.015	0.012	0.011	0.010	0.017	0.011
260	0.014	0.011	0.010	0.009	0.016	0.010
270	0.013	0.010	0.010	0.009	0.015	0.009
280	0.012	0.010	0.009	0.008	0.014	0.009
290	0.012	0.009	0.009	0.008	0.013	0.008
300	0.011	0.009	0.008	0.007	0.012	0.008

Table 7. Power Output and RMS-To-Peak Ratios for 700 Foot LORAN-C Monopoles

Station	Rated Power(kW)	GRI 1	GRI 2	RMS-To-Peak Ratio
Seneca, NY	800	9960 M	8970 S	0.085
Grangeville, LA	800	7980 S		0.063
Malone, FL	800	7980M	8970 S	0.090
Raymondville, TX	400	7980 S		0.063
Baudette, MN	500	8970 S		0.060

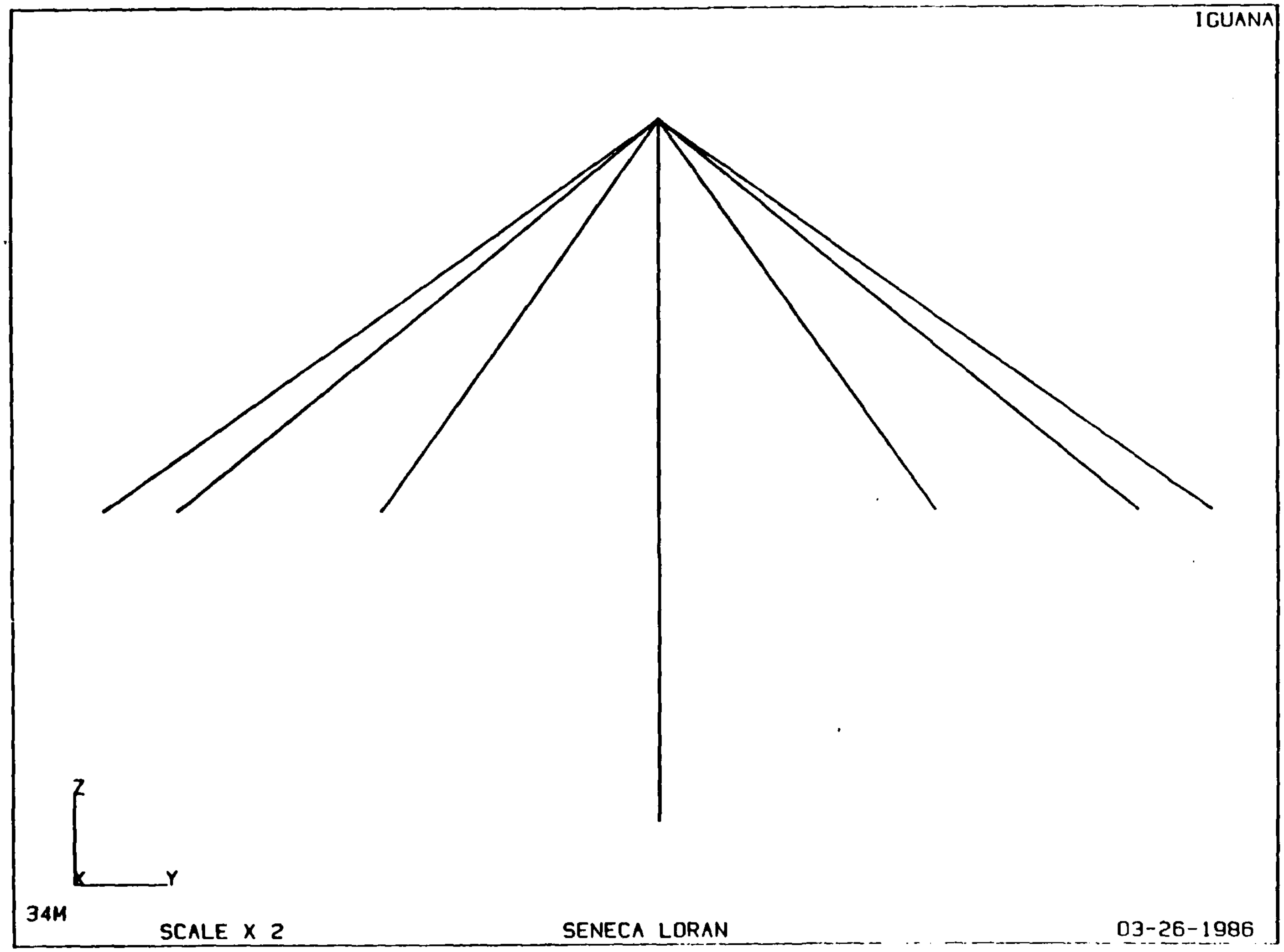


Figure 17. Seneca LORAN NEC wire model (700' monopole)

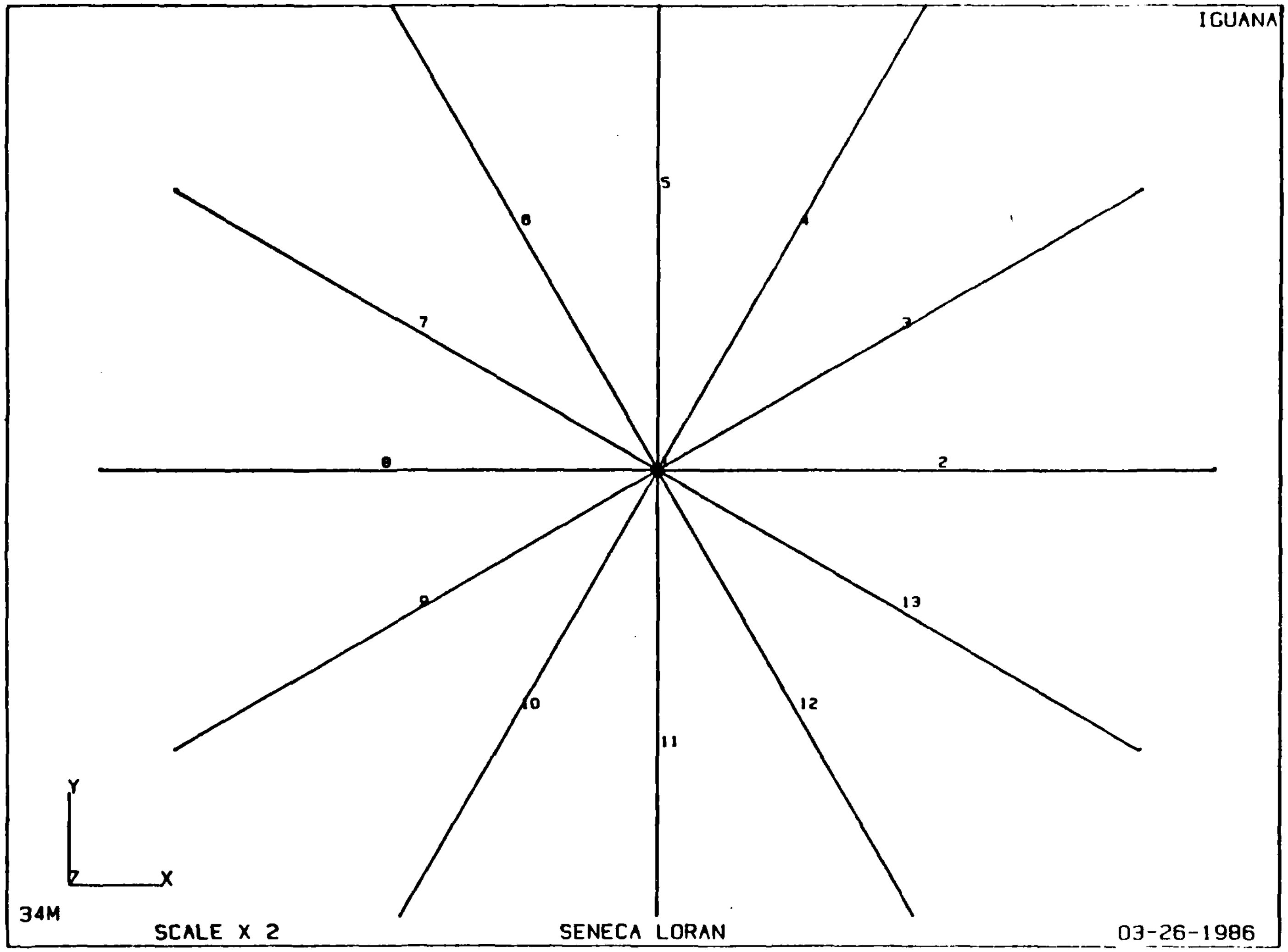


Figure 18. Seneca LORAN NEC model (top view, numbered)

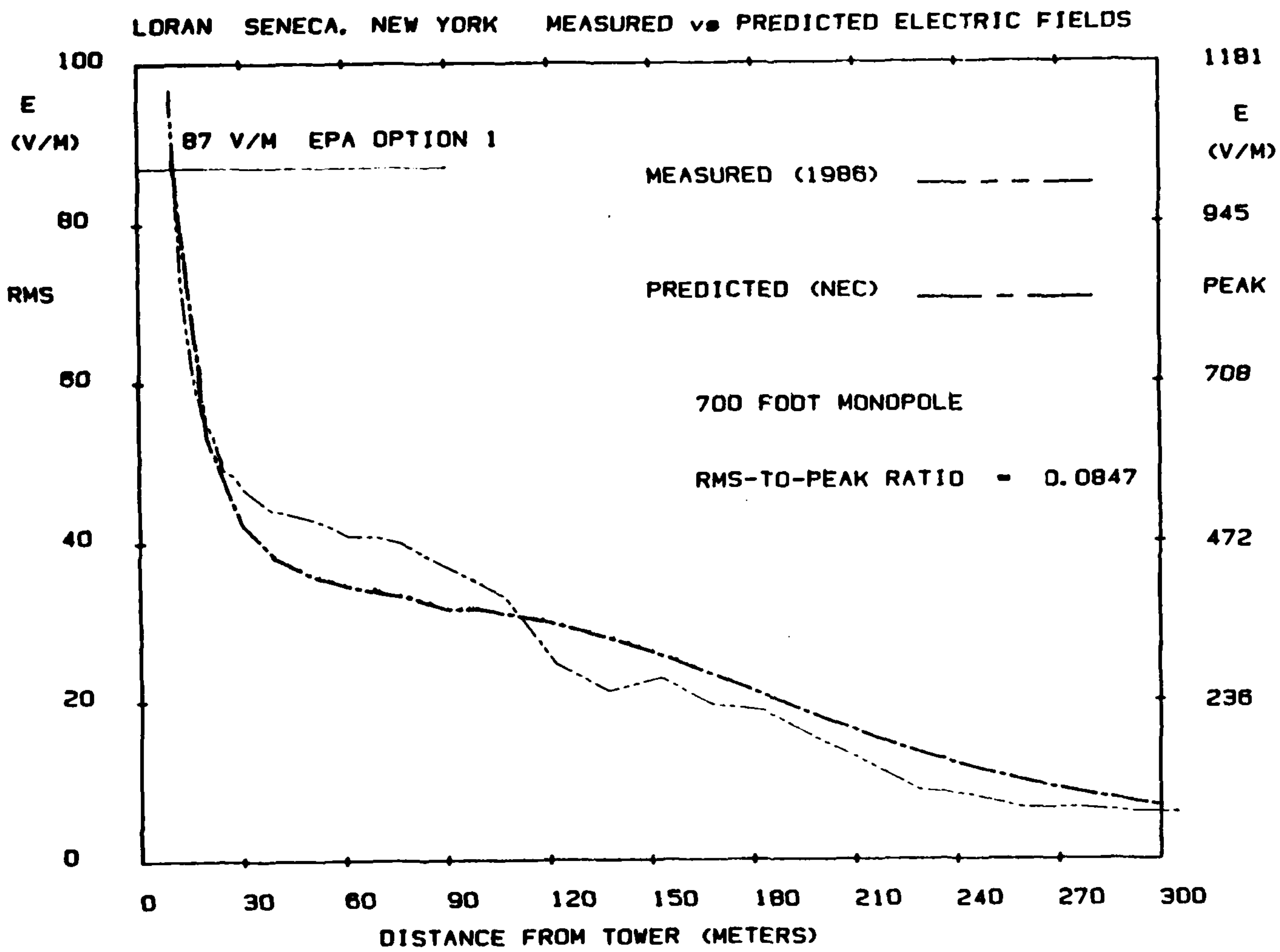


Figure 19. Seneca LORAN measured vs. predicted E fields

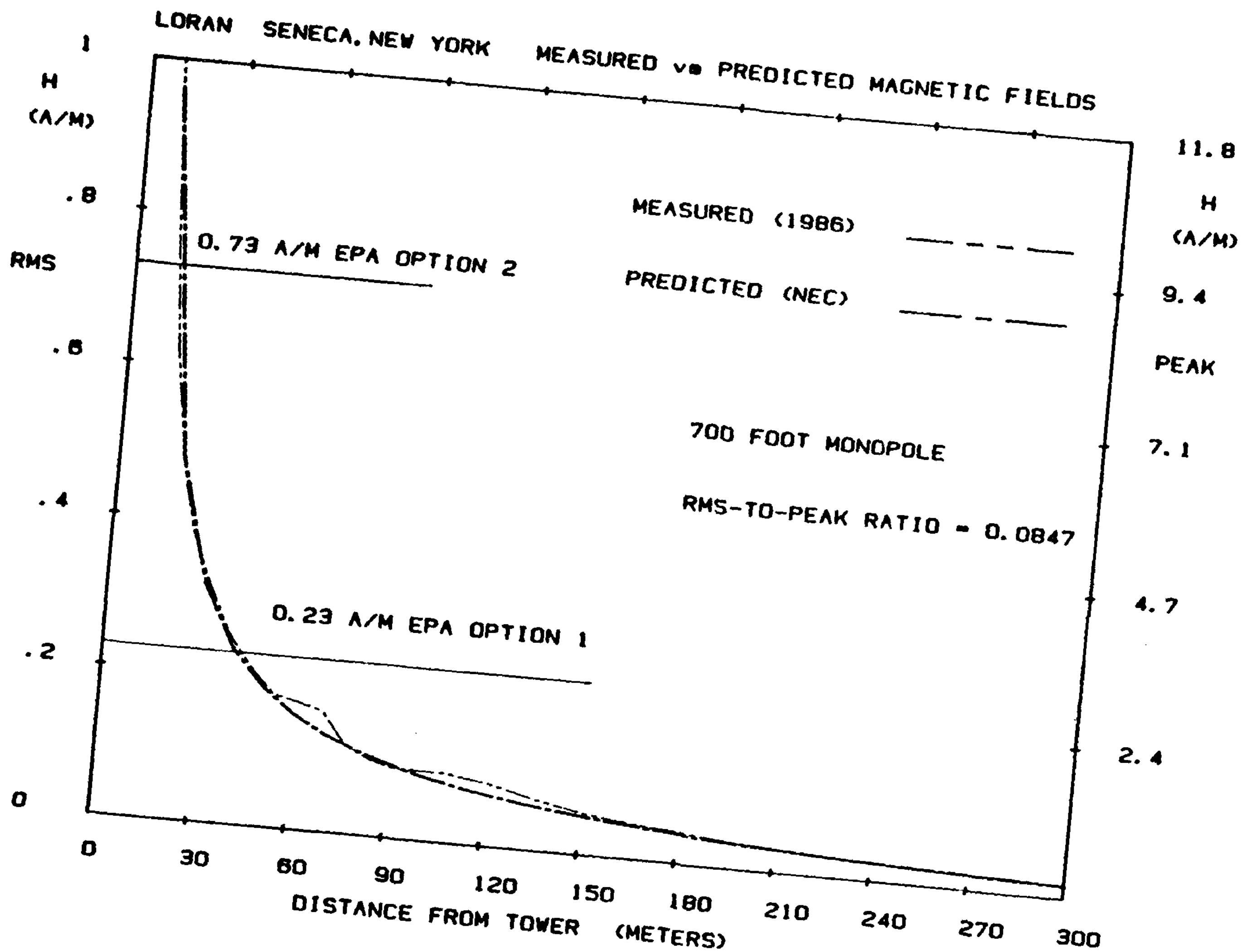


Figure 20. Seneca LORAN measured vs. predicted H fields

Table 8. NEC Predicted Electric Field Strength for 700 Foot LORAN-C Monopoles

Distance From Tower (Meters)	Peak Electric Fields at 1 kW (Volts/meter)	Seneca RMS Fields (Volts/meter)	Grangeville RMS Fields (Volts/meter)	Malone RMS Field (Volts/meter)	Raymondville RMS Field (Volts/meter)	Baudette RMS Fields (Volts/meter)
10	36.71	87.9	65.4	93.3	46.3	49.3
20	22.17	53.1	39.5	56.4	27.9	29.7
30	17.64	42.3	31.4	44.9	22.2	23.7
40	15.83	37.9	28.2	40.3	19.9	21.2
50	14.93	35.8	26.6	38.0	18.8	20.0
60	14.39	34.5	25.6	36.6	18.1	19.3
70	14.02	33.6	25.0	35.6	17.7	18.8
80	13.72	32.9	24.4	34.9	17.3	18.4
90	13.43	32.2	23.9	34.1	16.9	18.0
100	13.13	31.5	23.4	33.4	16.5	17.6
110	12.79	30.6	22.8	32.5	16.1	17.2
120	12.41	29.7	22.1	31.6	15.6	16.6
130	11.96	28.7	21.3	30.4	15.1	16.0
140	11.44	27.4	20.4	29.1	14.4	15.3
150	10.87	26.0	19.4	27.6	13.7	14.6
160	10.24	24.5	18.2	26.0	12.9	13.7
170	9.56	22.9	17.0	24.3	12.0	12.8
180	8.86	21.2	15.8	22.5	11.2	11.9
190	8.15	19.5	14.5	20.7	10.3	10.9
200	7.45	17.8	13.3	18.9	9.4	10.0
210	6.77	16.2	12.1	17.2	8.5	9.1
220	6.14	14.7	10.9	15.6	7.7	8.2
230	5.55	13.3	9.9	14.1	7.0	7.4
240	5.02	12.0	8.9	12.8	6.3	6.7
250	4.53	10.9	8.1	11.5	5.7	6.1
260	4.10	9.8	7.3	10.4	5.2	5.5
270	3.71	8.9	6.6	9.4	4.7	5.0
280	3.34	8.0	6.0	8.5	4.2	4.5
290	3.06	7.3	5.5	7.8	3.9	4.1
300	2.79	6.7	5.0	7.1	3.5	3.7

Table 9. NEC Predicted Magnetic Field Strengths for 700 Foot LORAN-C Monopoles

Distance From Tower (Meters)	Peak Magnetic Fields at 1 kW (Amps/meter)	Seneca RMS Fields (Amps/meter)	Grangeville RMS Fields (Amps/meter)	Malone RMS Field (Amps/meter)	Raymondville RMS Field (Amps/meter)	Baudette RMS Fields (Amps/meter)
10	0.4011	0.961	0.715	1.020	0.505	0.538
20	0.1994	0.478	0.355	0.507	0.251	0.268
30	0.1320	0.316	0.235	0.336	0.166	0.177
40	0.0982	0.235	0.175	0.250	0.124	0.132
50	0.0778	0.186	0.139	0.198	0.098	0.104
60	0.0641	0.154	0.114	0.163	0.081	0.086
70	0.0543	0.130	0.097	0.138	0.068	0.073
80	0.0466	0.112	0.083	0.118	0.059	0.063
90	0.0409	0.098	0.073	0.104	0.052	0.055
100	0.0360	0.086	0.064	0.092	0.045	0.048
110	0.0321	0.077	0.057	0.082	0.040	0.043
120	0.0287	0.069	0.051	0.073	0.036	0.039
130	0.0259	0.062	0.046	0.066	0.033	0.035
140	0.0234	0.056	0.042	0.060	0.029	0.031
150	0.0213	0.051	0.038	0.054	0.027	0.029
160	0.0193	0.046	0.034	0.049	0.024	0.026
170	0.0176	0.042	0.031	0.045	0.022	0.024
180	0.0162	0.039	0.029	0.041	0.020	0.022
190	0.0149	0.036	0.027	0.038	0.019	0.020
200	0.0137	0.033	0.024	0.035	0.017	0.018
210	0.0127	0.030	0.023	0.032	0.016	0.017
220	0.0118	0.028	0.021	0.030	0.015	0.016
230	0.0109	0.026	0.019	0.028	0.014	0.015
240	0.0102	0.024	0.018	0.026	0.013	0.014
250	0.0095	0.023	0.017	0.024	0.012	0.013
260	0.0090	0.022	0.016	0.023	0.011	0.012
270	0.0084	0.020	0.015	0.021	0.011	0.011
280	0.0079	0.019	0.014	0.020	0.010	0.011
290	0.0074	0.018	0.013	0.019	0.009	0.010
300	0.0070	0.017	0.012	0.018	0.009	0.009

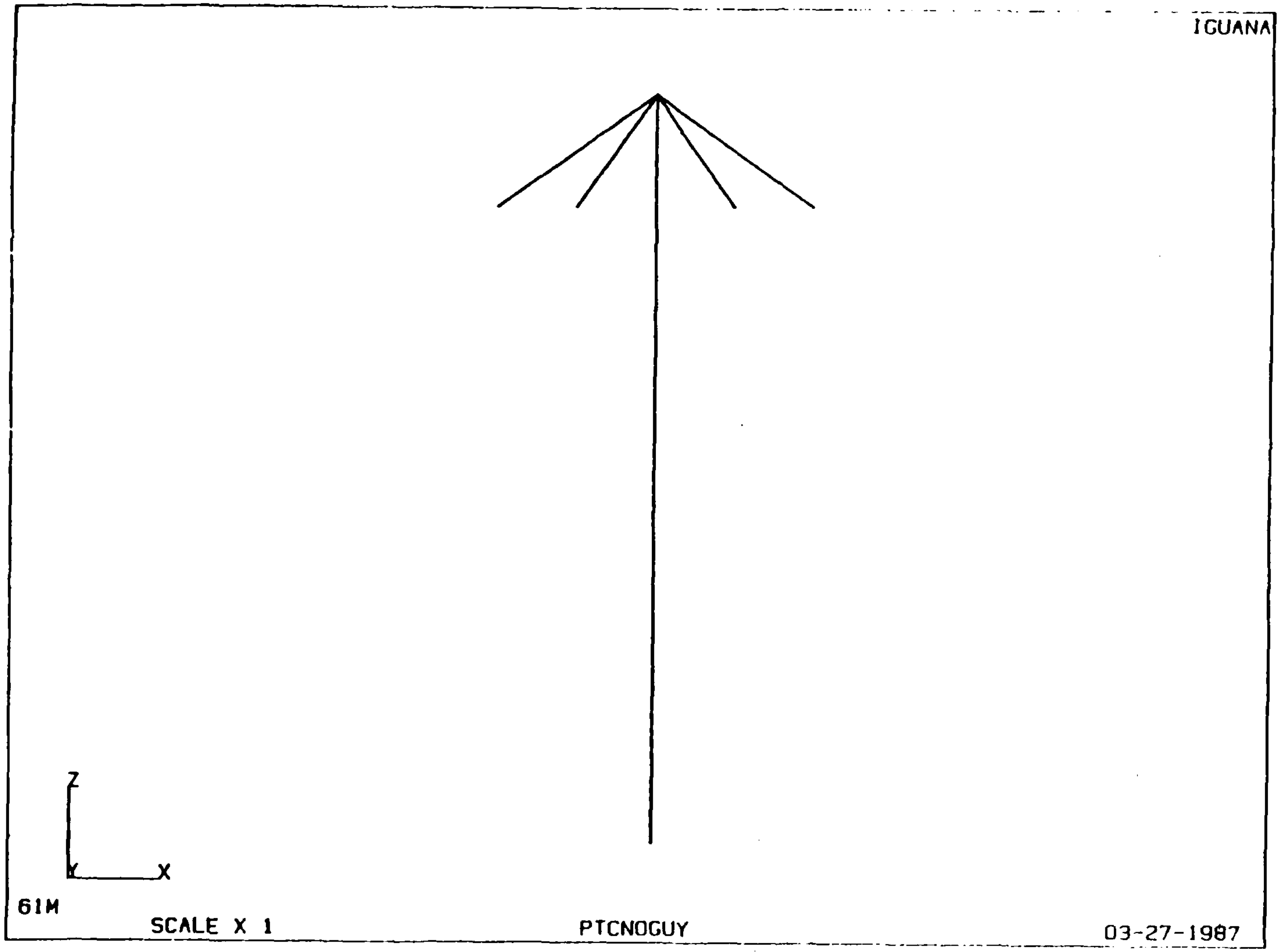


Figure 21. Port Clarence LORAN NEC wire model

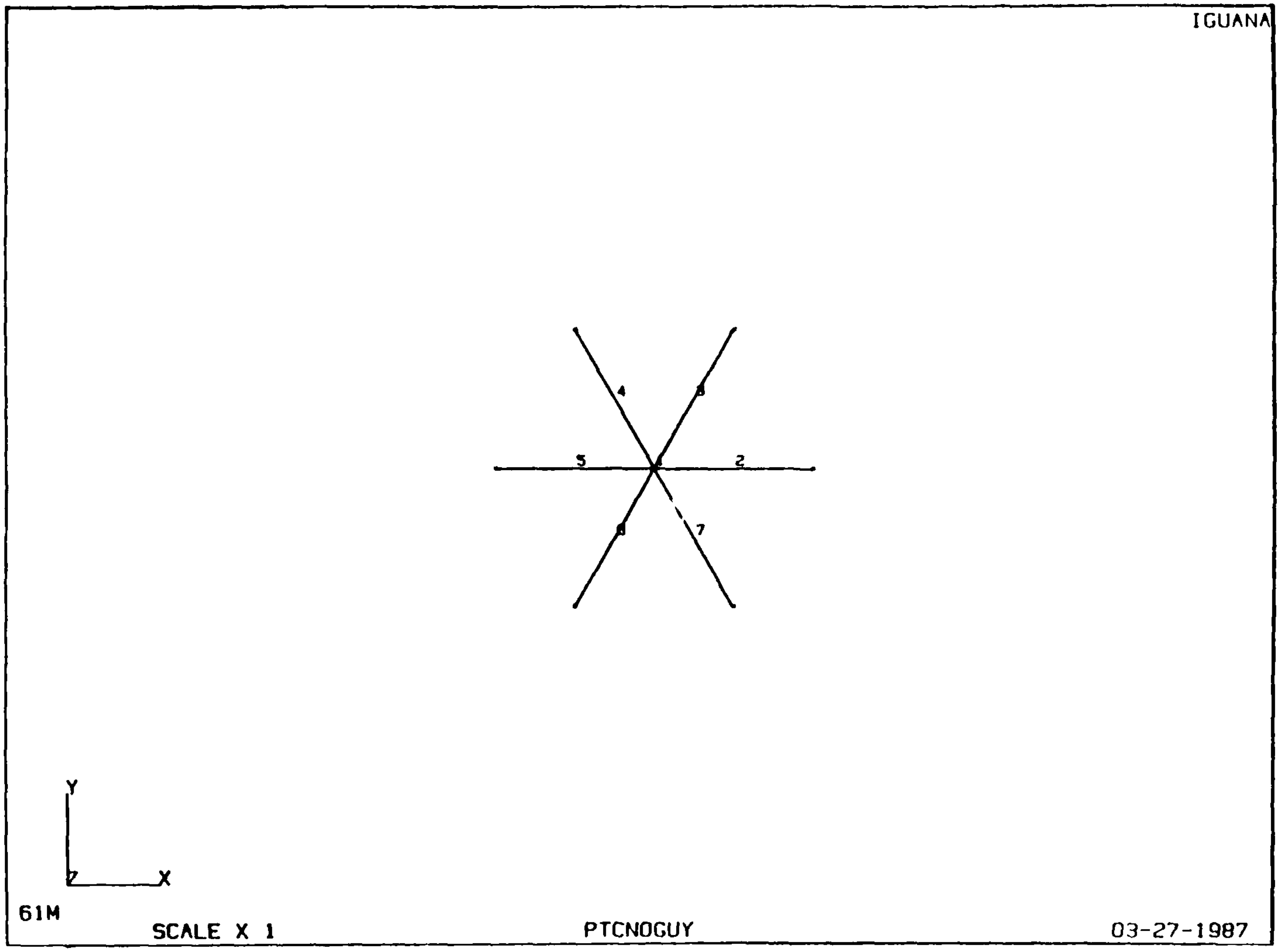


Figure 22. Port Clarence LORAN NEC model-(top view, numbered)

Table 10. NEC Predicted Electric and Magnetic Field Strengths for 1350 Foot LORAN-C Monopoles

Distance From Tower (Meters)	Peak Electric fields at 1 kW (Volts/Meters)	Peak Magnetic Fields at 1 kW (Amps/Meters)	Port Clarence RMS E-Fields (Volts/Meters)	Port Clarence RMS H-Fields (Amps/Meters)
10	39.83	0.1885	71.3	0.337
20	15.82	0.0933	28.3	0.167
30	9.52	0.0617	17.0	0.110
40	6.72	0.0459	12.0	0.082
50	5.17	0.0364	9.3	0.065
60	4.20	0.0301	7.5	0.054
70	3.53	0.0256	6.3	0.046
80	3.05	0.0222	5.5	0.040
90	2.69	0.0196	4.8	0.035
100	2.40	0.0176	4.3	0.032
110	2.18	0.0158	3.9	0.028
120	1.99	0.0144	3.6	0.026
130	1.83	0.0132	3.3	0.024
140	1.70	0.0122	3.0	0.022
150	1.59	0.0113	2.8	0.020
160	1.49	0.0105	2.7	0.019
170	1.40	0.0098	2.5	0.018
180	1.33	0.0092	2.4	0.016
190	1.26	0.0087	2.3	0.016
200	1.20	0.0082	2.1	0.015
210	1.15	0.0077	2.1	0.014
220	1.10	0.0073	2.0	0.013
230	1.05	0.0070	1.9	0.013
240	1.01	0.0066	1.8	0.012
250	0.98	0.0063	1.8	0.011
260	0.94	0.0061	1.7	0.011
270	0.91	0.0058	1.6	0.010
280	0.88	0.0056	1.6	0.010
290	0.86	0.0053	1.5	0.009
300	0.84	0.0051	1.5	0.009

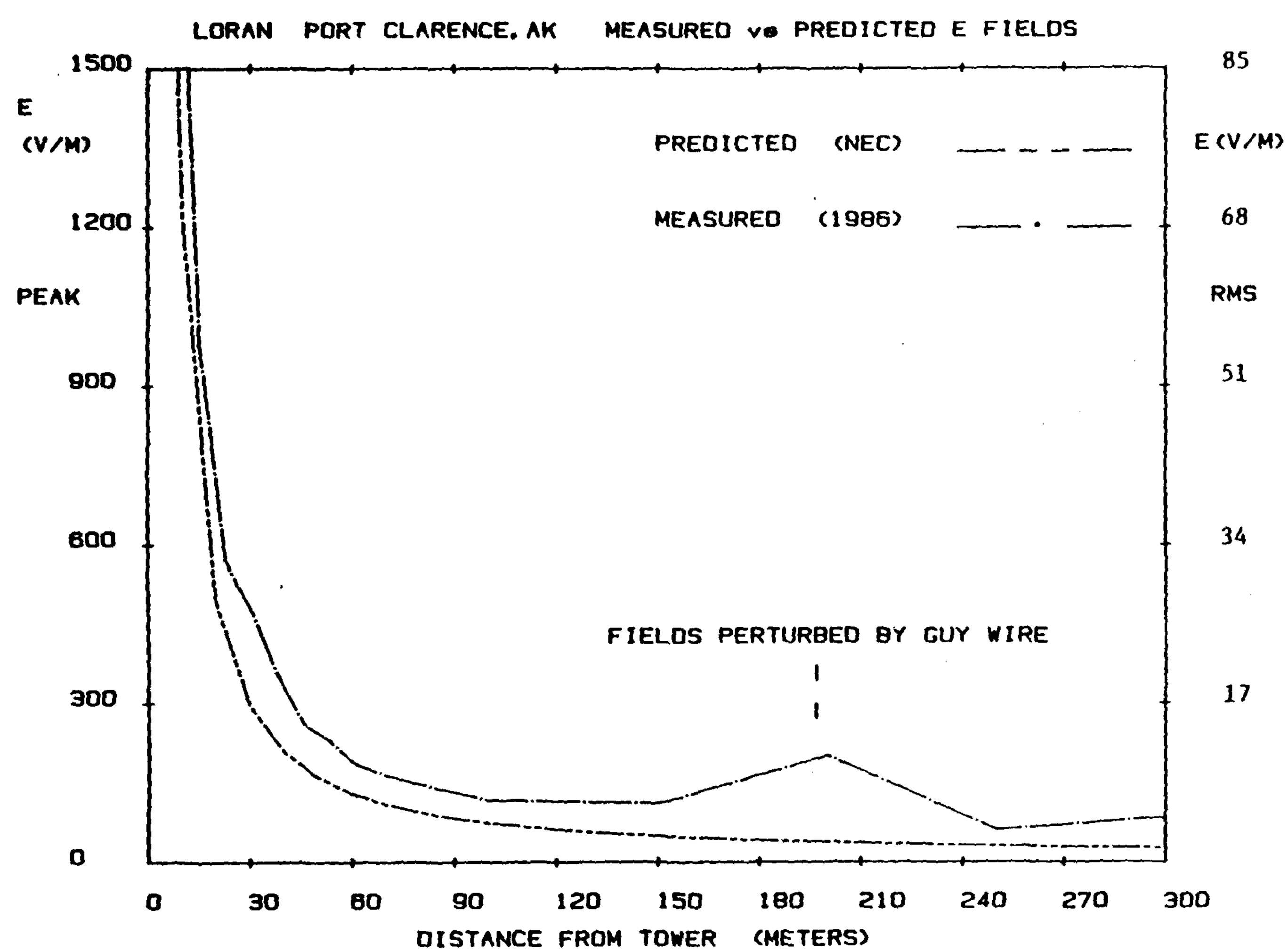


Figure 23. Port Clarence LORAN measured vs. predicted E fields

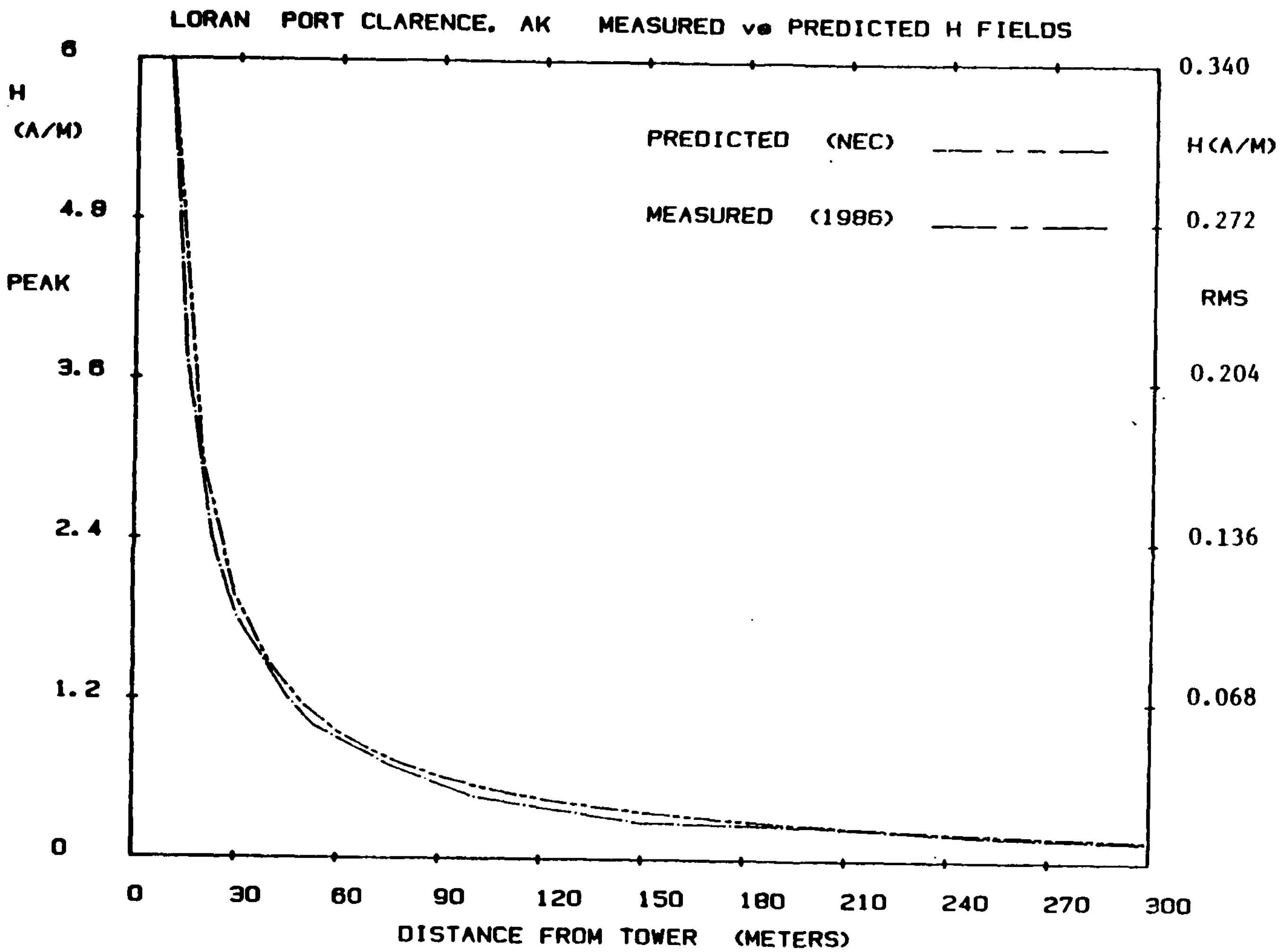


Figure 24. Port Clarence LORAN measured vs. predicted H fields

STATION GEORGE

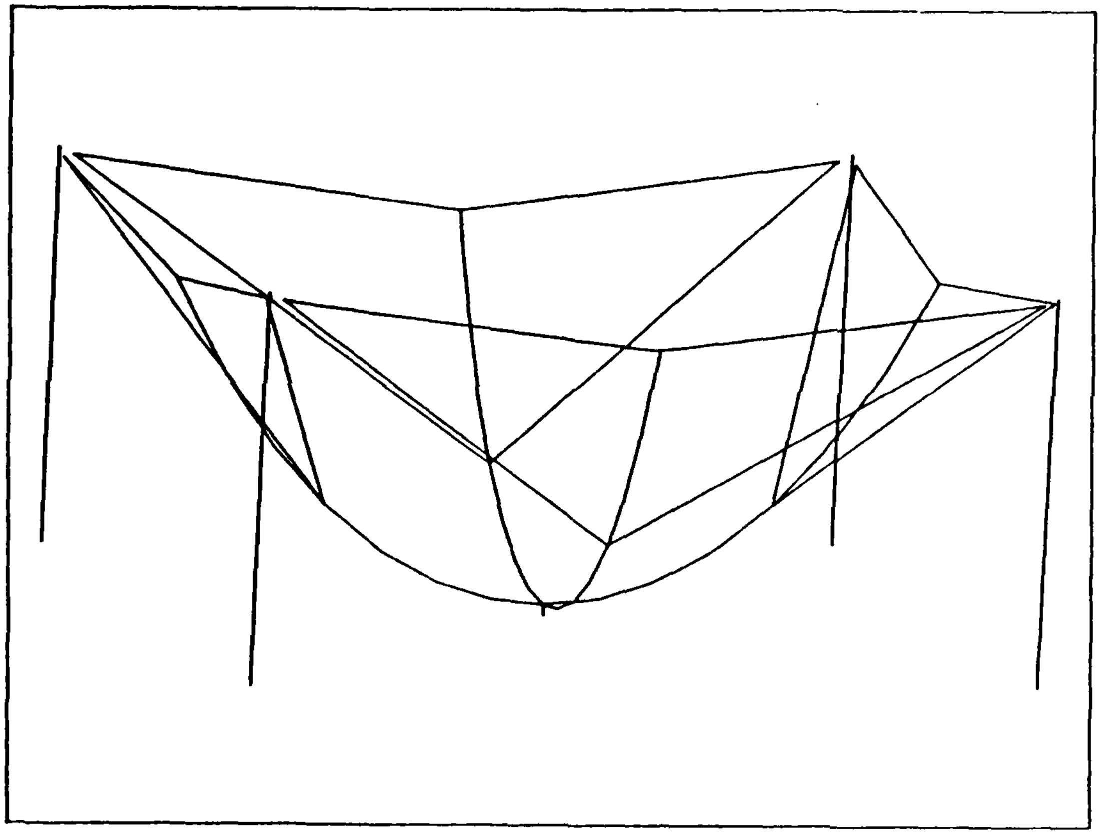


Figure 25. George LORAN NEC wire model

The remaining antenna configurations fall into the category of extended antenna systems and consist of a large wire network supported by four grounded towers. These systems function as vertical monopoles but with greater capacitance and effective height due to the wire network. Five of the existing U. S. extended systems are of the Sectionalized LORAN Tower (SLT) design, and the remaining system is known as a TIP antenna. The NEC model for these antennas is based on the more prevalent SLT design shown in Figure 25. Note that the catenaries and risers of the antenna do not contact the towers, which are present for support of the antenna only. A top view of the antenna is shown in Figure 26 to clarify the wire connection points. Catenary equations were used to approximate the shape of these antennas based on limited information available from the mechanical drawings. The wire segments used to approximate the catenaries are more easily visible in Figure 27 which shows numbered segments for a portion of the antenna. The feed point can be seen at the bottom center of the antenna.

Modeling results of the Searchlight, NV, SLT are compared with measured values in Figures 28 and 29. Good agreement is seen for both electric and magnetic fields with some under prediction occurring beyond 60 meters for electric fields. A similar situation is noted in Figures 30 and 31 comparing measured and predicted fields for the George, WA, LORAN. This station operates at 1.6 MW and represents the highest power output of any U.S. LORAN station. Perturbations of the measured magnetic fields are apparent in Figure 31. These effects resulted from proximity to ground radials, some of which were above ground and visible during measurements.

The TIP antenna at Carolina Beach, NC, is similar to the SLT design, but utilizes shorter support towers (620 feet instead of 700 feet) and has a different wire network between the towers. In spite of these differences, the SLT model provided good predictions of electric and magnetic fields near the antenna (Figures 32 and 33). Irregularities resulting from proximity to ground radials can be seen for both electric and magnetic fields. The rise in electric field strength at 280 meters (Figure 32) coincides with the location of a guy wire anchor. Tables 12 and 13 present the NEC results scaled to the rated power outputs of the existing U.S. extended LORAN antennas.

A review of the NEC modeling results reveals certain generalities that can be used to describe the fields around LORAN and OMEGA stations. One important point is that, from a safety standards viewpoint, magnetic fields are the limiting factor around LORAN antennas, while electric fields predominate near OMEGA antennas. This effect occurs because the OMEGA antennas represent a smaller fraction of a wavelength and, therefore, require a greater excitation voltage to achieve a given power output. A related fact is that for LORAN stations, a higher rated power output does not necessarily indicate higher field strengths. Note, for example, the lower field strengths produced by the Port Clarence LORAN compared to Carolina Beach LORAN which operates at just over one-half the power output. Intensity of the near-fields is directly related to excitation voltage and current rather than power output.

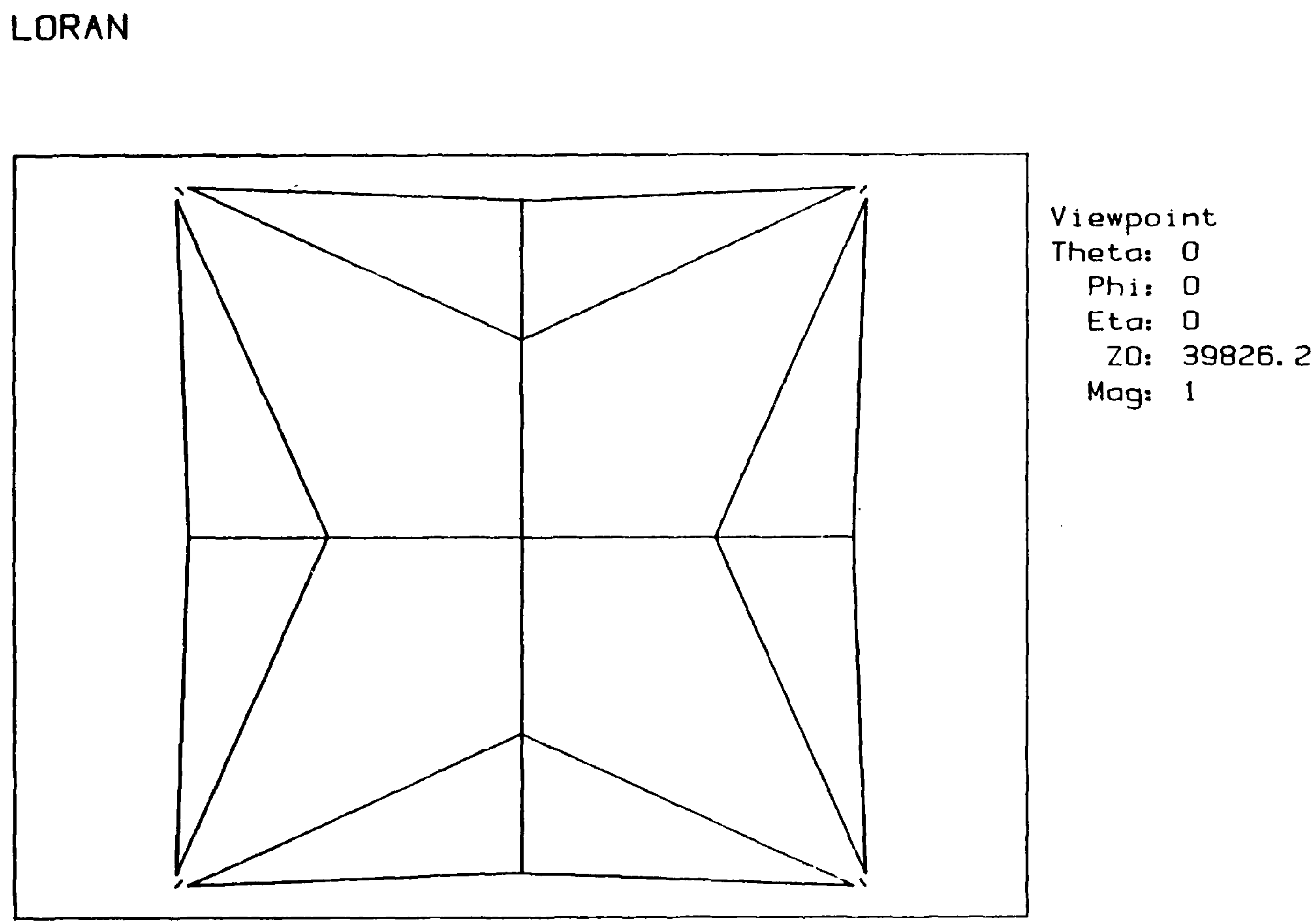


Figure 26. George LORAN NEC model (top view)

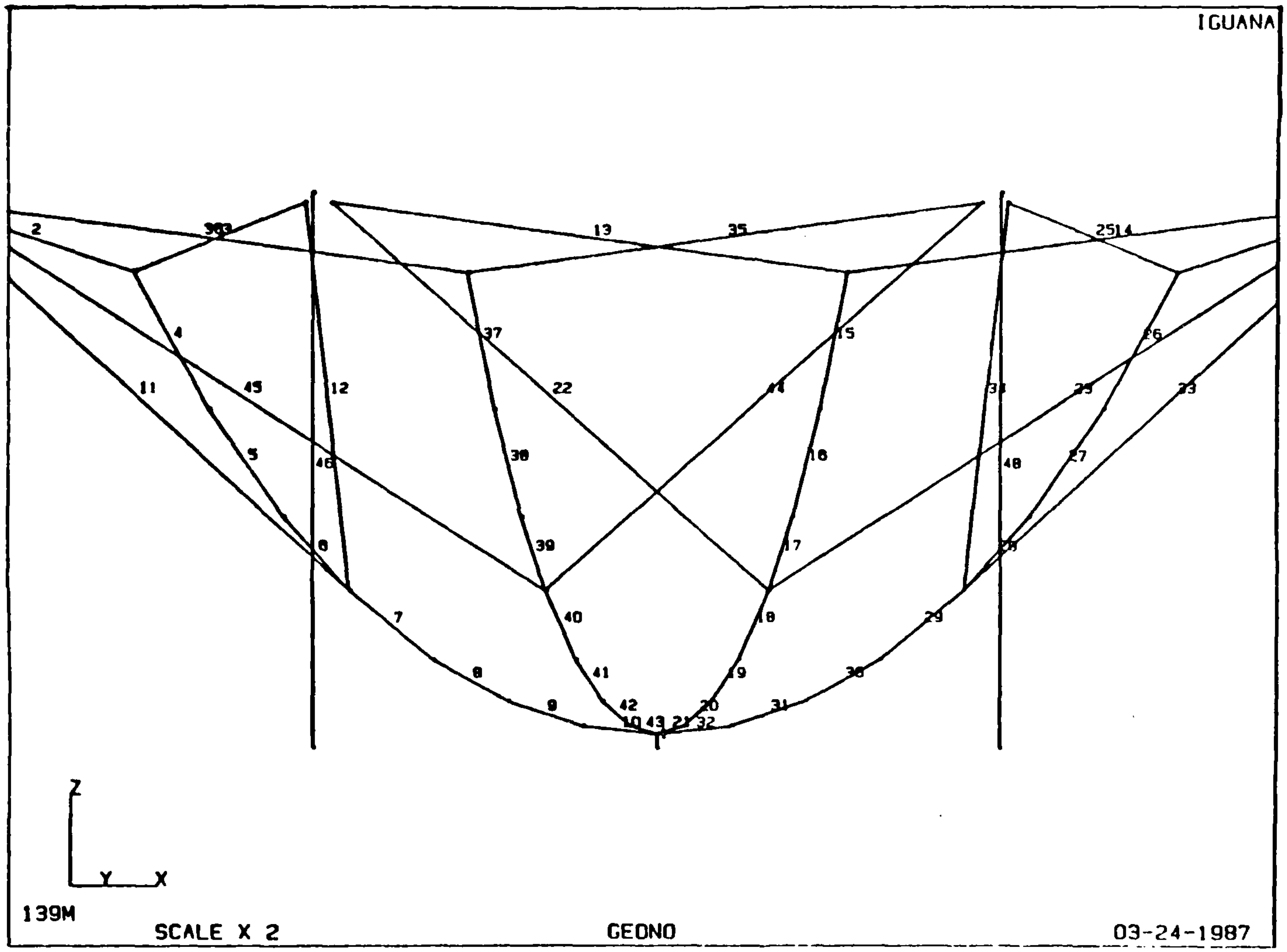


Figure 27. George LORAN NEC model showing wire numbers

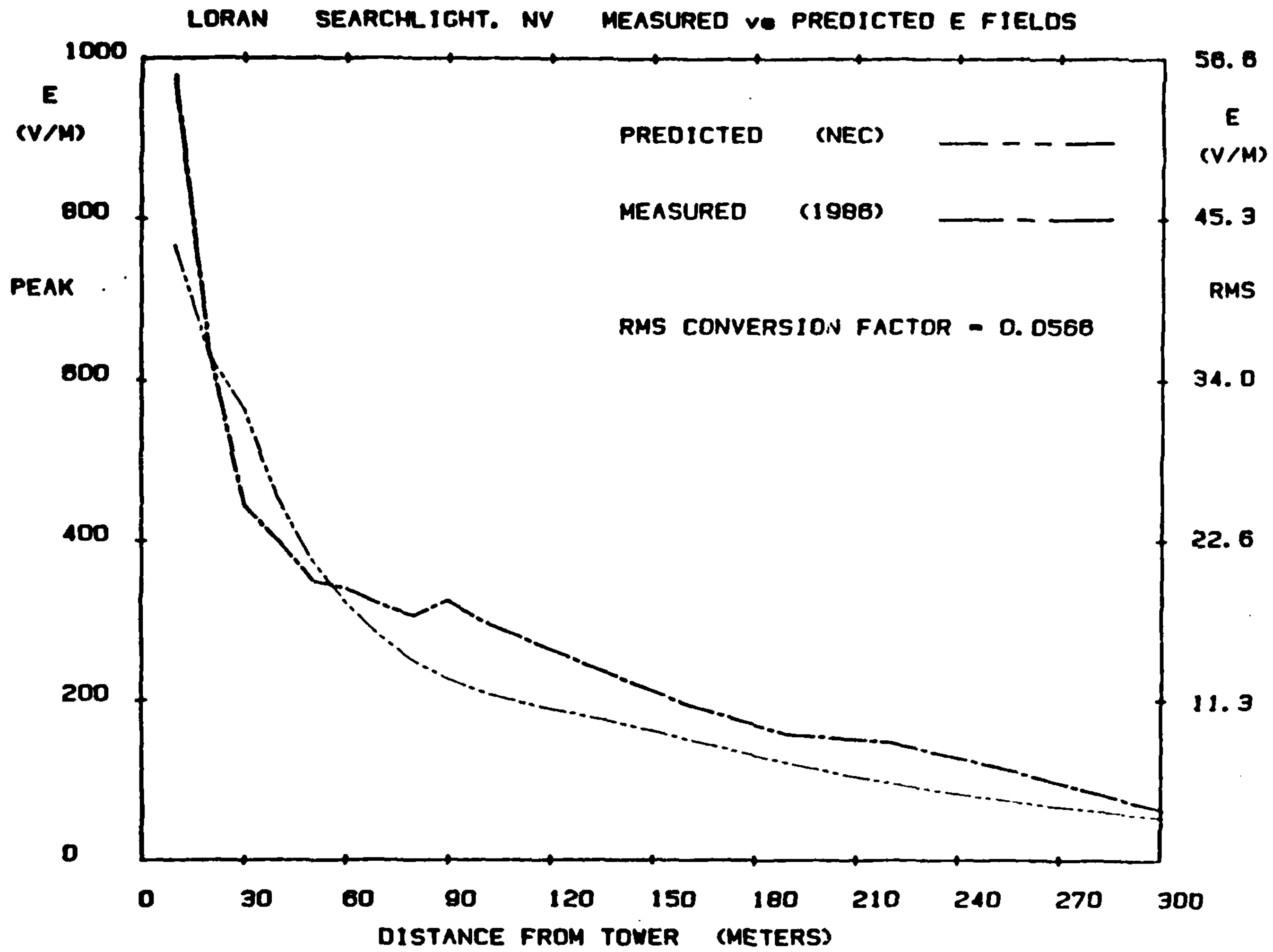


Figure 28. Searchlight LORAN measured vs. predicted E fields

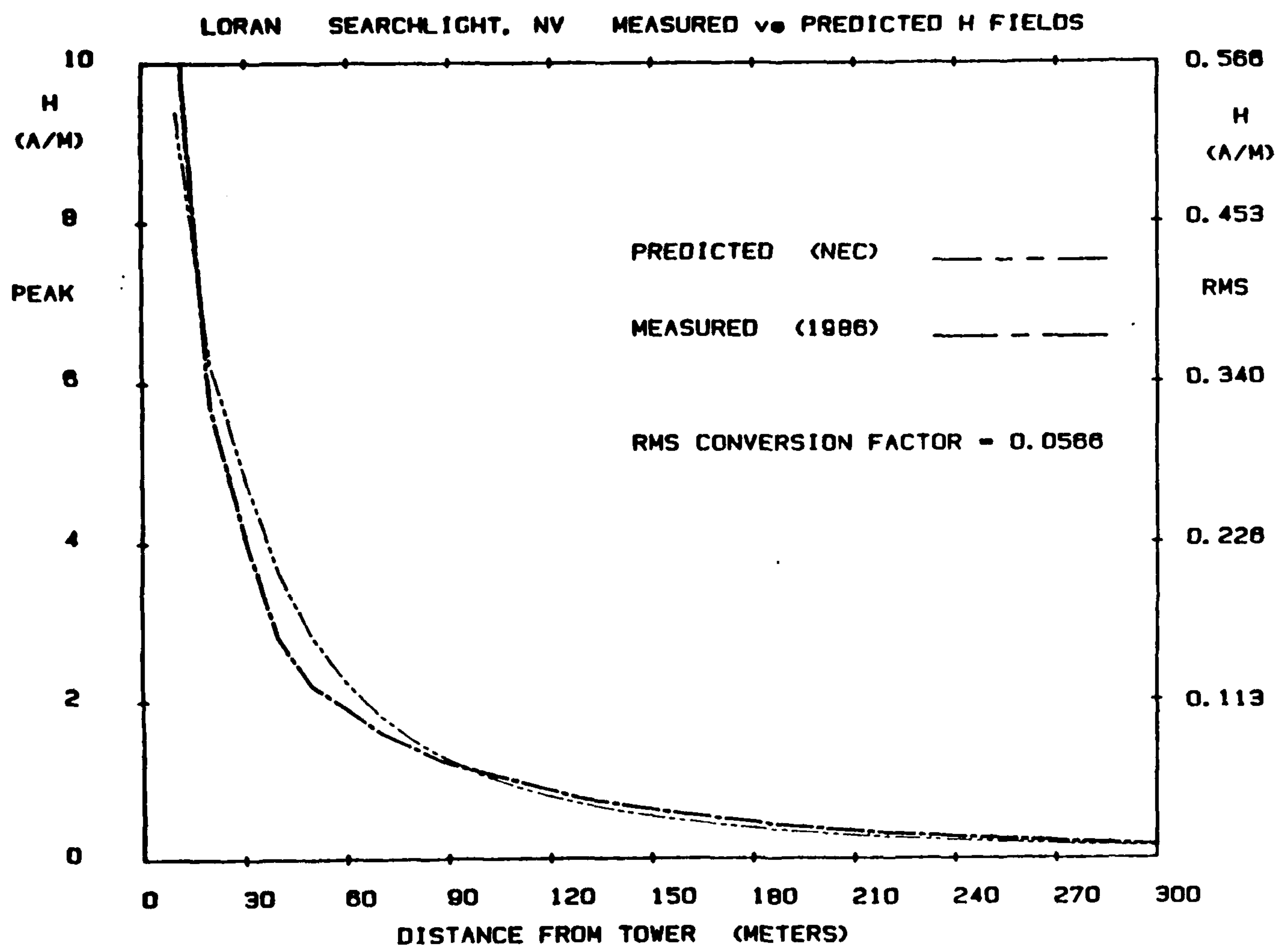


Figure 29. Searchlight LORAN measured vs. predicted H fields

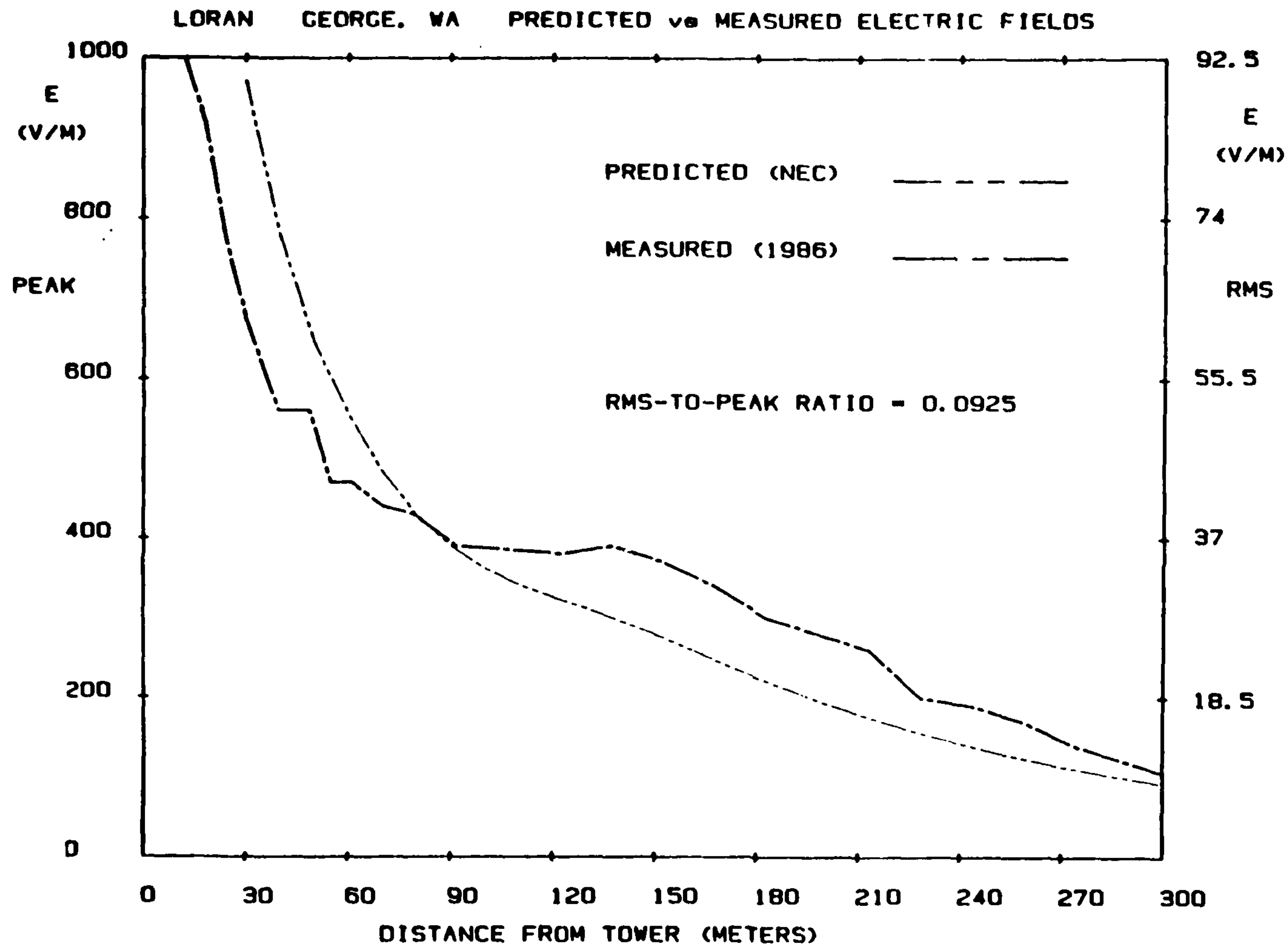


Figure 30. George LORAN measured vs. predicted E fields

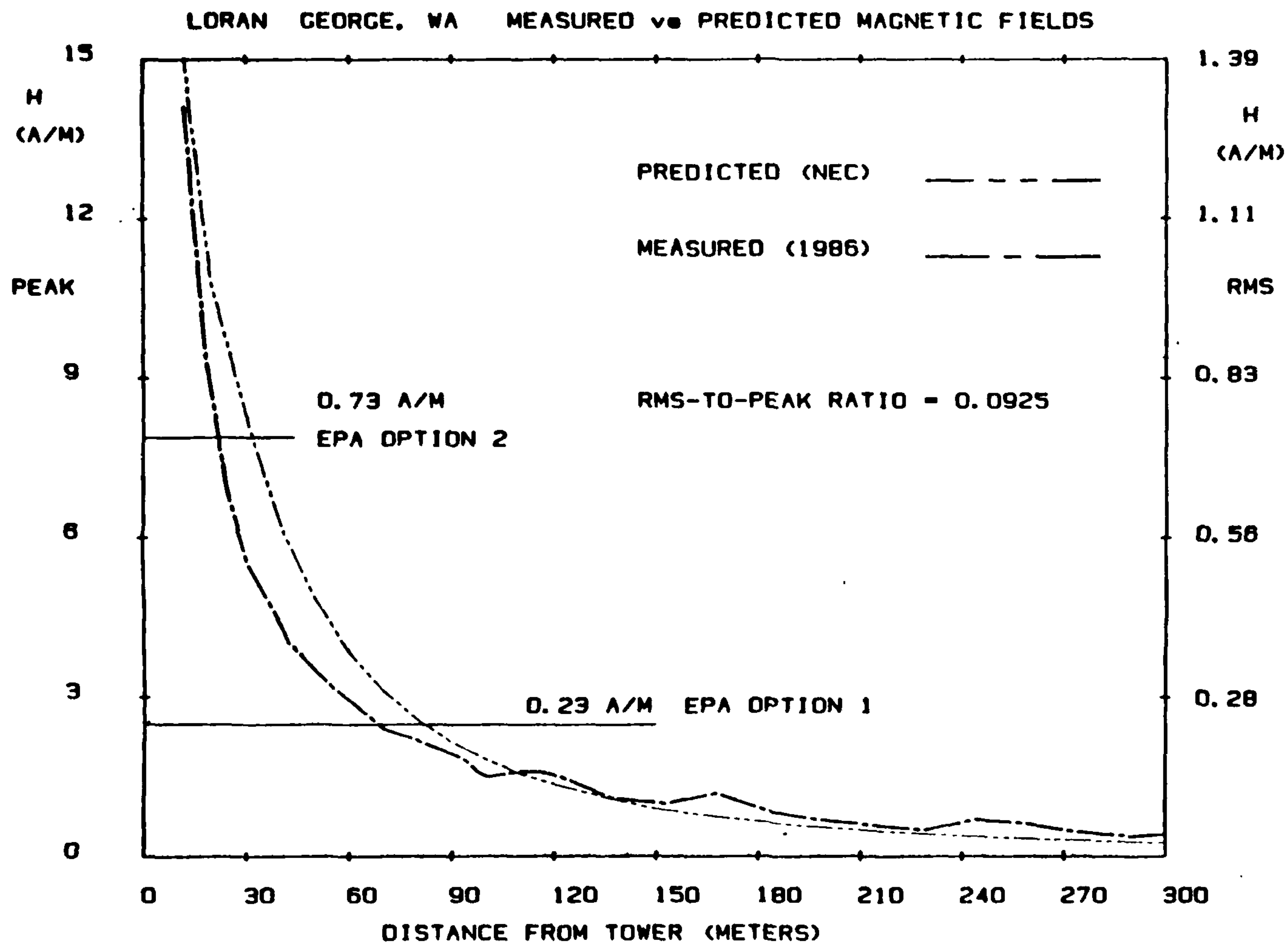


Figure 31. George LORAN measured vs. predicted H fields

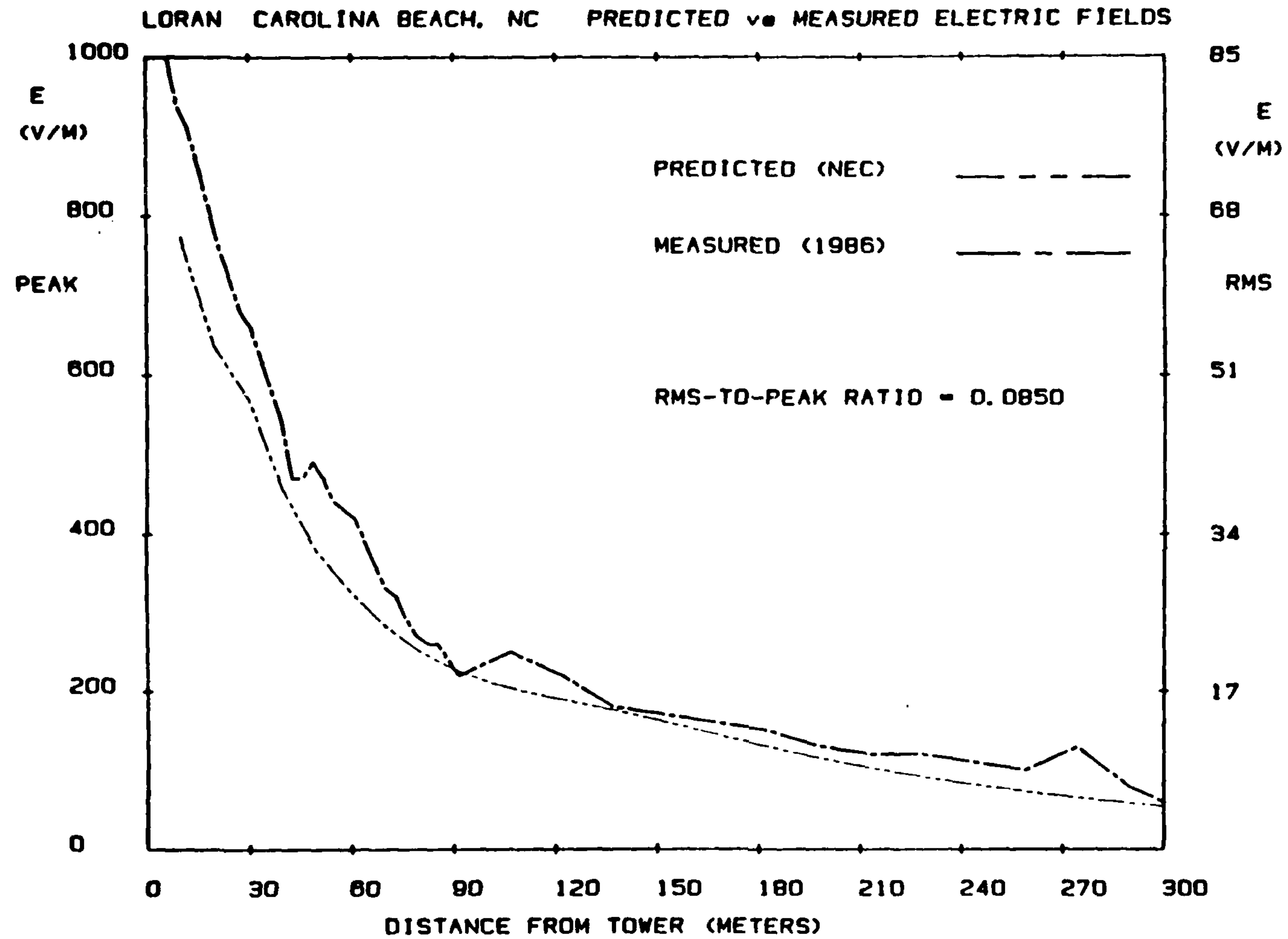


Figure 32. Carolina Beach LORAN measured vs. predicted E fields

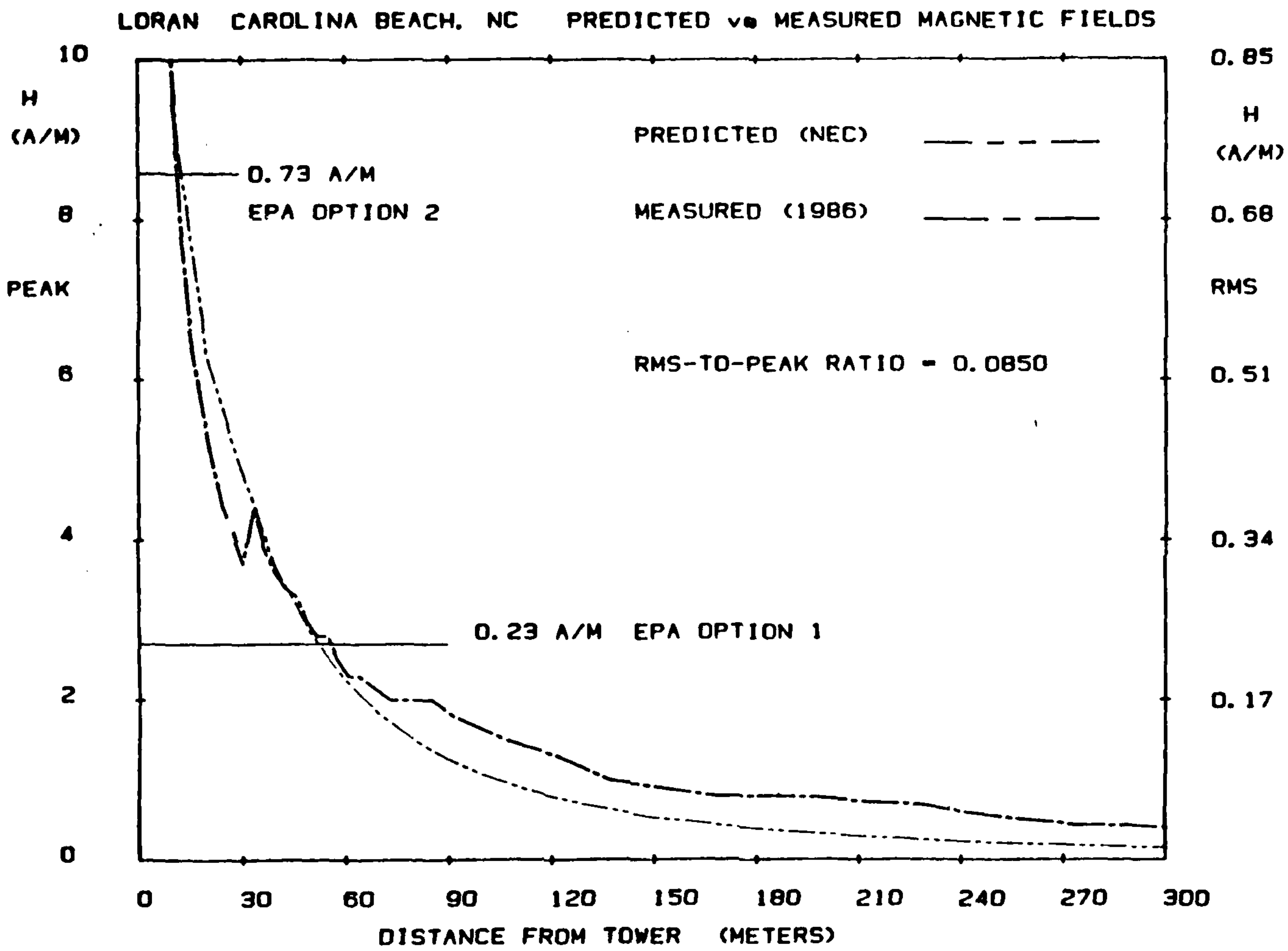


Figure 33. Carolina Beach LORAN measured vs. predicted H fields

Table 11. Power Output and RMS-To-Peak Ratios for Extended LORAN-C Antennas

Station	Type	Rated Power (KW)	GRI 1	GRI 2	RMS-To-Peak Ratio
George, WA	SLT	1600	5990 S	9940 S	0.093
Searchlight, NV	SLT	540	9940 S	--	0.057
Caribou, ME	SLT	350	5930 M	9960 S	0.096
Shoal Cove, AK	SLT	540	5990 S	7960 S	0.097
Tok, AK	SLT	540	7960 M	--	0.067
Carolina Beach, NC	TIP	550	7980 S	9960 S	0.085

Table 12. NEC Predicted Electric Field Strength for Extended LORAN-C Antennas

Distance From Tower (Meters)	Peak Electric Fields at 1 kW (Volts/meter)	George RMS E-Fields (Volts/meter)	Searchlight RMS E-Fields (Volts/meter)	Shoal Cove RMS E-Fields (Volts/meter)	TOK RMS E-Fields (Volts/meter)	Carolina Beach RMS E-Fields (Volts/meter)	Caribou RMS E-Fields (Volts/meter)
10	32.98	122.0	43.7	74.2	51.3	65.7	59.5
20	27.12	100.3	35.9	61.0	42.2	54.1	48.9
30	24.31	89.9	32.2	54.7	37.8	48.5	43.8
40	19.47	72.0	25.8	43.8	30.3	38.8	35.1
50	16.15	59.8	21.4	36.3	25.1	32.2	29.1
60	13.91	51.5	18.4	31.3	21.7	27.7	25.1
70	12.09	44.7	16.0	27.2	18.8	24.1	21.8
80	10.72	39.7	14.2	24.1	16.7	21.4	19.3
90	9.76	36.1	12.9	22.0	15.2	19.5	17.6
100	9.07	33.6	12.0	20.4	14.1	18.1	16.4
110	8.56	31.7	11.3	19.3	13.3	17.1	15.4
120	8.15	30.2	10.8	18.3	12.7	16.2	14.7
130	7.79	28.8	10.3	17.5	12.1	15.5	14.0
140	7.41	27.4	9.8	16.7	11.5	14.8	13.4
150	6.99	25.9	9.3	15.7	10.9	13.9	12.6
160	6.55	24.2	8.7	14.7	10.2	13.1	11.8
170	6.10	22.6	8.1	13.7	9.5	12.2	11.0
180	5.66	20.9	7.5	12.7	8.8	11.3	10.2
190	5.24	19.4	6.9	11.8	8.2	10.4	9.5
200	4.86	18.0	6.4	10.9	7.6	9.7	8.8
210	4.50	16.7	6.0	10.1	7.0	9.0	8.1
220	4.17	15.4	5.5	9.4	6.5	8.3	7.5
230	3.87	14.3	5.1	8.7	6.0	7.7	7.0
240	3.59	13.3	4.8	8.1	5.6	7.2	6.5
250	3.33	12.3	4.4	7.5	5.2	6.6	6.0
260	3.10	11.5	4.1	7.0	4.8	6.2	5.6
270	2.88	10.7	3.8	6.5	4.5	5.7	5.2
280	2.68	9.9	3.5	6.0	4.2	5.3	4.8
290	2.49	9.2	3.3	5.6	3.9	5.0	4.5
300	2.31	8.5	3.1	5.2	3.6	4.6	4.2

Table 13. NEC Predicted Magnetic Field Strengths for Extended LORAN-C Antennas

Distance From Tower (Meters)	Peak Magnetic Fields at 1 kW (Amps/meter)	George RMS H-Fields (Amps/meter)	Searchlight RMS H-Fields (Amps/meter)	Shoal Cove RMS H-Fields (Amps/meter)	TOK RMS H-Fields (Amps/meter)	Carolina Beach RMS H-Fields (Amps/meter)	Caribou RMS H-Fields (Amps/meter)
10	0.4040	1.495	0.535	0.909	0.629	0.805	0.729
20	0.2690	0.995	0.356	0.605	0.419	0.536	0.485
30	0.2078	0.769	0.275	0.467	0.324	0.414	0.375
40	0.1565	0.579	0.207	0.352	0.244	0.312	0.282
50	0.1212	0.448	0.161	0.273	0.189	0.242	0.219
60	0.0966	0.357	0.128	0.217	0.150	0.193	0.174
70	0.0783	0.290	0.104	0.176	0.122	0.156	0.141
80	0.0645	0.239	0.085	0.145	0.100	0.129	0.116
90	0.0541	0.200	0.072	0.122	0.084	0.108	0.098
100	0.0459	0.170	0.061	0.103	0.071	0.091	0.083
110	0.0395	0.146	0.052	0.089	0.061	0.079	0.071
120	0.0342	0.127	0.045	0.077	0.053	0.068	0.062
130	0.0299	0.111	0.040	0.067	0.047	0.060	0.054
140	0.0263	0.097	0.035	0.059	0.041	0.052	0.047
150	0.0226	0.084	0.030	0.051	0.035	0.045	0.041
160	0.0207	0.077	0.027	0.047	0.032	0.041	0.037
170	0.0185	0.068	0.025	0.042	0.029	0.037	0.033
180	0.0167	0.062	0.022	0.038	0.026	0.033	0.030
190	0.0151	0.056	0.020	0.034	0.024	0.030	0.027
200	0.0137	0.051	0.018	0.031	0.021	0.027	0.025
210	0.0126	0.047	0.017	0.028	0.020	0.025	0.023
220	0.0116	0.043	0.015	0.026	0.018	0.023	0.021
230	0.0106	0.039	0.014	0.024	0.017	0.021	0.019
240	0.0098	0.036	0.013	0.022	0.015	0.020	0.018
250	0.0091	0.034	0.012	0.020	0.014	0.018	0.016
260	0.0085	0.031	0.011	0.019	0.013	0.017	0.015
270	0.0080	0.030	0.011	0.018	0.012	0.016	0.014
280	0.0074	0.027	0.010	0.017	0.012	0.015	0.013
290	0.0069	0.026	0.009	0.016	0.011	0.014	0.012
300	0.0065	0.024	0.009	0.015	0.010	0.013	0.012

Another important factor in determining compliance with safety standards is the relationship between peak and rms field strengths. The power output rating of a LORAN station describes the power output during the peak of a pulse (see Appendix A). Silent periods between pulses and the pulse shape result in rms values that are far below the predicted peak field strengths. Dual-rated stations emit twice as many pulses and, therefore, produce higher rms field strengths when peak values are equivalent. Similarly, lower GRIs mean that the pulse train is repeating more frequently resulting in a higher rms-to-peak ratio. The implication of these effects is that no simple generalization can be made to predict field strengths at all LORAN stations. Instead, parameters such as power output, antenna type, and GRI(s) must be considered before realistic predictions can be made.

Predictions of electric and magnetic fields around LORAN stations can be made using the tables in this chapter if allowances are made for the differences between measured and predicted values shown in the figures. In general, compliance with safety standards will depend on magnetic field strengths which show better agreement between measured and predicted values. Local magnetic field concentrations should be expected near ground radials and any extended conductors which might carry induced currents. Local electric field concentrations will occur above ground radial anchors and other grounded conductors. Very close to the antenna feeds (less than 10 meters), field predictions are not reliable because of extensive perturbations by fences, rain shields, lightning gaps, and feed lines. The presence of buildings will also distort the expected field distributions, generally lowering field strengths.

V. Instrumentation and Calibration

LORAN-C and OMEGA signals present a unique set of measurement problems in the nearfield. The resulting instrumentation requirements include wide dynamic range, peak detection, and self-contained electronics. At the very low frequencies used by these systems (10.2-13.6 KHz for OMEGA and 100 KHz for LORAN-C), many of the commercially available field strength meters do not function correctly. These instruments utilize high resistance leads to connect the probe and electronics which are effectively transparent to fields at RF frequencies, but create interference at lower frequencies. An effective solution to this problem is to incorporate the probe and measurement electronics in the same package. A commercial meter, the Instruments For Industry EFS-2, houses the circuitry in a small metal enclosure which serves as a floating "ground plane" for the attached monopole sensing element. This instrument solves the interference problem but does not have the required dynamic range.

Prior to the study reported here, the Coast Guard contracted with the Johns Hopkins University Applied Physics Laboratory (JHU/APL) to develop electric and magnetic field probes which would satisfy the measurement requirements. Table 14 summarizes these requirements.

Table 14. Electric and Magnetic Field Strength Meter Requirements

	Electric Field Meter	Magnetic Field Meter
Frequency Response	10 KHz - 100 KHz	10 KHz - 100 KHz
Dynamic Range	1 V/M - 30,000 V/M	.001 A/M - 100 A/M
Response	Peak Detecting	Peak Detecting
Configuration	Integral probe and battery operated electronics	Integral probe and battery operated electronics
Accuracy	5% Full Scale	5% Full Scale

The completed meters served as the primary measurement instrumentation for this study. Each unit consists of an aluminum enclosure with a front panel digital LCD display and transducing element mounted above. The meters are supported on dielectric handles to electrically isolate the electronics from the operator and associated field distortion. Detection circuitry for the electric field meter is comprised of a high impedance FET buffer amplifier followed by high speed peak detector and adjustable readout circuitry. A high slew rate op amp and low leakage diode are used in the peak detector in order to capture and hold the single cycle LORAN-C peaks in less than one microsecond. The transducing element is a single

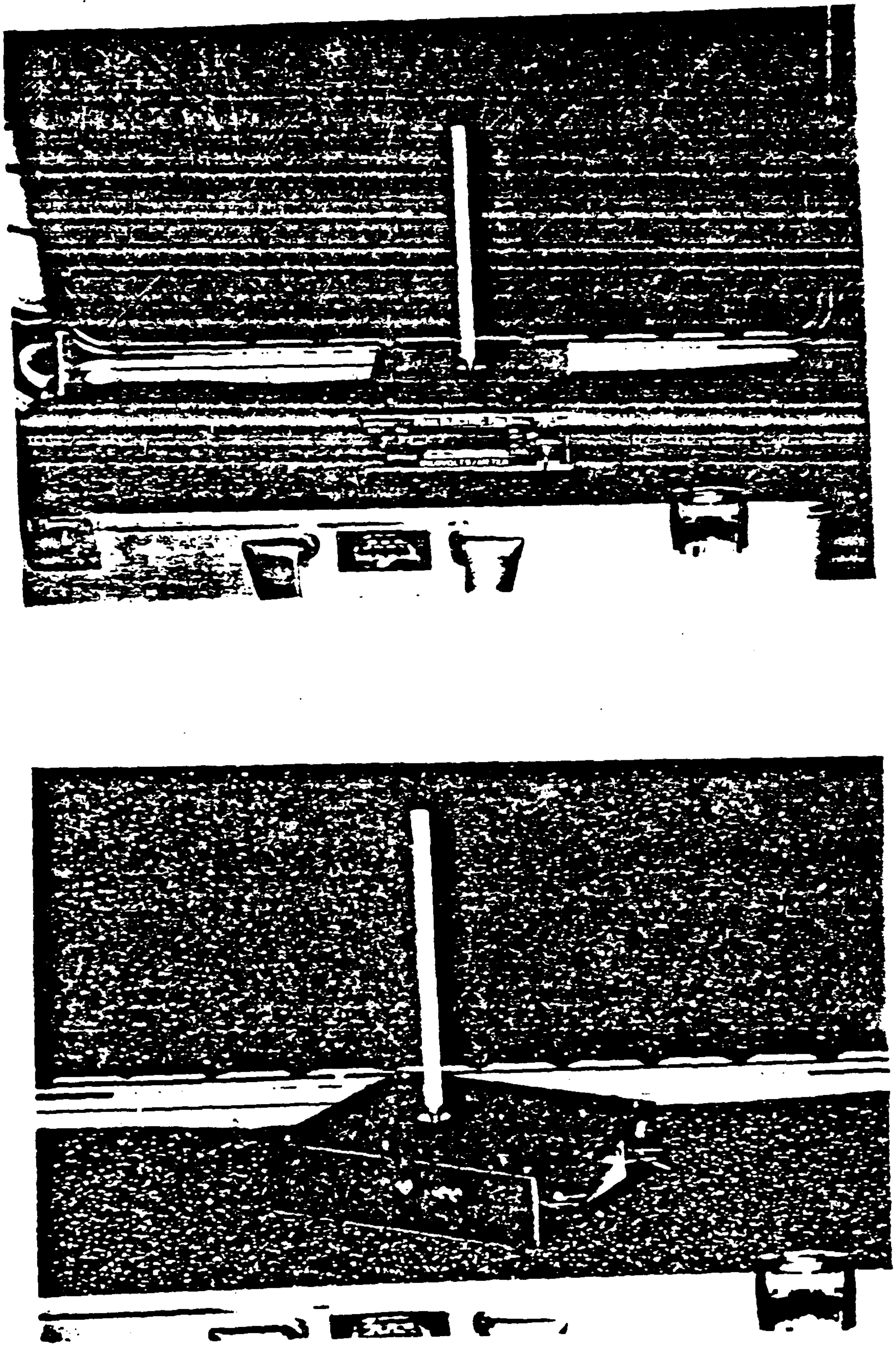
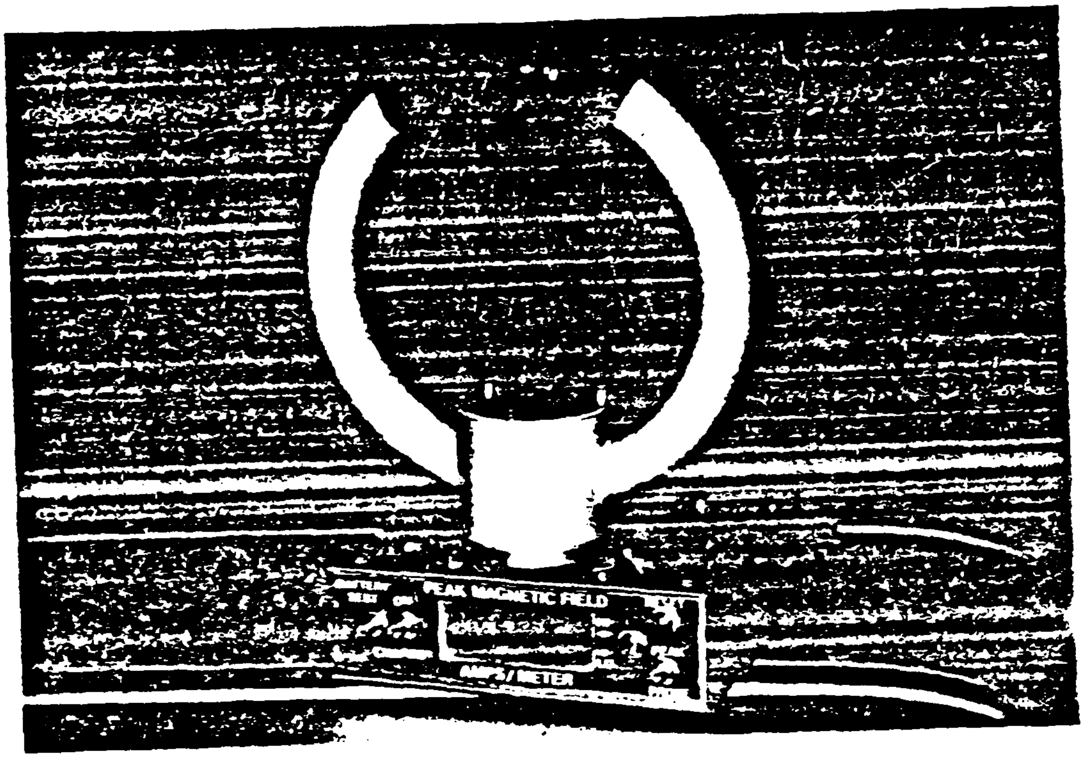


Figure 34. Coast Guard peak electric field strength meter



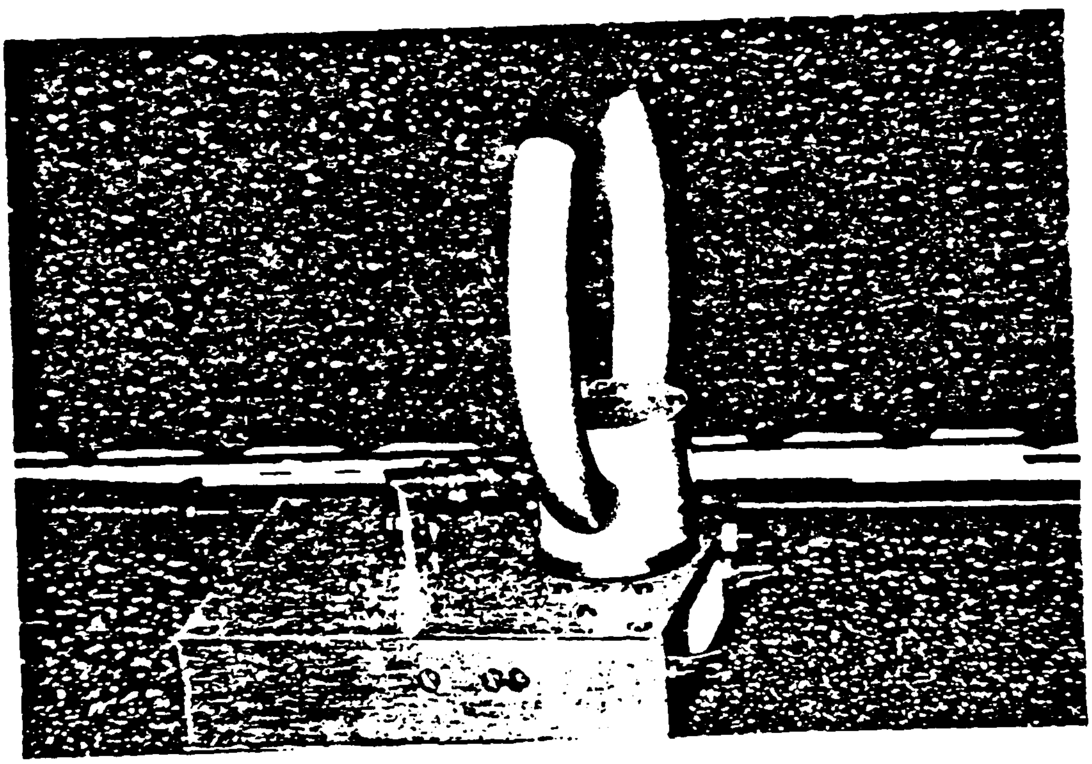


Figure 35. Coast Guard peak magnetic field strength meter

copper monopole sheathed in teflon to prevent damage from arcing in high voltage environments. Ranging is accomplished by means of a single front panel switch with no requirement for changing the monopole element.

The magnetic field meter is similar in design except that a 300 turn, 5 1/4 inch loop serves as the transducer. A split aluminum shield surrounds the entire loop and attaches directly to the electronics housing to avoid interference problems. Frequency response at 10 KHz and 100 KHz is equalized by a capacitor network. Resetting after a peak measurement is accomplished on both meters by depressing a front panel momentary switch. Photographs of the meters are shown in Figures 34 and 35.

An IFI EFS-2 electric field strength meter was purchased as a backup instrument for electric field measurements although its highest full-scale range is only 300 V/M. The backup magnetic field instrumentation included an Ailtech 94605-1 loop antenna and Tektronix 212 battery operated oscilloscope. To avoid line pick-up, the scope was mounted inside a shielded enclosure and connected to the loop directly using a feed-through BNC connector. This configuration was useful in examining pulse shape and measuring magnetic fields too intense for the magnetic field meter described above.

Shock hazards were evaluated by measuring open - circuit voltages and short - circuit currents. Voltages were measured using a Ballantine 1301A high voltage probe connected to the shielded Tektronix 212 oscilloscope. A Ballantine 323 true rms voltmeter was also purchased for this purpose, but it was later decided that the peak readings provided by the oscilloscope were more useful than rms values for shock hazard evaluation. Current measurements were performed by shorting the energized conductor to ground through a Pearson 1010 current transformer. A wire with clip-on connectors,similar to an automobile jumper cable, was used to connect the conductor to a ground rod or other nearby grounded object. The Pearson monitor was connected directly to the shielded oscilloscope for output readings. A voltage reading of one volt indicates that ten amps are passing through the loop.

Calibration of the instruments was performed at the U.S. Environmental Protection Agency's Non-ionizing Radiation Laboratory. EPA's facility is capable of calibrations from DC (static fields) to 26 GHz. A large TEM cell (Instruments For Industry CC 101.5) was used to calibrate the Coast Guard E and H Field meters described above. Original plans called for calibration of the instruments in parallel plate and Helmholtz coil systems, but EPA personnel decided instead to use the large TEM cell system because it has been more thoroughly characterized (8).

TEM cells create transverse electric and magnetic fields related in the same way as free space plane waves, that is, E = 377H, when terminated in a 50 ohm load. This condition is useful for many testing situations but makes generation of very intense fields difficult. Given the 40 cm septum-to-shield spacing of EPA's TEM cell, the induced electric field, E, is related to the input power, P, by E = SQR (51.3 * P/0.16) = SQR

(319*P). Thus, 1000 watts of input power produces only 565 V/M. This is a relatively small value compared to the electric field meter's full scale range of 30,000 V/M. A doubling of the TEM cell field strength is possible by open-circuiting the cell's output. In this configuration, a power meter can no longer be used to determine field strength, and a higher impedance device such as an oscilloscope must be used to determine impressed voltage, V. Now the electric field strength is determined as E = V/0.4 meters. Using EPA's high power class A amplifier, a maximum field strength of 1675 V/M was achieved.

A similar situation exists for magnetic fields in the TEM cell. In this case, doubling of the field strength is achieved by short circuiting the cell. Magnetic fields are related to current, I, by H = 0.339I. Field strengths of 7.7 A/M were achieved in this manner. Current through the cell was determined by reading the voltage across the current shunt with an oscilloscope.

The obtainable field strengths described above were sufficient for calibration of the low ranges and the bottom of the high ranges of both instruments. Calibration for higher values was achieved using signal injection. The rationale for the validity of this approach is based on basic field probe theory. When an (electrically short) antenna is placed in a field, the resulting open - circuit voltage will depend on the field strength, frequency (in the case of loops), and polarization of the field, and the capacitance, inductance, and physical shape of the probe. If the last three factors, the probe parameters, are held constant, then the response will be directly proportional to the component of field strength aligned with the probe. This concept is most simply illustrated in the equations for the response of electrically short probes (9).

$$Voc = He * E \qquad \text{Equation 1}$$

$$Voc = Ae * uH \qquad \text{Equation 2}$$

He = effective height
Ae = effective area
u = permeability
E = electric field strength
H = magnetic field strength
Voc = open circuit voltage

The effective height, He, and area, Ae, depend on the physical shapes and heights of the probes, and do not vary with field strength. Thus, the voltage presented to the meter circuitry is directly proportional to field strength as long as the physical dimensions of the meter remain the same. Once the meter output has been determined for a known field exposure, a voltage applied to the input can be varied to produce an equivalent output. The ratio of the field strength and applied voltage can then be used to check the meter response at higher voltages to simulate higher field strengths. This technique can also be used to check a meter's response when field calibration facilities are not available.

Calibration was performed by placing the meters on a styrofoam block inside the large TEM cell and recording meter reading versus the open - circuit voltage or short - circuit current applied to the cell. The test signals were generated using a LORAN-C simulator borrowed from the Coast Guard, and EPA's signal generators. The LORAN-C simulator has a maximum peak output voltage of about 0.26 volts and required amplification to achieve the desired field strengths. Table 15 lists the voltages applied to the TEM cell, the calculated field strength, and the electric field meter response on the low range along with relative error. These results are plotted in Figure 36.

Table 15. Electric Field Meter Calibration Results (Low Range)

Measured Voltage (Volts)	Field Strength (Volts/Meter)	Meter Reading (Volts/Meter)	Relative Error (dB)
5	12.5	11	-1.11
10	25	22	-1.11
20	50	48	-0.35
30	75	70	-0.60
60	150	152	-0.12
100	250	285	1.14
200	500	527	0.46
300	750	790	0.45
400	1000	1024	0.21

The highest obtainable peak LORAN-C field strength in the TEM cell was 1.2 K V/M. The meter responded accurately to this field on the high range with an output reading of 1.2 KV/M which provides a scaling ratio for higher voltages. An input voltage of 1.0 volts, for example, is equivalent to a calibration field of (1.0 / 0.26) * 1.2, or 4.6 KV/M. The high range calibration results are shown in Table 16 and plotted in Figure 37.

Table 16. Electric Field Meter Calibration Results (High Range)

Injected Voltage (Volts)	Equivalent Electric Field Strength (KV/M)	Meter Reading (KV/M)	Relative Error (dB)
0.26	1.2	1.2	0.0
0.52	2.4	2.5	0.35
1.00	4.6	4.9	0.55
2.00	9.2	10.2	0.90
3.00	13.9	15.4	0.92
4.00	18.4	20.4	0.90
5.00	23.1	25.6	0.89
6.00	27.7	30.9	0.95
7.00	32.3	35.8	0.89

A similar arrangement was used for calibrating the magnetic field meter except that voltages were read across a current shunt with a resistance

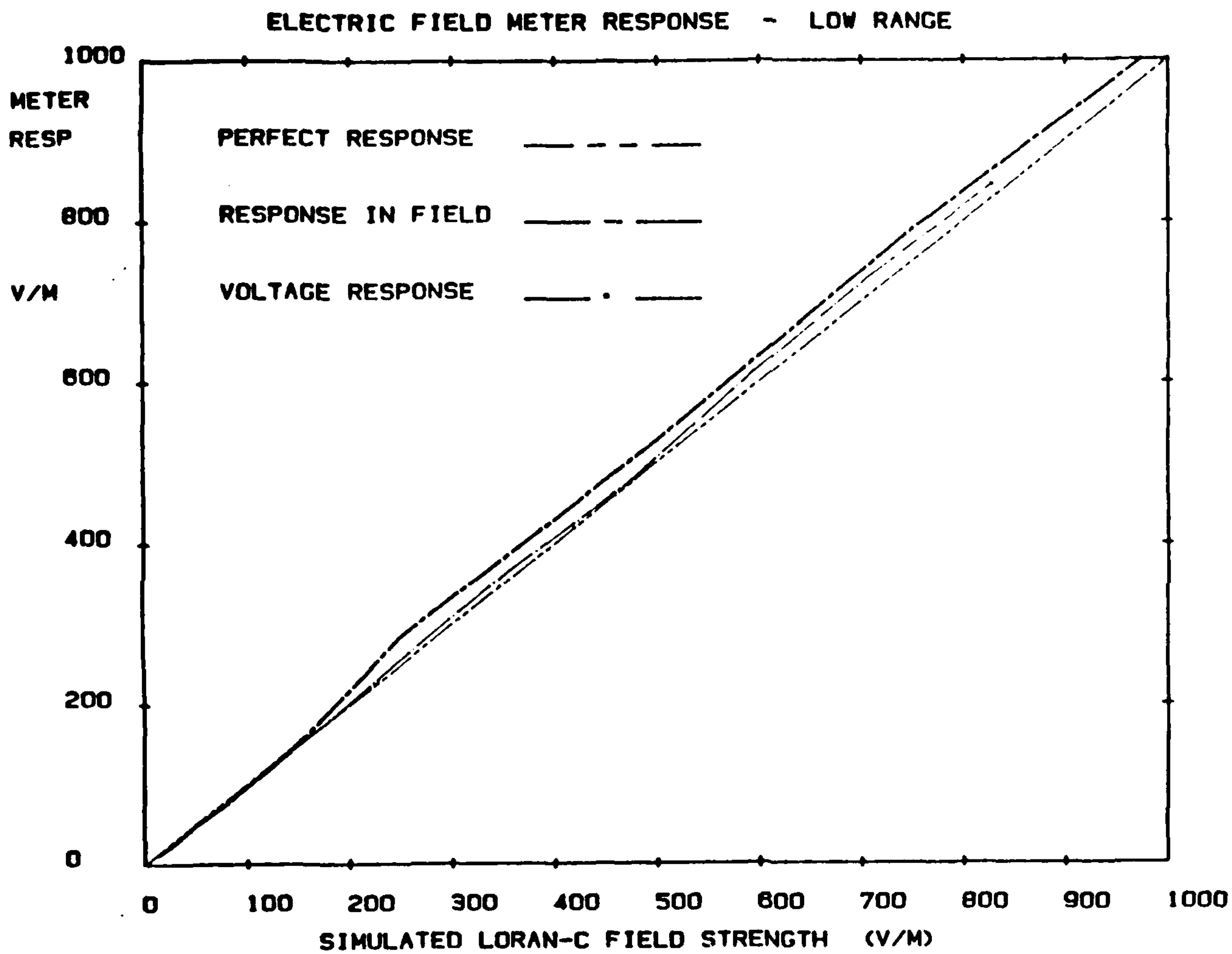


Figure 36. Electric field strength meter response, low range

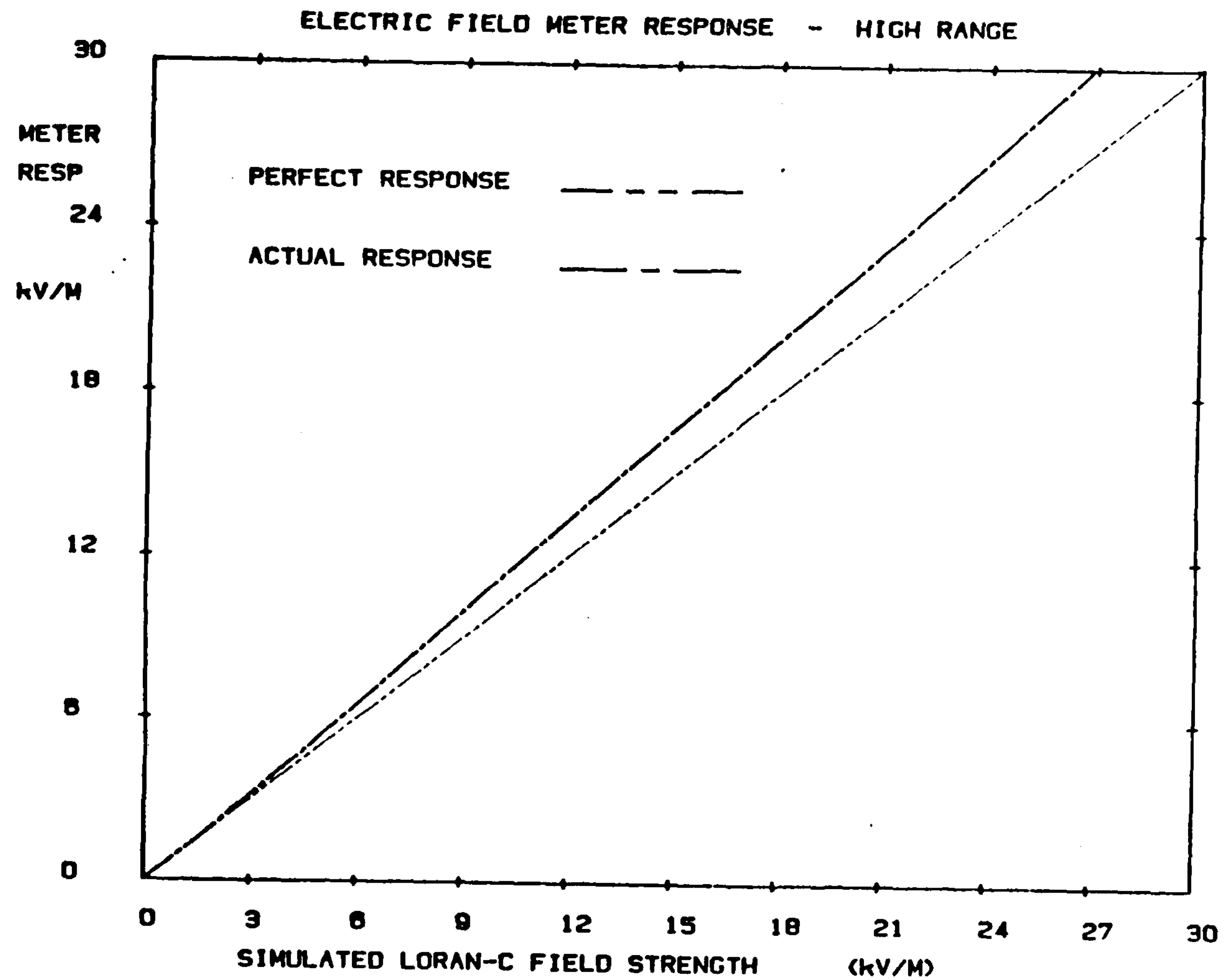


Figure 37. Electric field strength meter response, high range

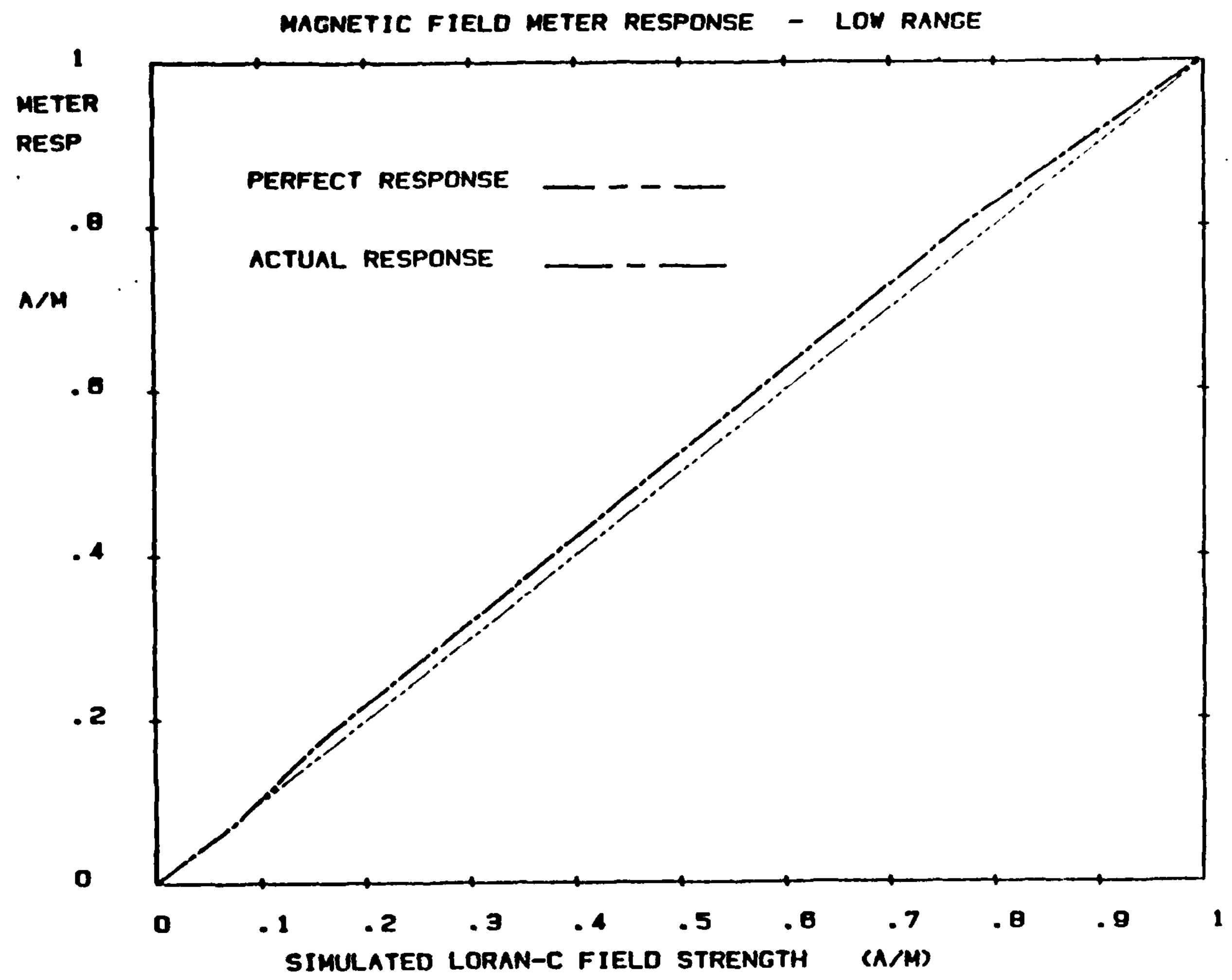


Figure 38. Magnetic field strength meter response, low range

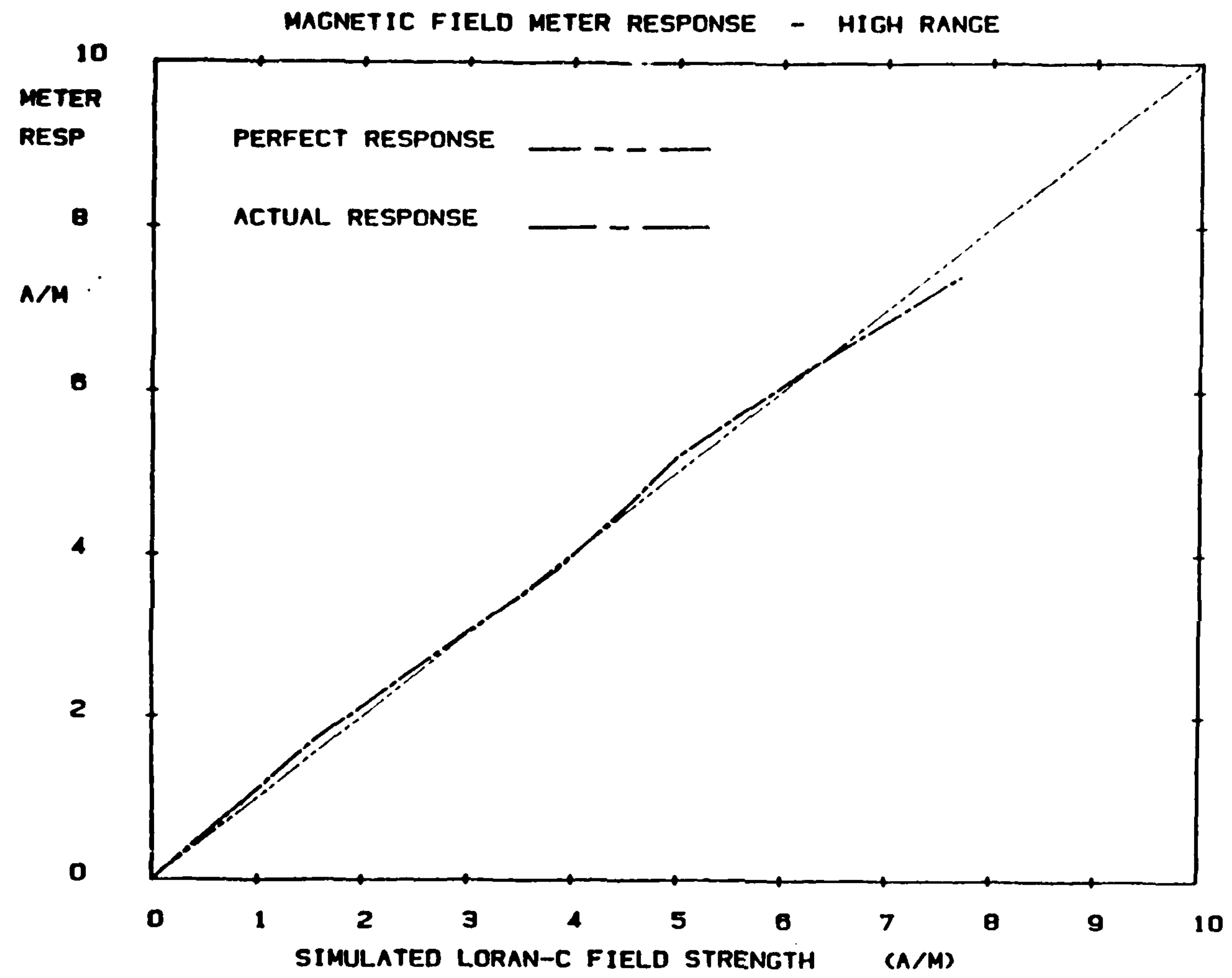


Figure 39. Magnetic field strength meter response, high range

of 0.044 ohms. Tables 17 and 18 show the calibration results for the low and high ranges, respectively. The results are plotted in Figures 38 and 39.

Table 17. Magnetic Field Meter Response (Low Range)

Measured Voltage (Volts)	Field Strength (Amps/Meter)	Meter Reading (Amps/Meter)	Relative Error (dB)
0.010	0.077	0.075	-0.23
0.021	0.162	0.180	0.92
0.050	1.385	0.406	0.46
0.100	0.770	0.800	0.33
0.150	1.155	1.140	-0.11

Table 18. Magnetic Field Meter Response (High Range)

Measured Voltage (Volts)	Field Strength (Amps/Meter)	Meter Reading (Amps/Meter)	Relative Error (dB)
0.20	1.54	1.7	0.85
0.50	3.85	3.8	-0.11
0.60	4.62	4.7	0.15
0.65	5.01	5.2	0.32
0.80	6.16	6.2	0.06
1.00	7.70	7.4	-0.35

Voltage injection was used to examine the examine the magnetic field meter's linearity at higher field strengths. Table 19 presents these results along with the equivalent field strengths and relative errors.

Table 19. Magnetic Field Meter Response to Injected Signals (High Range)

Injected Voltage (Volts)	Equivalent Magnetic Field Strength (A/M)	Meter Reading (A/M)	Relative Error (dB)
1.00	4.78	4.9	0.22
2.00	9.55	9.9	0.31
4.00	19.10	19.8	0.31
5.00	23.88	24.9	0.36
6.00	28.66	30.0	0.40
10.00	47.76	50.0	0.40

More emphasis was placed on the LORAN-C calibrations because the higher frequency and short duration of the peaks are more likely to create measurement errors. OMEGA signals, operating at carrier frequencies of 10.2 - 13.6 KHz and pulse durations of about one second, are less demanding to the detection circuitry. Electrically short monopoles, as used in the electric field meter are generally frequency independent and no response variations were expected between the LORAN-C and OMEGA frequencies. The circuit response was tested by injecting simulated

OMEGA signals into the electric field meter, and was found to be equivalent to LORAN-C response to within 0.2 dB. Loop antennas, in contrast, have a frequency dependent response unless compensated by circuit components, and must be calibrated at the frequencies in question. Tables 20 and 21 show the response of the magnetic field meter to 10 KHz fields in the large TEM cell, and Table 22 presents the response to injected signals.

Table 20. Magnetic Field Meter Response at OMEGA Frequencies (Low Range)

Measured Voltage (Volts)	Field Strength (Amps/Meter)	Meter Reading (Amps/Meter)	Relative Error (dB)
0.005	0.039	0.044	1.05
0.010	0.077	0.082	0.55
0.020	0.154	0.152	-0.11
0.040	0.308	0.281	-0.80
0.080	0.616	0.571	-0.66
0.150	1.155	1.215	0.44

Table 21. Magnetic Field Meter Response at OMEGA Frequencies (High Range)

Measured Voltage (Volts)	Field Strength (Amps/Meter)	Meter Reading (Amps/Meter)	Relative Error (dB)
0.040	0.308	0.3	0.00
0.080	0.616	0.6	0.00
0.150	1.155	1.2	0.00
0.200	1.540	1.6	0.33
0.350	2.690	2.8	0.35
0.600	4.620	5.1	0.86

Table 22. Magnetic Field Meter Response to Injected OMEGA Frequencies (High Range)

Injected Voltage (Volts)	Equivalent Magnetic Field Strength (A/M)	Meter Reading (A/M)	Relative Error (dB)
0.50	2.59	2.7	0.36
1.00	5.18	5.3	0.20
2.00	10.36	10.5	0.12
3.00	15.54	15.9	0.20
4.00	20.72	21.3	0.24
5.00	25.90	26.6	0.23
6.00	31.08	31.5	0.12
7.00	36.26	36.8	0.13
8.00	41.44	42.2	0.16
9.00	46.62	47.6	0.18
10.00	51.80	53.0	0.20
11.00	56.98	58.1	0.17

The response of the EFS-2 electric field strength meter was also examined in the large TEM cell system. Tables 23 and 24 present the calibration results for simulated OMEGA and LORAN-C fields.

Table 23. Response of EFS-2 at OMEGA Frequencies

Measured Voltage (Volts)	Field Strength (Volts/Meter)	Meter Reading (Volts/Meter)	Relative Error (db)
3.9	9.75	30	9.76
10.5	26.3	50	5.58
15.0	37.5	60	4.08
20.0	50.0	70	2.92

Table 24. Response of EFS-2 to Simulated LORAN-C Fields

Measured Voltage (Volts)	Field Strength (Volts/Meter)	Meter Reading (Volts/Meter)	Relative Error (db)
1.6	4.0	10	7.96
4.0	10.0	20	6.02
10.0	25.0	40	4.08
17.0	42.5	60	3.00
21.0	52.5	70	2.50
25.0	62.5	80	2.14

The calibration data in Tables 15-22 demonstrates good overall performance of the Coast Guard electric and magnetic field strength meters. Relative errors are limited to + 1.2 dB and are significantly lower in most cases. This level of accuracy is well within acceptable limits for field strength measurements over the large dynamic range required for this study. A further check of the electric field meter was performed by comparing its response to that of EPA's fiber optically coupled spherical dipole in actual LORAN-C fields. For this experiment, EPA personnel participated in the field study at the Searchlight, NV LORAN-C Station. Readings from the fiber optic antenna and the electric field meter were taken at the same physical location a few minutes apart. The fiber optic reading of 118 V/m agreed with the electric field meter reading of 110 V/m to 0.61 dB.

A similar test was performed by comparing the magnetic field meter reading with the output of the Ailtech loop antenna in the intense fields of the Plenum room. A meter reading of 33.6 A/m compared with 31.8 A/m indicated by the Ailtech, and a meter reading of 63.0 A/m compared with a loop indication of 61.0 a/m. Agreement for both measurements is better than 0.5 dB. The Ailtech loop is provided with a factory calibration curve from the manufacturer and can also be theoretically calibrated based on simple electromagnetic theory. Thus, the good agreement demonstrated by this experiment supports the results of the meter calibration.

The data in Tables 23 and 24 indicate large errors in the response of the EFS-2 to the calibration fields. These errors may be the result of a circuit malfunction or a calibration adjustment problem, as no time was available to perform a thorough investigation. Because of the large discrepancies, the EFS-2 was not used during the study.

Calibration checks were performed on the electric and magnetic field meters between each site visit. The checks were performed by injecting the output of the LORAN-C simulator (0.26 volts peak) into both meters and comparing the response to that documented during the EPA calibration. No variations in response were observed throughout the study. High and low range responses for both meters are shown in Table 25.

Table 25. Electric and Magnetic Field Meter Response to Injected 260 mV peak LORAN-C Signal

Range	Electric Field Meter Response (V/m)	Magnetic Field Meter Response (A/m)
Low	0.028	0.655
High	1.2	1.3

Chapter VI. Measurement Methodology

Accurate characterization of the electromagnetic environment in the near-field of any source requires a certain knowledge based on theory and experience. The frequency, modulation, intensity, and polarization of the fields all play a part in dictating the measurement techniques required. Following is a discussion of the basis for the methodology used in this study.

The extremely long wavelengths of LORAN-C and OMEGA signals (3,000 to 30,000 meters) mean that measurements for hazard assessment will generally be in the antenna near-fields. In this region, only a portion of the energy in the fields will be radiated while the remainder collapses back into the transmission system. The fraction of total energy existing in these reactive fields depends, in part, on the electrical length of the antenna. Electrically short antennas, including OMEGA antennas and most LORAN-C antennas, must produce large reactive fields in order to radiate sufficient energy. A characteristic of the reactive field or near-field environment is that the wave impedance differs from the free-space value of 377 ohms. In free space, the relationship between the electric and magnetic field strengths of propagating waves is $E=377H$, and measurement of either E or H is sufficient to characterize both. This relationship varies significantly in the near-field, and measurement of both quantities is necessary to determine compliance with most safety standards.

The low frequencies of these systems have other measurement implications as well. At higher frequencies, standing wave or interference patterns are expected which result in large, repeating field strength variations over short distances. The wavelengths of LORAN-C and OMEGA signals are too long to produce observable standing waves. Characteristic of these frequencies are quasi-static effects which are predictable from electrostatic theory. The wavelengths here are so long compared to the scale of humans and associated objects that the voltage and current distributions are practically constant across most objects. The result is that a time-varying version of electrostatic effects occur. Such effects include electric field enhancement around high curvature conductors and magnetic field enhancements near linear conductors. Higher electric fields, for example, are often observed near building corners and edges, above cars and fences, and above grounded guy wires. Increased magnetic fields are found near conduit, flag poles, and grounded support towers. The spatial extent of these concentrations must be considered when performing hazard assessments as the high field strength areas may be only partially accessible.

Field polarization is another important consideration in determining measurement technique. LORAN-C and OMEGA antennas are variations of vertical monopoles and create primarily vertically polarized electric fields. This concept is easily visualized by picturing the field lines extending between the overhead top radials and ground, at which point only a perpendicular component is possible. Exceptions to this generalization occur near the antenna feed and wherever the fields are perturbed by conductive objects. Field lines near the feed curve rapidly and polarization often varies with height above ground and location depending on the placement of lightening gaps, rain shields, feed lines, and fences. Similar variations occur near buildings, guy wires, and other conductive objects. In open, flat areas, away from conductive objects, electric fields from the ground to two meters high can be assumed to be vertically polarized.

Magnetic field polarization follows a different principle. In general, magnetic fields near vertical monopoles are polarized horizontally in a direction perpendicular to a line connecting the measurement point and the antenna tower or feed. More simply, the magnetic field lines occur as circles centered on the antenna. The same principle applies to the polarization of secondary fields resulting from currents induced in nearby conductors. Complications occur in areas where the antenna fields and secondary fields add to produce unpredictable polarizations. Near the antenna feed, polarization is complicated by addition of fields from the horizontal feed lines and vertical antenna structure, as well as nearby objects. As in the case of electric fields, magnetic field polarization in open areas away from the feed can be predicted as described above.

Polarization of the fields is important in determining total field strength which is the quantity limited by most safety standards. Both the electric and magnetic field strength probes used in this study measure only a single polarization at one time. There are two basic methods for determining total field strength with a single polarization probe. The first is to make three orthogonal measurements and calculate the total field strength as the vector sum of the results according to Equation 3.

$$E\ Total^2 = E_x^2 + E_y^2 + E_z^2 \qquad \text{Equation 3}$$

The disadvantage of this technique is that three measurements are required at each location.

The second method is to rotate the probe systematically until a maximum reading is obtained. Peak holding instruments, as used in this study, lend themselves to this technique because the maximum value reached at any orientation is the displayed reading. The disadvantage is that it is possible to miss the exact polarization alignment which would produce a maximum reading, and increased carefulness means more time for each measurement. The most practical approach, in general, is to use the rotation or probing technique when the polarization is fairly well known. In this case, a maximum reading is obtained by small variations of the probe orientation. Orthogonal measurements are usually more useful in complex environments, such as near the antenna feed. At LORAN-C stations, the pulses are repeating rapidly and there is little chance of missing a peak reading by rotating past the correct orientation in-between pulses. OMEGA signals, in contrast, repeat every 10 seconds and probing is impractical. Maximum values of both E and H occur during the 10.2 kHz portion of the cycle and would likely be missed during rotation. Thus, orthogonal measurements are required at OMEGA stations and each orientation must be maintained for the length of a single cycle, or at least 10 seconds.

Operator interference is another potential source of error. The human body is sufficiently conductive to create significant electric field perturbations. This effect is apparent during measurements, as readings will change if the operator moves too close to the field strength meter. Such interference was found to be avoidable by holding the meter at arm's length by the dielectric handle. Resetting the peak detector was accomplished using a non-conductive rod to depress the reset button. Finger contact with the button proved to be unacceptable unless the meter was oriented for a low reading and afterwards re-oriented for maximum reading. The magnetic field meter was shielded against electric field interactions and was far less sensitive to operator position. A small interference resulted from fields generated by induced body currents, but was undetectable unless the meter was held very close to the body. Resetting of this meter by finger contact produced no change in reading.

Variations of field strength with height above ground were also considered in regard to field characterization. Electric field strengths were found to increase with height above ground as occurs near other low frequency sources such as AM radio stations. This effect was consistent between stations and it was decided that a measurement height of between 1.5 and 2.0 meters above ground would be used at most locations. The rationale for this approach is that the exposure standards limit maximum field strength or specific absorption rate (SAR). Because no SAR measurements were included in this study, maximum field strengths in accessible areas are the limiting factor. The same height was used for magnetic field strength measurements. Magnetic fields did not vary as much with height as electric fields except near ground radials where very localized increases result from the confined return currents. The magnitude of this intensification depends on the ground conductivity and the depth of the ground radials. This effect was noted where observed.

Measurement locations were chosen with the goal of determining areas in which field strengths exceed the proposed EPA standards discussed in Chapter X. Typically, a higher density of measurements were taken near the antenna feed and any frequently traveled nearby areas such as parking lots, sidewalks, and building entrances. Field strength distributions in these areas are typically complex and unpredictable due to the numerous perturbing features. Further from the feed, advantage was taken of the symmetry of the antenna systems. Field strengths near monopole antennas are cylindrically symmetric except for variations resulting from top and ground radials and guy wires. In other words, the field strengths measured 100 feet from the antenna in one direction should be the same at

100 feet in any other direction. Slightly more intense electric fields are sometimes observed under top radials, and increased magnetic fields may occur near ground radials.

At most stations, measurements were taken at intervals in two radial directions away from the feedpoint, but dense vegetation prevented measurements along more than one radial direction in some cases. The measurement interval varied from 10 feet to 100 feet depending on distance from the feed. The extended antenna systems such as the SLTs are not cylindrically symmetric and measurement radials were chosen to characterize maximum differences in field drop off. The least symmetry occurred at the Kaheohe, HI OMEGA station where measurements were required at all points of interest. Measurement radials at most stations extended 300 meters from the feed or until field strengths dropped below the lowest EPA standard.

Field strengths in and around buildings were carefully mapped to determine personnel exposures during normal work routines. Indoor fields can vary widely over short distances and probing was used to find maximum indoor field strengths. In many cases, typical exposure levels were recorded along with maximum "hot spot" readings which often occur in very limited areas. Higher electric field strengths were found near windows and exterior walls, while higher magnetic fields occurred near conduit, water pipes, and other long conductors. A higher density of measurement points was required near the transmitters and tuning coils which produce extremely high and variable magnetic field strengths.

Chapter VII. Measurement Results

This chapter presents electric and magnetic field measurement data gathered at nine LORAN-C stations and two OMEGA stations during 1986. The purpose of the measurements was to determine personnel exposures during normal work routines and to identify areas in which the proposed EPA standards are exceeded. Results are presented separately for each station and summarized in Table 60 which gives the distances from each antenna or feed point which must be maintained to avoid exposures above the various standards. All values shown are in terms of rms field strength and are derived from the peak measurement data according to the analyses presented in Appendices A and B. Conversion of the rms values back to peak field strengths can be accomplished by dividing by the rms-to-peak ratio specified for the station.

Table 26

Station:	Searchlight, NV LORAN-C
Peak Power Output:	540 KW
Pearson Current:	700 amps
Antenna Type:	SLT
Rate(s):	9940 - Secondary
RMS - to - Peak Ratio:	0.0567

	RMS Electric Field Strength (V/M)		RMS Magnetic Field Strength (A/M)	
Area	Typical	Local Maxima	Typical	Local Maxima
Inside				
Garage	1		0.028	
Mechanical Room	<1		0.009	0.040
Generator Room	<1		0.011	
Engineering Office	<1		0.023	
C.O. Office	<1		0.004	0.011
ETC Office	<1		0.011	
Passage Way	<1		0.022	
Day Room	<1		0.007	0.040
Operations Room	<1		0.011	0.046
Transmitter Room	<1		0.057	0.102-0.278
Transmitter Cage				0.681
(Inside)	1	2		
Plenum Room	11		1.305	
Near Tuning Coils		533		3.8
Under Feed lines		57		3.7
Outside				
Inner Feedpoint Fence (3.7 meters from feed)		79	1.163	
Inside Outer Feedpoint Fence		30-79	0.113-1.163	
Under Feed Lines		34	3.5	
Near Support Tower Fence	<5		0.068	

Table 27. Searchlight, NV - Measured RMS Field Strengths

Distance From Feed (Feet)	RMS Electric Field Strength (V/M)	RMS Magnetic Field Strength (A/M)
10	55.5	0.607
20	36.0	0.323
30	25.2	0.233
40	22.7	0.159
50	19.9	0.125
60	19.3	0.108
70	18.2	0.091
80	17.4	0.079
90	18.4	0.068
100	17.0	0.062
130	13.9	0.043
160	11.1	0.032
190	8.9	0.023
220	8.3	0.018
250	6.7	0.014
280	4.8	0.011
310	3.0	0.009

Comments: The feedpoint at this station is located to the side of a single building which houses administrative and operational functions. A wooden fence surrounds the feedpoint preventing approach to distances less than about 12 feet. High field strengths were measured near the fenced area and inside the Plenum room which houses the antenna tuning coils. The parking lot and front entrance area are shielded from the feed point by the building, and field strengths in these areas as well as inside most of the building are below the lowest EPA option. Station personnel reside in Boulder City, NV, and commute to the station. Field strengths drop off quickly with distance and are far below the lowest EPA option at the station property boundary.

Table 28

Station:	Port Clarence, AK LORAN-C
Peak Power Output:	1000 KW
Pearson Current:	400 Amps
Antenna Type:	1350' Monopole
Rate(s):	9990 - Secondary
RMS-to-Peak Ratio:	0.0566

	RMS Electric Field Strength (V/M)		RMS Magnetic Field Strength (A/M)	
Area	Typical	Local Maxima	Typical	Local Maxima
Inside				
Admin. Bldg.	<1	<1	<0.001	<0.001
Bldg. 1-2 Hallway	<1	<1	0.003	0.005
Building 2	<1	<1	<0.001	<0.001
Bldgs. 2-3 Hallway	<1	<1	0.005	0.008
Building 3	<1	1	<0.001	0.001
"Greenhouse"	<1	<1	0.003	
Building 3-4 Hallway	<1	<1	0.003	0.008
Building 4	<1	<1	<0.001	0.002
Hallway to Tx Bldg.				
To 1st Ladder	<1	<1	0.002	0.005
1st to 2nd ladder	<1	2	0.003	0.011
Near Conduit	2			0.069
2nd ladder to Corner			0.017	0.045
"Dog Leg"	2		0.079	
Transformer Room	<1		0.002	
Transmitter Room				
Near Entrance	<1	<1	0.007	0.010
Near Active Tx	2	8	0.011	1.30
Near Standby Tx "off"	1	2	0.226	0.962
Into Dummy Load	3	6	0.283	0.883
3' From Tuning Coil	2		0.436	
Front of Tuning Coils	38		1.25	3.37
Left of Tuning Coils	1189	1840	3.57	>6.0
Outside				
Near Tower Base	2830		>4	
Near Climb-On Point	767		1.08	
At Tower Fence	226		0.566	
On Road Next to Tower	11		0.079	
Front of Admin. Bldg.	1		0.002	

Table 29. Port Clarence, AK - Measured RMS Field Strengths

Distance From Tower Base (Feet)	RMS Electric Field Strength (V/M)	RMS Magnetic Field Strength (A/M)
25	119	0.391
50	56	0.209
75	32	0.136
100	27	0.102
125	20	0.085
150	15	0.068
175	13	0.057
200	11	0.051
225	9.5	0.045
250	8.7	0.040
328	6.7	0.027
492	6.3	0.016
656	11.4	0.014
820	3.5	0.010
984	4.9	0.008

Comments: The administration and operations buildings and the living quarters are located about 2000 feet from the antenna resulting in very low typical exposures. High fields strengths were found only near the tower base and tuning coils. Maximum tuning coil fields were greater than full scale on the magnetic field meter and appeared to be greater than 800 A/M peak (45 A/M rms) using the Ailtech loop. Field strengths near the active and standby transmitters were high and increased when the standby unit was driving a dummy load.

Table 30

Station:	George, WA LORAN-C
Peak Power Output:	1600 KW
Pearson Current:	1220 Amps
Antenna Type:	SLT
Rate(s):	5590-Secondary, 9940-Secondary
RMS-to-Peak Ratio	0.0925

	RMS Electric Field Strength (V/M)		RMS Magnetic Field Strength (A/M)	
Area	Typical	Local Maxima	Typical	Local Maxima
Inside				
Garage	<1	1	0.023	
Mech. Room	<1		0.023	0.046
Shop	<1		0.009	0.037
Generator Room	<1		0.004	0.046
Day Room	<1		0.009	0.051
Bunk Room	<1		0.028	0.074
Offices	<1		0.019	0.028
Operations Area	<1		0.046	0.083
Transmitter Area	1		0.028	0.065
Near Active Tx	1		0.277	0.741
Near Standby Tx	1		0.037	0.083
Plenum Room	19	93	0.463	4.16
Under Feedlines	93	463		>6.4
Outside				
Feedpoint Fence	185	214	2.32	3.24
Service Road Near Feed	75		0.862	
Picnic Table Near Feed	82		0.848	
Parking Lot	37	46	0.139	0.734
Parking Lot-Near Feed	83		1.85	
Near Support Tower Fence	4		0.185	

Table 31. George, WA - Measured RMS Field Strengths (Measurement Radial Towards Tower)

Distance from Feed (Feet)	RMS Electric Field Strength (V/M)	RMS Magnetic Field Strength (A/M)
30	130	1.76
40	111	1.30
50	89	1.06
60	85	0.869
70	76	0.734
80	71	0.639
90	65	0.555
100	62	0.509
110	58	0.463
120	56	0.425
130	52	0.407
140	52	0.370
150	53	0.351
160	52	0.333
170	46	0.314
180	43	0.296
190	43	0.277
200	43	0.268
210	41	0.257
220	43	0.240
230	41	0.222
240	41	0.212
250	41	0.204
260	40	0.204
270	38	0.195
280	38	0.185
290	39	0.176
300	36	0.176
320	37	0.176
340	36	0.185
360	35	0.185
380	35	0.185
400	35	0.176
420	37	0.176
500		0.148

Table 32. George, WA - Measured RMS Field Strengths (Measurement Radial Along Road Bisecting Towers)

Distance from Feed (Feet)	RMS Electric Field Strength (V/M)	RMS Magnetic Field Strength (A/M)
54	75	0.862
67.2	66	0.592
80.7	61	0.537
96.5	58	0.472
113.7	57	0.463
131.6	53	0.324
150.1	51	0.259
168.9	47	0.240
187.9	46	0.240
207.2	46	0.249
226.5	43	0.249
246.0	46	0.213
265.6	46	0.222
285.2	44	0.213
304.8	45	0.167
324.5	45	0.148
344.3	43	0.139
364.0	41	0.148
383.8	41	0.148
403.6	39	0.139
453.2	36	0.102
502.9	34	0.093
552.6	31	0.111
602.4	28	0.080
652.2	26	0.064
702.1	24	0.055
751.9	19	0.046
801.8	18	0.065
851.7	16	0.057
901.6	13	0.043
951.5	11	0.035
1001.5	9	0.041
1051.4		0.028

Comments: This station produces relatively high rms field strengths over large areas because of its high power output and dual rating. High magnetic field strengths were found in the Plenum room and outside near the feedpoint fence, as well as in the parking lot corner nearest the feed. Other parts of the parking lot are shielded from the feed by the building resulting in lower exposures. Local increases in magnetic field strength were found near the support towers (due to induced currents), and near ground radials.

Table 33

Station:	Dana, IN LORAN-C
Peak Power Output:	400 KW
Pearson Current:	650 Amps
Antenna Type:	625' Monopole
Rate(s):	8970 - Master, 9960 - Secondary
RMS-To-Peak Ratio:	0.0850

	RMS Electric Field Strength (V/M)		RMS Magnetic Field Strength (A/M)	
Area	Typical	Local Maxima	Typical	Local Maxima
Inside				
Plenum Room				
Entrance	7	11	0.731	0.791
In Front of Coupler	28		1.45	
Under Active Feed	145	527	3.23	>5.7
Under Standby Feed	<1	1	0.094	1.02
Transmitter Room				
Door To Plenum	<1		0.102	
Next To Active Tx	<1		0.085	0.221
Next To Standby Tx	<1		0.034	0.092
Inside Active Tx	1		0.340	3.00
Inside Standby Tx	1		0.004	0.02
Hallway	<1		0.074	0.094
Work Area	<1		0.012	0.031
Operations Area	<1		0.001	0.009
Screen Room	<1		0.012	
CO Office	<1		0.004	
Storeroom	<1		0.001	
ET Office	<1		0.001	
Station Office	<1		0.004	
Watchstanders Quarters	7		0.004	
Recreation Room	<1		0.004	0.085
Garage	<1		0.001	
Outside				
			0.020	
Near Parking Lot	17			
Inside Antenna Fence	162	1700	2.6	5.1
Antenna Fence	111		2.1	
Under Top Radial Guy	18		0.012	

Table 34. DANA, IN - Measured RMS Field Strengths (Measurement Radial Along Underground Feedline)

Distance From Tower Base (Feet)	RMS Electric Field Strength (V/M)	RMS Magnetic Field Strength (A/M)
12	111	2.13
15	102	1.87
20	94	1.40
30	87	0.978
40	74	0.730
50	66	0.646
60	64	0.528
70	58	0.468
80	55	0.425
90	54	0.417
100	53	0.357
110	55	0.340
120	53	0.349
130	52	0.315
140	51	0.306
150	50	0.298
160	50	0.289
170	51	0.289
180	50	0.272
190	50	0.264
200	52	0.264
225	51	0.230
250	52	0.196
275	52	0.170
300	47	0.119

Table 35. Dana, IN - Measured RMS Field Strengths (Measurement Radial Perpendicular to Underground Feedline)

Distance From Tower Base (Feet)	RMS Electric Field Strength (V/M)	RMS Magnetic Field Strength (A/M)
10	349	2.89
20	111	1.48
30	102	0.935
40	81	0.680
50	72	0.510
60	67	0.408
70	64	0.332
80	61	0.281
90	59	0.247
100	57	0.221
120	56	0.179
140	54	0.153
160	55	0.136
180	56	0.128
200	56	0.119
220	56	0.116
240	56	0.108
260	55	1.808
280	52	0.094
300	52	0.088
350	51	0.073
400	47	0.061
450	42	0.050
500	35	0.043
550	30	0.033
600	24	0.026
650	21	0.024
700	17	0.021
750	13	0.018
800	11	0.017
850	9	0.014
900	8	0.013
950	6	0.011
1000	5	0.010

Comments: All Station functions (except housing which is off-site) are performed in a single building which is located about 500 feet from the antenna. Consequently, fields strengths produced by the antenna are low in and around the building. Intense fields generated by the tuning coils and feed lines are found in the Plenum room and inside the transmitter cages. The antenna is surrounded by a fence about 12 feet from the base, and high field strengths were found in and around the fenced area. Magnetic field strengths are also higher near the underground feedline.

Table 36

Station:	SENECA, NY LORAN-C
Peak Power Output:	800 KW
Pearson Current:	750 Amps
Antenna Type:	700' Monopole
Rates(s):	9960 - Master, 8970 - Secondary
RMS-To-Peak-Ratio:	0.0847

	RMS Electric Field Strength (V/M)		RMS Magnetic Field Strength (A/M)	
Area	Typical	Local Maxima	Typical	Local Maxima
Inside				
Generator Room	<1		0.026	0.051
Shop	<1		0.009	0.034
Garage	<1	4	0.009	0.042
Mechanical Room	<1		0.009	0.051
Secure Storage	<1		0.009	0.017
Office	<1		0.017	0.068
Hallway	<1		0.004	0.013
Day Room	<1		0.042	
Bunk Room	<1		0.042	
Storage Room	<1		0.011	
Operations Room	1	3	0.034	0.068
Transmitter Room				
Near Desk	<1		0.034	
Near Entrance	<1		0.042	
Near Active Tx	1	17	0.424	>5.7
Open Areas	<1	1	0.170	0.339
Outside				
At Tower Fence	170	212	1.70	2.1
Inside Fence				
Under Feed	76		>5.7	
Near Insulator	2405		5.3	
3'From Fence	254		2.54	
Near top Radial Anchors	6		0.013	
Parking Lot				
Away From	17		0.170	
Middle	30		0.254	
Near Tower	42		0.474	0.643

Table 37. Seneca, NY - Measured RMS Field Strengths (Measurement Radial Bisecting Support Guys and Under a Top Radial)

Distance From Tower Base (Feet)	RMS Electric Field Strength (V/M)	RMS Magnetic Field Strength (A/M)
13	212	2.12
20	110	1.71
30	86	1.07
40	69	0.742
50	57	0.551
60	56	0.449
70	53	0.390
80	49	0.339
90	47	0.305
100	45	0.271
110	45	0.271
120	43	0.245
130	42	0.220
140	45	0.212
150	42	0.204
160	42	0.204
170	41	0.187
180	40	0.178
190	41	0.161
200	39	0.153
210	35	0.144
220	35	0.136
230	31	0.136
240	28	0.136
250	24	0.127

Table 38. Seneca, NY - Measured RMS Field Strengths (Measurement Radial Along Support Guy and Bisecting Two Top Radial)

Distance From Tower Base (Feet)	RMS Electric Field Strength (V/M)	RMS Magnetic Field Strength (A/M)
13	212	2.08
20	127	1.49
30	97	1.03
40	73	0.778
50	62	0.619
60	56	0.517
70	53	0.441
80	49	0.390
90	48	0.356
100	47	0.322
125	44	0.254
150	43	0.212
175	42	0.178
200(Near Guy Wire Anchor)	41	0.170
225	41	0.161
250	40	0.119
275	38	0.102
300	37	0.093
350	33	0.093
400(Near Guy Wire Anchor)	25	0.083
450	21	0.066
500	23	0.053
550	20	0.046
600(Near Guy Wire Anchor)	18	0.041
650	16	0.035
700	12	0.031
750	8	0.027
800	8	0.024
850	6	0.021
900	6	0.021
950	6	0.020
1000	6	0.013

Comments: This station is located on a fenced Army base and is not accessible to the public. The single administration and operations building is located next to antenna resulting in relatively high magnetic field strengths in the parking lot. Indoor field strengths are low except in the transmitter room which also houses the tuning coils. Highest field strengths were found at various points near the active transmitter especially at the end containing the tuning coils. Away from the active transmitter, field strengths were typically above the lowest EPA proposed standard but below the ACGIH standard. Living quarters are located on the Army base, but far away from the antenna.

Table 39

Station:	Nantucket, MA LORAN-C
Peak Power Output:	350 KW
Pearson Current:	620 Amps
Antenna Type:	625' Monopole
Rate(s):	9960 - Secondary, 5930 - Secondary
RMS-To-Peak-Ratio:	0.0928

Area	RMS Electric Field Strength (V/M) Typical	RMS Electric Field Strength (V/M) Local Maxima	RMS Magnetic Field Strength (A/M) Typical	RMS Magnetic Field Strength (A/M) Local Maxima
Inside Tx Building				
Near Wall Facing Tower	3	9	1.49	1.67
Exit Near Tower	3		0.686	
Near Active Tx	1	4	0.34-0.61	>5.7
Between Tx	1	13	0.622	0.713
Near Standby Tx	2		0.148	0.585
Near Control Room Door	1	1	0.093	0.121
Control Room	1		0.148	0.204
Exit	1		0.121	
Desk	1		0.148	
Restroom	1		0.204	
Inside Mechanical Building	1		0.093	
Desk Nearest To Tower	2		0.343	
Near Wall Facing Tower		1		1.36
Near Exit Door		12	0.214	0.984
Near Workbench	1		0.061	
Desk Opposite Tower	1		0.111	
Maintenance Shop	<1		0.006	
Police Barracks	<1		0.014	
Old Control Bldg.	<1		0.005	
Police Barracks Parking	4		0.011	
Public Road by Station	6		0.014	
Admin. Bldg. - Outside	5	7	0.014	0.033
Admin. Bldg. - Inside	<1	1	0.014	0.074
Barracks -Outside	3		0.012	
Barracks - Inside	<1	1	0.007	0.037
Fence at Nearest Private Residence	3		0.006	
Last Housing Unit - Outside	4		0.009	0.011
Last Housing Unit - Inside	<1	2	0.010	0.046
Playground	3	10	0.007	0.012
Antenna Fence	74		1.51	
Near Antenna Base	1856		>6.4	
Under Feed			>8.6	
6'From Tower	566		3.39	
10'From Tower	185		2.32	
Parking Lot	63		0.557	1.11

Table 40. Nantucket, MA - Measured RMS Field Strengths (Measurement Radial Bisecting Support Guy Wires)

Distance From Tower Base (Feet)	RMS Electric Field Strength (V/M)	RMS Magnetic Field Strength (A/M)
20	63	1.15
30	64	0.813
40	64	0.706
50	61	0.613
60	61	0.529
70	61	0.464
80	63	0.408
90	62	0.352
100	63	0.315
110	62	0.288
120	64	0.260
130	64	0.241
140	64	0.213
150	63	0.204
160	63	0.186
170	63	0.176
180	63	0.167
190	63	0.158
200	63	0.148
250	63	0.111
300	61	0.084
350	60	0.064
400	56	0.062
450	48	0.053
500	41	0.039
550	34	0.027
600	26	0.021
650	21	0.027
700	16	0.019
750	13	0.015
800	10	0.014

Table 41. Nantucket, MA - Measured RMS Field Strengths (Measurement Radial Along Station Road)

Distance From Tower Base (Feet)	RMS Electric Field Strength (V/M)	RMS Magnetic Field Strength (A/M)
100	59	0.260
150	61	0.167
200	61	0.130
250	62	0.102
300	61	0.091
350	56	0.074
400	53	0.061
450	44	0.052
500	39	0.044
550	31	0.036
600	25	0.031
650	19	0.024
700	16	0.021
750	13	0.018
800	11	0.019
850	9	0.021
900	7	0.016
950	6	0.014
1000	5	0.012

Comments: The antenna for this station is located between the transmitter and mechanical buildings which are separated by about 30 feet. High field strengths were found in the adjacent parking lot and inside the buildings near the walls facing the tower. On base single and family housing units are located about 1000 feet from the tower, and field strengths in and around the units are below the lowest EPA option.

Table 42

Station: Carolina Beach LORAN-C
Peak Power Output: 550 KW
Pearson Current: 640 Amps
Antenna Type: TIP
Rate(s): 9960 - Secondary, 7980 - Secondary
RMS-to-Peak Ratio: 0.0850

Area	RMS Electric Field Strength (V/M)		RMS Magnetic Field Strength (A/M)	
	Typical	Local Maxima	Typical	Local Maxima
Signal Building				
Generator Room	<1		0.043	0.068
CO Office	<1		0.026	0.031
Bunk Room	<1	3	0.037	
Recreation Room	<1	1	0.031	
Office	<1	1	0.060	
Entrance Hallway	<1		0.068	
Sitting Room	<1	1	0.111	0.247
Near Conduit		3		0.510
Electronics Shop	<1	1	0.162	0.238
Near Conduit		4		1.62
Signal Room	<1		0.004	0.009
Transmitter Building				
Entrance Area	1	52	0.085	0.170
Between Tx's	<1	9	0.085	1.87
Near Active Tx		170		>5.7
Near Standby Tx	1	9	0.255	3.49
Near Side Exit	1	9	0.255	
Fro. . of Tuning Coils	5	14	0.255	0.680
Side of Tuning Coils		340		5.1
Barracks - Inside	<1	1	0.043	0.077
- Outside	18		0.094	
Volley Ball Court	27		0.213	
Parking Lot	4		0.264	
Next to Tx Building	38		0.366	0.502
On Support Tower	<1	47	0.170	0.425
At Feedpoint Fence	85	1	2.13	2.2
Inside Feedpoint Fence	1530	179	3.8	

Table 43. Carolina Beach, NC - Measured RMS Field Strengths (Measurement Radial Bisecting Support Towers)

Distance From Feedpoint (Feet)	RMS Electric Field Strength (V/M)	RMS Magnetic Field Strength (A/M)
11	94	2.14
20	85	1.28
30	80	0.893 - 0.978
40	77	0.680 - 0.772
50	73	0.553 - 0.629
60	69	0.485 - 0.544
70	64	0.425 - 0.468
80	61	0.374 - 0.442
90	58	0.349 - 0.400
100	56	0.323 - 0.374
110	52	0.374
120	50	0.332
130	46	0.306
140	40	0.289
150	40	0.281
160	42	0.255
170	40	0.238
180	38	0.238
190	37	0.213
200	35	0.196
210	33	0.196
220	30	0.187
230	28	0.179
240	27	0.170
250	25	0.170
260	23	0.170
270	22	0.170
280	22	0.170
290	21	0.162
300	18	0.153
350	21	0.128
400	18	0.111
450	16	0.085
500	13	0.085

Table 44. Carolina Beach, NC - Measured RMS Field Strengths (Measurement Radial Along Station Road)

Distance From Feedpoint (Feet)	RMS Electric Field Strength (V/M)	RMS Magnetic Field Strength (A/M)
50	38	0.366 Next to Tx Bldg.
100	47	0.502
150	38	0.264
200	27	0.213
250	23	0.187
300	20	0.128
350	18	0.094
400	17	0.085
450	16	0.077
500	14	0.077
550	13	0.068
600	13	0.068
650	11	0.067
700	10	0.061
750	10	0.059
800	9	0.050
850	9	0.043
900	11	0.037
950	7	0.037
1000	4	0.033

Comments: Station functions are housed in three buildings including a signal building, transmitter building, and barracks. The buildings are located underneath the antenna structure resulting in relatively high outdoor fields (parking lot, volley ball court, etc), although most exposures are far below the ACGIH standard. High field strengths were measured near the active transmitter, near the tuning coils, and around the feedpoint. Most indoor exposures were very low except near the fire alarm system conduit where higher magnetic fields were caused by induced currents. These fields were examined using the Ailtech loop antenna and oscilloscope to insure that measured fields were due to LORAN-C, and not 60 Hz currents.

Table 45

Station: Upolu Point, HI LORAN-C
Peak Power Output: 250 Kw
Pearson Current: 500 Amps
Antenna Type: 625'Monopole
Rate(s): 4990 - Secondary
RMS-To-Peak-Ratio: 0.0801

	RMS Electric Field Strength (V/M)		RMS Magnetic Field Strength (A/M)	
Area	Typical	Local Maxima	Typical	Local Maxima
Signal Building	<1	1	0.002	0.004
Outside	1		0.003	
Visitor Parking	4		0.008	
Transmitter Building	1		0.080	
Between Tx's	1		0.320	
Near Active Tx	2	3	>5	
Near Coils			>5	
Parking Lot	35		0.192	0.328
Outside by Door	8		0.505	
At Tower fence	128		1.7	
Nearest Tower Base	705		3.2	>10
Nearest housing				
Inside	<1		0.009	0.012
Outside	5		0.010	
Bachelor's Quarters				
Inside	<1		0.008	
Outside	3		0.008	
Playground	2	8	0.006	0.008
Beach	2		0.004	

Table 46. Upolu Point, HI - Measured RMS Field Strengths (Measurement Radial Towards Ocean)

Distance From Tower Base (Feet)	RMS Electric Field Strength (V/M)	RMS Magnetic Field Strength (A/M)
11	128	1.5
20	72	0.937
30	56	0.657
40	50	0.505
50	43	0.409
60	40	0.344
70	40	0.288
80	37	0.256
90	38	2.224
100	36	0.200
110	37	0.184

Table 47. Upolu Point, HI - Measured RMS Field Strengths (Measurement Radial Along Road)

Distance From Tower Base (Feet)	RMS Electric Field Strength (V/M)	RMS Magnetic Field Strength (A/M)
100	40	0.224 - 0.264
150	40	0.136 - 0.160
200	42	0.104 - 0.112
250	42	0.080 - 0.088
300	38	0.076
350	44	0.062
400	34	0.048
450	26	0.040
500	22	0.034
550	18	0.030
600	14	0.024
650	12	0.019
700	9	0.017
750	7	0.014
800	6	0.010
850	5	0.010
900	4	0.009
950	4	0.008
1000	3	0.008

Comments: On-base housing units at this station are located outside the top-radial anchors resulting in low overall exposures in and around the units. High field strengths were found only near the tower base and inside the Transmitter building close to the coils. The Signal building and administrative office are over 1000 feet from the tower.

Table 48

Station:	Jupiter, FL LORAN-C
Peak Power Output:	325 Kw
Pearson Current:	630 Amps
Antenna Type:	625' Monopole
Rate(s):	7980 - Secondary
RMS-To-Peak-Ratio:	0.0633

	RMS Electric Field Strength (V/M)		RMS Magnetic Field Strength (A/M)	
Area	Typical	Local Maxima	Typical	Local Maxima
Transmitter Building				
Timer Room	<1	2	0.063	0.108
Bathroom	<1	2	0.063	0.108
Transmitter Room	1		0.127 - 0.209	0.392
Near Tuning Coil	8	9	1.46	3.77
Old Tx Building	<1		0.019	0.190
Signal Building	<1		0.004	
Parking Lot	3		0.008	
Garage	<1		0.004	0.006
Generator room	<1		0.004	0.006
Shop	<1		0.005	0.007
Waiting Room	1		0.004	
Barracks	<1		0.003	0.004
Parking Lot	2		0.005	
Near Tower fence	38		1.34	
Station Entrance	3		0.008	
180' South of Entrance	4		0.008	
Near Ungrounded Guy Segment West of Tower	70		0.063	

Table 49. Jupiter, FL - Measured RMS Field Strengths (Measurement Radial West of Tower)

Distance From Tower Base (Feet)	RMS Electric Field Strength (V/M)	RMS Electric Field Strength (A/M)
10	28	1.39
20	35	0.804
30	39	0.582
40	38	0.456
50	37	0.373
60	37	0.317
70	38	0.272
80	38	0.241
90	39	0.215
100	39	0.196
110	39	0.177
120	35	0.158
130	36	0.146
140	36	0.139
150	36	0.127
160	35	0.120
170	35	0.114
180	35	0.108
190	35	0.101
200	35	0.095
220	34	0.089
240	35	0.076
260	35	0.070
280	35	0.063
300	36	0.063
320	37	0.063
340	36	0.056
360	38	0.051
380	38	0.047
400	36	0.043
420	31	0.040
440	30	0.037
460	29	0.034
480	28	0.031
500	28	0.029
550	23	0.030
600	17	0.022

Table 50. Jupiter, FL - Measured RMS Field Strengths (Measurement Radial Along Road To Tx Building)

Distance From Tower Base (Feet)	RMS Electric Field Strength (V/M)	RMS Magnetic Field Strength (A/M)
100	34	0.203
120	37	0.158
140	38	0.139
160	37	0.120
180	39	0.114
200	39	0.101
250	37	0.082
300	39	0.070
350	36	0.060
400	35	0.049
450	29	0.040
500	27	0.033
550	23	0.028
600	19	0.024
650	15	0.022
700	13	0.021
750	10	0.020
800	8	0.017
850	6	0.013
900	5	0.011
950	4	0.008
1000	3	0.006

Comments: All buildings except the transmitter building are located over 1000 feet from the antenna. Field strengths around these buildings, including the barracks, are well below the lowest EPA option. High field strength were found around the tuning coils and the tower fence which connects to the transmitter building and is about 10 feet from the tower.

Table 51

Station:	LaMoure, ND OMEGA
Peak power Output:	10 kW
Pearson Currents:	382,316,316,414,308,375,316,316 Amps
Frequencies:	11.05,13.1,13.1,10.2,13.6,11.33 13.1, 13.1
Antenna Type:	1200' Monopole
RMS-To-Peak Ratios:	0.468 - E, 0.544 - H

Area	RMS Electric Field Strength (V/M) Typical	RMS Electric Field Strength (V/M) Local Maxima	RMS Magnetic Field Strength (A/M) Typical	RMS Magnetic Field Strength (A/M) Local Maxima
Transmitter Building				
Parking Lot	122		0.027	
Outside Front	108		0.022	
Back	136		0.044	
Garage	1		0.001	
DC Shop	1		0.011	
Generator Room	1		0.033	
CO Office	5		0.027	
XPO office	6		0.011	
Lounge	5		0.005	
Other offices	4		0.011	
Dummy Load Rm	1		0.016	
Elec. Shop	2		0.011	
Screen room	3		0.038	0.125
Tx Room	2		0.011	0.022
Battery room	<1		0.022	0.049
Mech. Room	3		0.022	0.033
GP building - Inside	<1		0.005	
Back	28		0.022	
Parking Lot	28		0.011	
Helix Building	1	2	0.544	
Inside Standby Tuner	1			7.1
Front of Active Tuners	1		1.58	4.7
Parking Area	702		1.8	2.3
Road by Tower Wall		1357-3416		
Wall Opposite Helix Bldg.		4493	3.1-4.5	
Wall Opposite Road		3931	2.2	
Perimeter Road	42		0.011	
Near Top Radial Anchor	33		0.011	
Station Entrance	6		<0.001	

Table 52. LaMoure, ND - Measured RMS Field Strengths (Measurement Radial Along Road Away From Signal Building)

Distance From Tower Base (Feet)	RMS Electric Field Strength (V/M)	RMS Magnetic Field Strength (A/M)
35	3400	2.9
36.4	3800	2.7
40.3	4400	2.6
46.1	3700	2.7
53.2		2.3
61.0	2600	2.0
69.5	2200	1.8
78.3	2200	1.6
87.3	1640	1.4
96.6	1690	1.4
106.0	1310	1.3
125.0		1.2
144.3	1170	1.1
163.8	1120	0.92
183.4	1030	0.87
203.0	980	0.76
252	840	0.60
302	702	0.51
352	608	0.44
402	608	0.37
451	562	0.34
501	608	0.29
551	608	0.25
601	562	0.22
701	515	0.18
801	562	0.16
901	468	0.14
1001	468	0.10
1100	337	0.08
1200	253	0.07
1300	290	0.05
1400	229	0.05
1500	215	0.04
1600	159	0.04
1700	131	0.03
1800	103	0.03
1900	98	0.02
2000	84	0.02
2100	66	0.02

Table 53. LaMoure, ND - Measured RMS Field Strengths (Measurement Radial Along Road Towards Signal Buildings)

Distance From Tower Base (Feet)	RMS Electric Field Strength (V/M)	RMS Magnetic Field Strength (A/M)
100	1357	1.9
200	842	0.71
300	655	0.44
400	608	0.38
500	608	0.27
600	468	0.22
700	468	0.17
800	468	0.14
900	421	0.12
1000	453	0.09
1100	393	0.08
1200	337	0.07
1300	318	0.06
1400	206	0.05
1500	136	0.04
1600	136	0.03
1700	108	0.02

Comments: Very high electric field strengths were found around the Helix building and for several hundred feet in all directions. Field strengths near the other station buildings (located over 1500 feet away) are well below the ACGIH standard but in some areas above the lowest EPA option. Indoor field strengths are far less than the lowest EPA option, but a distance of 2000 feet from the tower is required for outdoor exposures below this level.

Table 54

Station: Kaneohe, HI OMEGA
Peak Power Output: 10 kW
Pearson Currents: 389, 389,446,333,402,389,389,410
Frequencies: 11.8,11.8,10.2,13.6,11.3,11.8,11.05
Antenna Type: Valley Span
RMS - To - Peak Ratio: 0.507 - E, 0.570 - H

Area		RMS Electric Field Strength (V/M) Typical	Local Maxima	RMS Magnetic Field Strength (A/M) Typical	Local Maxima
Subdivision Near Station		4		0.005	
Station Main Gate		7		0.021	
Near Building 9		14		0.037	
Station Road-Point	A	245		0.346	
(see Fig. 40)	B	101		0.532	
	C	339		0.483	
	D	66		0.272	
	E	95		0.216	
	F	5		0.117	
Hikers Parking Area	G	48		0.115	
	H	5		0.060	
	I	6		0.052	
	J	23		0.089	
	K	30		0.189	
	L	128		0.307	
	M	102		0.318	
Quarantine Bldg-Parking		3		0.041	
Maintenance Ladder					
Near Beginning		87		0.147	
Segment 87		114		0.189	0.456
Top of 1st Vertical Ascent		118		0.176	
Proposed H-3 Site		216-236		0.351 (Near Pier 3)	
Counterweight Tower					
Center		963		0.296	0.351
Near Rails		1977		0.855	
Corner		2636		0.342	
Above Co's Head		2231			
While Holding Rail		2636			
Near Ladder		2332		0.798	
Near Cable					

OMSTA HAWAII

STATION ROAD & BUILDINGS

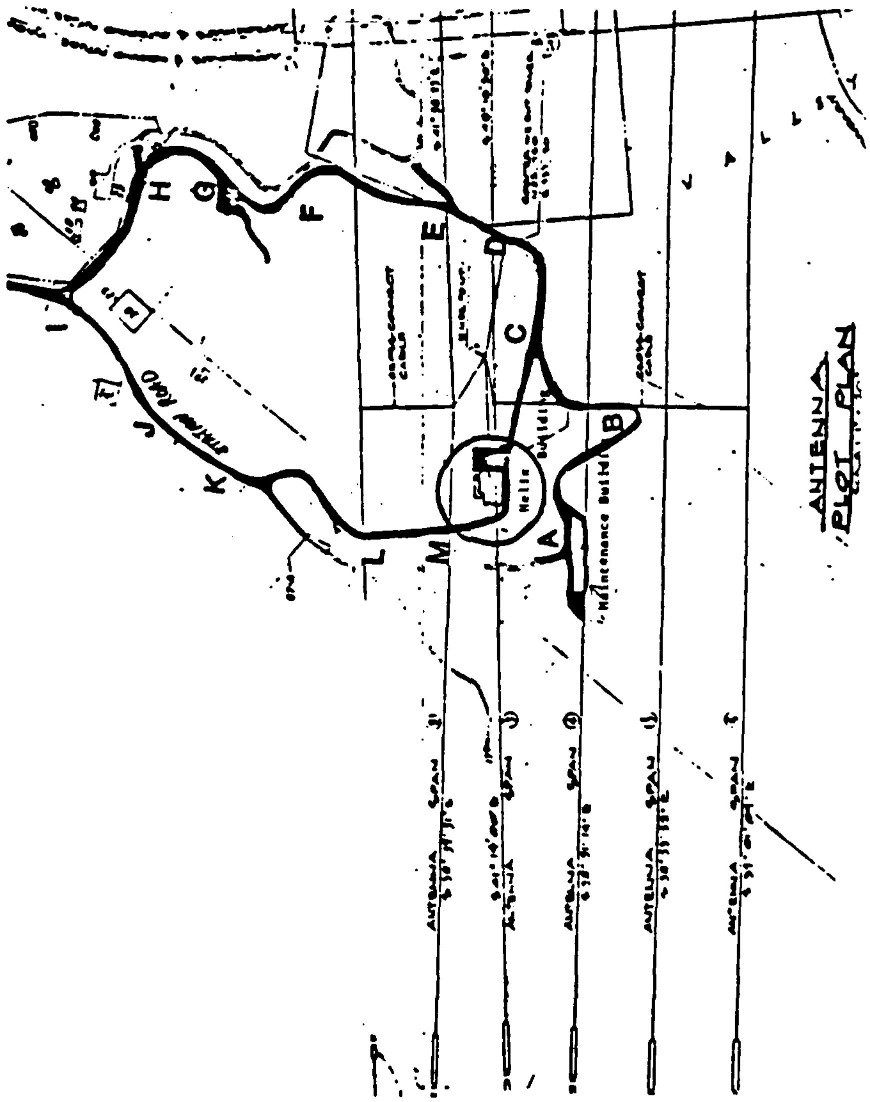


Figure 40. Kaneohe OMEGA station road measurement locations

Table 55. Kaneohe, HI - Station Building Electric Fields (See Fig. 41)

Location	Peak Electric Field Strength (V/M)	RMS Electric Field Strength (V/M)
A	211	107
B	281	143
C	255	129
D	336	170
E	653	331
F	312	158
G	382	194
H	875	443
I	831	421
J	717	363
K	1849	938
L	608	308
M	1486	754
N	1947	987
O	714	362
P	1105	560
Q	1463	742
R	1039	527
S	550	279
T	191	97
U	116	57
Station Road		
Far edge of parking lot	1300	659
25 feet past edge	1367	693
50 feet past edge	1253	635
75 feet past edge	1063	539
100 feet past edge	970	492
First Deck	1-4	0-2

OMSTA HAWAII

STATION BUILDING

E Field Measurements

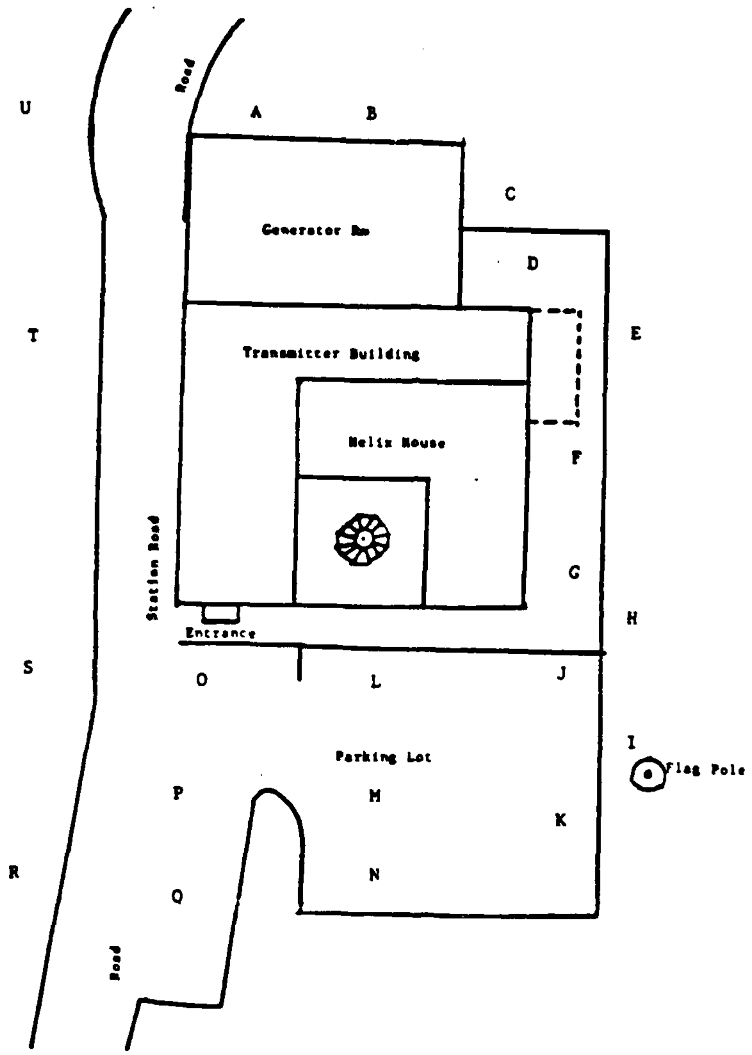


Figure 41. Kaneohe OMEGA station building E field measurement locations

Table 56. Kaneohe, HI - Station Building Magnetic Fields (See Fig. 42)

Location	Peak Magnetic Field Strength (A/M)	RMS Magnetic Field Strength (A/M)
A'	2.57	1.46
B'	2.13	1.21
C'	2.59	1.47
D'	2.83	1.62
E'	2.66	1.52
F'	3.62	2.06
G'	3.84	2.19
H'	4.29	2.44
I'	5.98	3.41
J'	7.73	4.40
K	6.53	3.72
L'	5.38	3.07
M'	6.81	3.88
N'	4.95	2.82
O'	3.66	2.09
P'	2.82	1.61
Q'	6.50	3.71
Entrance	6.64	3.79
Station Road		
Far edge of parking lot	3.35	1.91
25 feet past edge	2.77	1.58
50 feet past edge	2.56	1.29
75 feet past edge	2.06	1.18
100 feet past edge	2.05	1.17
First Deck		
Generator Room	0.1-1.0	0.057-0.570
Tx Room	0.1-1.0	0.057-0.570
Electronics Workshop	0.02-1.5	0.011-0.855
CO office	0.1-0.15	0.057-0.086
Adm Office	0.1-0.25	0.057-0.143
Break Room	0.15	0.086
Entry Room	0.2-0.3	0.114-0.171
Screen Room	0.05	0.029

OMSTA HAWAII

STATION BUILDING

H Field Measurements

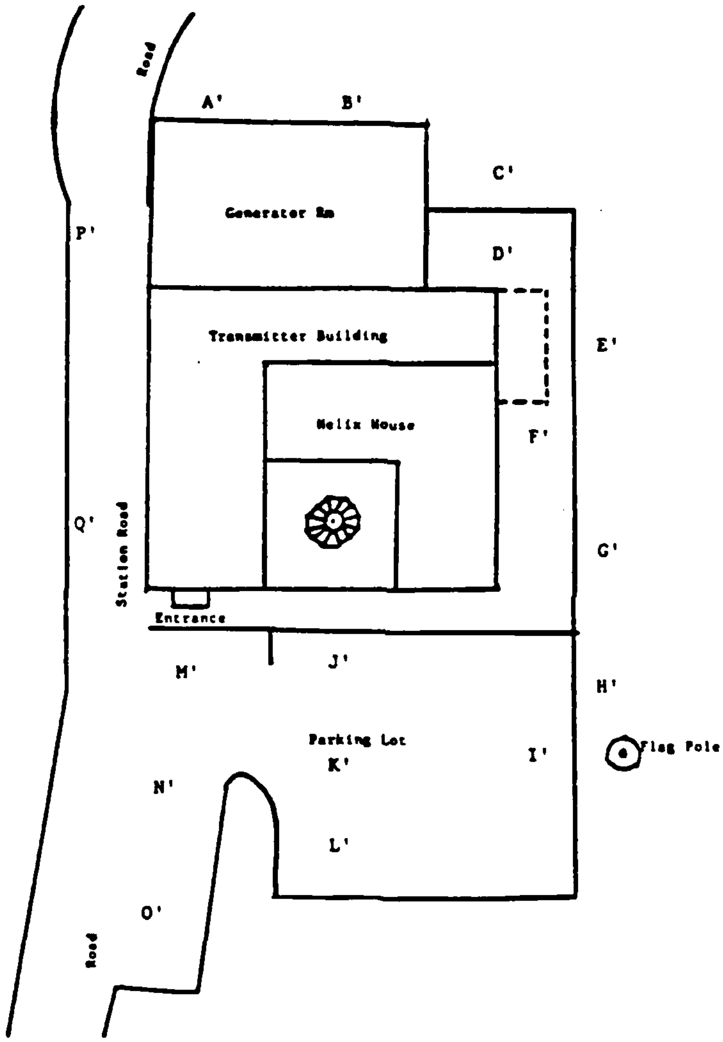


Figure 42. Kaneohe OMEGA station building H field measurement locations

Table 57. Kaneohe, HI - Station Building, Second Deck Field Strength

Location	RMS Electric Field Strength (V/M)	RMS Magnetic Field Strength (A/M)
Tech. Offices	2 - 8	0.285 - 1.03
Recreation Room	10 - 18	0.228 - 0.342
Dummy Load Rm. (Near Feed)		0 - 8.55
Open Air Deck		
Near Feed Line	262	1.83
Middle	167 - 421	
Far Side	321	3.27

Table 58. Kaneohe HI - Station Building, Third Deck Electric Field Strengths (See Fig. 43)

Location	Peak Electric Field Strength (V/M)	RMS Electric Field Strength (V/M)
A	436	221
B	714	362
C	831	421
D	1136	576
E	244	123
F	307	156
G	1122	569
H	1449	735
I	2834	1437
J	2002	1015
K	2	1
L	1	1
M	2	1
N	1	1
O	4	2
P	2	1
Q	3	2

OMSTA HAWAII

3rd DECK–HELIX BUILDING

E Field Measurements

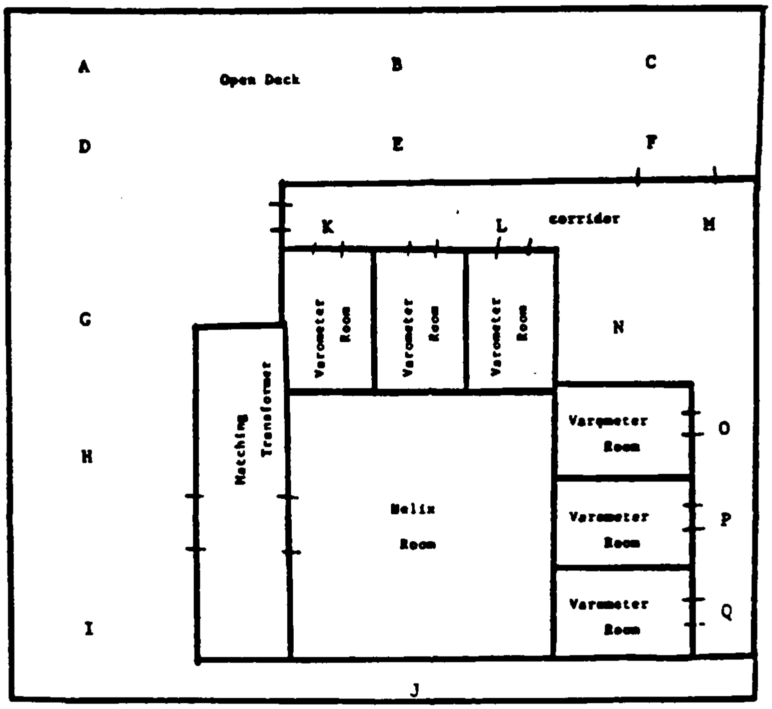


Figure 43. Kaneohe OMEGA third deck E field measurement locations

Table 59. Kaneohe, HI Station Building, Third Deck Magnetic Field Strengths (See Figure 44)

Location	Peak Magnetic Field Strength (A/M)	RMS Magnetic Field Strength (A/M)
A'	4.54	2.59
B'	4.63	2.64
C'	5.24	2.99
D'	7.28	4.15
E'	9.43	5.38
F'	0.860	0.490
G'	0.412	0.235
H'	0.104	0.059
I'	1.73	0.990
J'	1.21	0.690
Corner Near Feed	19.8-31.4	11.3-17.9
Under Feed	12.7	7.26
Near Matching Transformer	1.97	1.13
Spare Varometer Room	0.271	0.155

Comments: High electric and magnetic field strengths occur near the station building due to the feedline which extends from the building top to the antenna spans. Field strengths drop off quickly with distance but are above the lower EPA options in several areas on the property. The roughness of the terrain produces significant electric field variations over short distances. Electric field strengths measured on the maintenance ladder were above the lowest EPA option, but outside the property boundaries field strengths dropped to negligible values (more than an order of magnitude below the lowest EPA option). Painful shocks were experienced in the station parking lot when grounded and in contact with large vehicles.

OMSTA HAWAII

3rd DECK–HELIX BUILDING

H Field Measurements

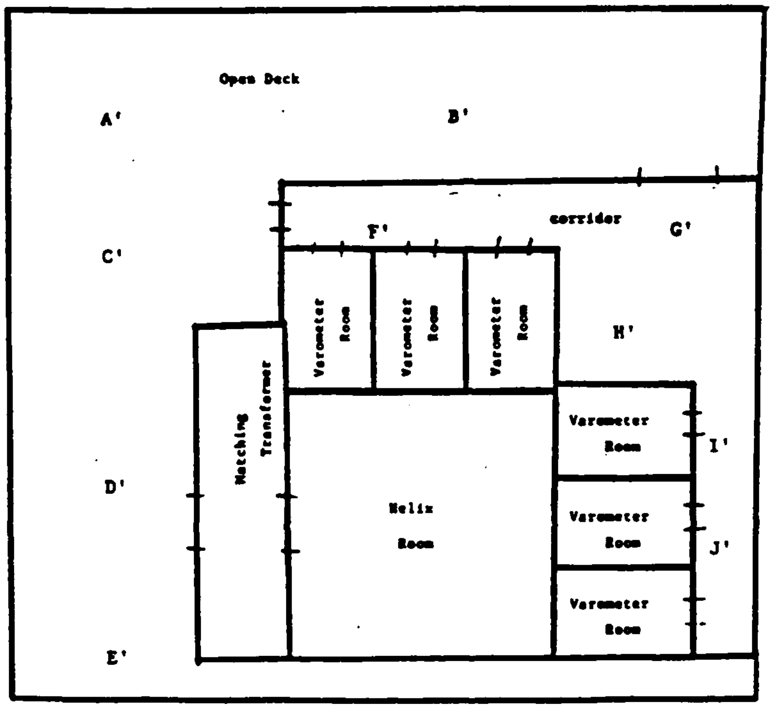


Figure 44. Kaneohe OMEGA third deck H field measurement locations

Table 60. Distances From Feedpoints Required to Meet EPA Proposed Standards (see Table 69 for list of EPA limiting values)

	Required Distance From Feedpoint (Feet)					
Station	87 V/M	0.23 A/M	275 V/M	0.73 A/M	614 V/M	1.63 A/M
Searchlight	<12	100	<12	25	<12	<12
Port Clarence	38	47	<6	<6	<6	<6
George	55	225	<20	70	<20	33
Dana	37	95	13	38	<7	19
Seneca	34	139	<13	43	<13	21
Nantucket	13	133	9	38	6	15
Carolina Beach	18	183	<11	40	<11	16
Upolu Point	18	100	<11	28	<11	12
Jupiter	<10	85	<10	28	<10	<10
LaMoure	2000	600	1350	225	350	80

Chapter VIII. On-Tower Field Strengths

Exposure of tower climbers to the intense electromagnetic fields on energized or "hot" towers is an area of concern to the Coast Guard. Certain maintenance and repair practices require that Coast Guard personnel climb the antenna towers during regular operation to avoid interruption of navigational services. High winds, rain and fog prevented on-tower measurements at most of the stations visited for this study, but climbs were accomplished on energized towers at Dana, Nantucket, Upolu Point and on a grounded support tower at George, WA. Maintenance operations on OMEGA antennas are performed only during specified periods when the system is de-energized, and on-tower measurements are not required.

The field measurements were performed by certified tower climbers who were given instruction in use of the electric and magnetic field strength instruments prior to climbing. Instrument readings were radioed down and recorded from the ground. Measurements were taken at a number of locations along the towers beginning at the mounting point and ending at the tower top. At each point, field strengths inside and outside the tower were recorded. The towers were mounted by leaning a non-conductive ladder against the tower (above the base insulator) and climbing onto the tower so that contact with the ground and tower never occurred simultaneously. Normally, the mounting process is the only time that the climber is positioned outside the tower. Climbing is accomplished on a metal ladder which is secured to the inside of the tower and includes a center slip rail for attachment of safety gear.

There is some misunderstanding among many of the tower climbers and technicians as to the existence of fields inside the tower. The general belief is that fields are present only on the outside of the tower and that no exposures occur inside the tower. This concept probably derives from the textbook case of perfectly symmetrical conductors and is only partially true in regard to antenna towers. Considering electric fields first, it can be demonstrated that the electric fields inside a conductor are zero for the electrostatic case and approximately so for the quasi-static case involved here. This cancellation of interior fields depends on charge distribution across the conductor surface. Because the tower does not present a closed surface, only partial cancellation occurs inside the structure. Electric field strengths are far more intense outside the tower, but substantial interior fields can occur. Magnetic field strengths depend on current distribution, and total cancellation of interior fields occurs in the case of a cylindrical conductor. Tower currents are confined to the tower legs, cross supports and ladder resulting in an uneven current distribution and interior fields. As for electric fields, the magnetic field strength is greatest just outside the tower, but substantial fields occur inside the tower. Interior magnetic field strengths are generally lowest in the center of the tower and highest near the tower legs and other conductors. The highest electric field strengths occur at the tower top and near the base insulator. Magnetic field strengths are highest near the tower base and feedline and lowest at the tower top.

The on-tower measurement results are presented in Tables 61-64. Heights of the measurement points were estimated by counting tower sections and are approximate. Measurements were performed using the Coast Guard electric and magnetic field strength meters and the Ailtech loop antenna directly connected to a shielded Tektronix 212 battery-operated oscilloscope.

Table 61. On-Tower Field Strength Measurements for Dana, IN LORAN-C

	Electric Field Strength (V/M)		Magnetic Field Strength (A/M)	
Location	Peak	RMS	Peak	RMS
Climb-on Point				
Inside	1800	153	61	5.2
Outside	9300	791	64	5.4
First Platform (45')				
Inside	800	68	63	5.4
Outside	9200	782	63	5.4
Second Platform (120')				
Inside	700	60	62	5.3
Outside	3300	281	63	5.4
Middle (312')				
Inside	230	20	32	2.7
Outisde	1200	102	61	5.2
Next Platform (500')				
Inside	267	23	50	4.3
Outside	976	83	61	5.2
Top Platform				
Inside	3800	323	0.82	0.070
Outside	61200	5202	1.09	0.093

Table 62. On-Tower Field Strength Measurements for Nantucket, MA LORAN-C

	Electric Field Strength (V/M)		Magnetic Field Strength (A/M)	
Location	Peak	RMS	Peak	RMS
Climb-On Ladder	10800	1405		
Climb-On Point				
Inside	600	56	32	3.0
Outside	4500	419	66	6.1

Table 63. On-Tower Field Strength Measurements for Upolu Point, HI LORAN-C

Location	Electric Field Strength (V/M) Peak	RMS	Magnetic Field Strength (A/M) Peak	RMS
Climb-On Point (15')				
Inside	2385	191	34.8	2.8
Outside	9652	773	63	5.0
Near Tower Leg			80	6.4
Platform (115')				
Inside	943	76	53	4.2
Outside	3140	252	60	4.8
Platform (230')				
Inside	469	38	32	2.6
Outside	1972	158	67	5.4
Platform (350')				
Inside	374	30	46	3.7
Outside	943	76	65	5.2
Platform (470')				
Inside	342	27	39	3.1
Outside	1001	80	66	5.3
Top (625')				
Inside	1805	145	2.3	0.184
Outside	10189	816	1.51	0.121

Table 64. On-Tower Field Strength Measurements for George, WA LORAN-C (Grounded Support Tower)

Location	Electric Field Strength (V/M) Peak	RMS	Magnetic Field Strength (A/M) Peak	RMS
First Platform (15')				
Inside	18	2	1.6	0.149
Outside			4.4	0.409
Second Platform (90')				
Inside	273	25	3.5 (Near Leg)	0.326
Outside	685	64	5.0	0.465
Third Platform (180')				
Inside	272	25	2.6	0.242
Outside	1333	124	5.2	0.484

Fifth Platform (300')				
Inside	282	26	2.6	0.242
Outside	2100	195	4.5	0.419
Seventh Platform (440')				
Inside	589	55	2.3	0.214
Outside	2800	260	3.4	0.316
Ninth Platform (625')				
Inside	1500	140	1.7	0.158
Outside	5300	493	2.8	0.260
Top (700')				
Inside	4100	381	0.605	0.056
Outside	15400	1432	0.815	0.076
2.5' Above Top Rail	5900	549		

Chapter IX. Shock Hazard and Body Current Measurements

In addition to determination of exposure levels, the possibility of shock hazards near LORAN-C and OMEGA stations was explored as a part of the present study. Shock hazards can arise from a number of different causes, but the primary case of interest here is that of induced voltages. Simply put, an isolated conductor in an electric field will take on a potential or voltage that is directly related to its position and the associated electric field strength. For a fixed conductor isolated from ground, the induced voltage is proportional to the field strength. Thus, a truck or bus exposed tc a given field strength may develop the same potential as a smaller vehicle exposed to a higher field strength. The shock hazards associated with various field strengths, frequencies, and vehicle sizes have been evaluated in two recent reports on the subject (10) (11).

Operating at higher frequencies and lower voltages, LORAN-C stations create fewer shock situations than do OMEGA stations. The most obvious hazard is the possibility of contact with the tower or feedline. Although the area around these points is fenced, there are occasions when station personnel enter the fenced areas. Another consideration is the possibility of unauthorized persons crossing the fences which are sometimes in disrepair. Outside the fenced areas, electric field strengths are usually too low to produce perceptible shocks on most objects. During the present study, no shocks were encountered when contacting vehicles, fences, or other objects close to LORAN-C feedpoints. At four of the stations, however, shocks were experienced when contacting ungrounded guy wire sections. These sections were isolated from ground by ceramic insulators and within easy reach of ground personnel. Normally, the lowest guy wire insulator is out of reach so that contact can only be made with the grounded section of the guy wire. In the above cases, the low insulator permitted contact with an electrically floating section resulting in a shock as the individual provided a current path to ground.

The guy wire sections described above are located hundreds of feet from the towers where peak electric field strengths range from about 75 to 800 V/M. High voltages are induced on the sections because of their large vertical extents. If similar sized objects were placed near the towers, higher induced voltages and more severe shocks would result. Shocks experienced on the guy wires were startling and painful, but did not cause a loss of muscle control. The primary hazards here are from startle reactions and accidental fuel ignition, as arcing was demonstrated between the guy sections and grounded cables.

Shock sources were characterized by measuring the open-circuit voltage, V_{oc}, and the short-circuit current, I_{sc}, of the source. Open-circuit voltages were measured using a 10,000:1 high voltage probe and the shielded Tektronix 212 oscilloscope. Short-circuit currents and body currents were measured by grounding the source with a jumper cable whi·h passed through a Pearson 1010 current transformer. Using these techniques, open-circuit voltages of 300-2000 volts and short-circuit currents of 160-300 mA were measured. The stations and measured voltages are shown in Table 65.

Table 65. LORAN-C Stations with Accessible Ungrounded Guy Wire Sections

Station	Voc, Volts Peak	Isc, mA Peak
Dana, IN	300	160
Port Clarence, AK	--	--
Upolu Point, HI	2000	300
Jupiter, FL	1500	150

Body current resulting from contact with an ungrounded guy wire section was measured at Upolu Point, HI. For this experiment the investigator contacted the guy section with one hand which passed through the Pearson monitor. A current of 200 mA through the arm was measured compared to the short-circuit current of 300 mA.

The same procedure was used to measure body currents through tower climbers when they reach the top of the insulating climb-on ladder and grasp the tower. At this time, the climbers are outside the tower structure and exposed to the highest electric field strengths they will encounter during the climb. Most climbers interviewed report a sharp "bite" at contact which can be avoided by slapping the tower or grasping it with a single motion. The reduced sensation experienced when using this technique is due to the increased contact area and resulting lower current density (11). On-tower body current measurements are presented in Table 66.

Table 66. On-Tower Body Current Measurements

Station	Peak Electric Field Strength (V/M)	Peak Current (mA)
Dana, IN	9300	125-260
Nantucket, MA	10,800	100
Upolu Point, HI	9650	40

Shock hazards are far more common around OMEGA stations due to the higher electric field strengths. At the LaMoure, ND OMEGA station, peak electric field strengths as high as 9600 V/M were measured in accessible areas outside the shielded tower fence. The elevated feed point at the Kaheohe, HI OMEGA results in lower values at that station, but peak electric field strengths of 1600-1900 V/M exist over much of the parking area. An additional factor in shock occurrence is that the body is more sensitive to shocks at lower frequencies (10). Near the LaMoure, ND OMEGA, shocks occur frequently within about 100 feet of the tower. During the site visit, shocks were experienced when touching fences or ground rods, when extending a tape measure more than a few feet and when touching isolated objects such as cars. The most common shocks at Kaneohe, HI occur when entering vehicles in the parking lot.

Vehicle shocks result when an individual provides a sufficiently conductive ground path to the ungrounded conductor. The degree of shock depends on the field strength, conductivity of the subject, and the effective height and impedance of the source. Another shock mode occurs when the individual is insulated from ground by shoes or other means and touches a grounded object. Here the field induces a voltage on the body and shock results when the current finds a path to ground. The first mode is generally more severe because higher voltages are induced on large objects such as trucks and the source impedance is lower implying greater current flow.

Experiments were performed at both OMEGA stations to investigate shock hazards near the feed points. Pickup trucks were parked in the high field strength areas, and open-circuit voltages and short-circuit currents were measured. Body currents through the investigator were also measured. It is worth noting that the shocks at both locations were so painful that station personnel went to some lengths to avoid them. The measurement results are shown in Table 67.

Table 67. Shock Measurements at OMEGA Stations - Pickup Truck.

Station	Peak Electric Field Strength (V/M)	Voc-Peak (Volts)	Isc-Peak (mA)
LaMoure, ND			
Pickup to ground	2000	350	30
Body to ground	3000	-	15
Kaneohe, HI			
Pickup to ground	1800	360	20
Through body			15

It is clear that dangerous shocks could result if larger vehicles are brought into these high field strength areas. The shocks may not be perceptible if the subject is insulated from ground, but rain or other conditions which lower overall body impedance will increase the current flow and resulting perception. Body to ground shocks are less severe but can be startling as was experienced on the counterweight tower at Kaneohe, HI. While taking measurements on top of the tower, the investigator experienced somewhat painful shocks when contacting the metal rail or cables near the floor.

Chapter X. Health Effects Review and Questionnaires

This chapter presents some of the relevant exposure standards and discusses some of health effects research to help provide a means for evaluating the modeling and measurement results. Although a respectable amount of research into the biological effects of electromagnetic fields has been performed, the extent, mechanisms, and importance of such effects are not well understood. Of the effects which have been documented, some are clearly harmful while the significance of others is unknown. Most of the proposed and existing safety standards have been developed by identifying known harmful effects and applying a safety factor. These standards are meant to serve as guidelines while further research is being performed, and "should not be regarded as a fine line between safe and dangerous levels" (12). Particular uncertainty arises in attempting to evaluate the safety of exposures to LORAN-C and OMEGA fields because of the lack of health effects data in this frequency range. The issue is further complicated by the unusual modulation characteristics of these signals including the high peak-to-rms ratios of LORAN-C. The brief overview and discussion provided here is in no way intended to be a comprehensive literature review or imply that the effects are well enough understood to be predicted.

Probably the most relevant standard to this study is the ACGIH guideline (12) which has been adopted by the U.S. Coast Guard (see Table 68). This standard is based on the 1982 American National Standards Institute (ANSI) guideline but extends the ANSI 0.3-3 MHz limit of 100 mW/cm^2 down to 10 kHz thereby including LORAN-C and OMEGA sources. The consensus scientific opinion, until recent years, has been that most biological effects of exposure to electromagnetic fields result from energy deposition in the body and the subsequent temperature increase. A measure of the amount of energy absorbed by the body at a given frequency and power density (or field strength) is the specific absorption rate (SAR). When the ANSI C.95.1 (1982) committee reviewed the existing, reproducible experimental data available at that time, they concluded that short-term SARs below 4 W/kg were not associated with harmful effects. Using a safety factor of 10, the committee proposed the present standard which limits SARs to 0.4 W/kg (13). Shortly afterwards, the United States Environmental Protection Agency (EPA) completed a comprehensive literature review (14) with the conclusion that effects, which may be significant, occur at SARs as low as 1 W/kg. Most of the existing standards have been developed by applying a safety factor of 10 or more to the 4 W/kg value.

Table 68. The Coast Guard Occupational Standard

Frequency	Power Density (mW/cm^2)	Elec. Field Strength Squared (V^2/M^2)	Mag. Field Strength Squared (A^2/M^2)
10 kHz - 3 MHz	100	377,000	2.65
3 MHz - 30 MHz	$900/F^2$	$3770 \times 900/F^2$	$900/37.7F^2$
30 MHz - 100 MHz	1	3770	0.027
100 MHz - 1000 MHz	F/100	3770 X F/100	F/37.7 X 100
IGHz - 300 GHz	10	37,700	0.265

F = Frequency in MHz

A consequence of using SARs as the basis is that the standards are frequency dependent, meaning that different exposure levels are permitted at different frequencies. The frequency dependence reflects the fact that the absorption of energy by biological substances varies with frequency (F). In the subresonant region, SARs vary as the square of frequency, as illustrated by the ACGIH limit of $900/F^2$ between 3 and 30 MHz. Below 3 MHz, the permissible exposure is limited to 100 mW/cm^2 to protect against shock and burn hazards. If the frequency dependent curve between 3 and 30 MHz is extrapolated to OMEGA and LORAN-C frequencies, the permissible exposure levels would be 9×10^6 and 9×10^4 mW/cm^2, respectively. These power densities translate to rms field strength limits in the tens to hundreds of kV/M and A/M. Magnetic fields are several times less efficient in coupling energy into the body than electric fields which the SAR limits are based on. Considering this fact and the measurement data presented in this report, it is unlikely that the Coast Guard SAR limit of 0.4 W/kg will be exceeded at LORAN-C and OMEGA stations.

Other national and international standards employ different safety factors in their SAR limits. The National Institute for Occupational Safety and Health (NIOSH) recommends an SAR safety factor 4 times stricter than ANSI and encourages a program of medical surveillance (15) for exposed workers although the standard extends only as low as 300 kHz. A more stringent standard is recommended by the International Radiation Protection Association (IRPA), which incorporates an SAR safety factor of 100 for occupational and 200 for general public exposures. The IRPA general population limit at LORAN-C frequencies is the equivalent to the lowest of three options currently under review by the United States Environmental Protection Agency (16). Of the other options, one is equivalent to the ACGIH standard for frequencies below 3 MHz, and the other is five times lower on the basis of power density. Electric and magnetic field strengths are related to the square root of power density so that a factor of ten in power density is equivalent to a factor of about 3.2 in field strength. Some of the relevant exposure limits at LORAN-C and OMEGA frequencies are summarized in Table 69.

Table 69. Some Exposure limits at LORAN-C and OMEGA Frequencies (Some of the limits do not apply to OMEGA frequencies)

Standard	Power Density (mW/cm^2)	Electric Field Strength (V/M)	Magnetic Field Strength (A/M)
Coast Guard (ACGIH)	100	614	1.64
USSR (Occupational)	-	50	5
IRPA (Occupational)	10	194	0.51
IRPA (General Pop.)	2	87	0.23
EPA Option 1		87	0.23
EPA Option 2		275	0.73
EPA Option 3		614	1.63
NATO		1000	2.6
U.K.NRPB		632	1.63
U.S.A. DOD	100	632	1.58
France (Gen. Public)	1	61	0.16
U.S. Air Force (Occ.)	100	614	1.6
For GWEN System		50	--
Portland, OR	0.5	43	0.12
Multnomah County, OR	20	283	0.71

The SAR criterion used to establish exposure limits for most standards is intended for frequencies above 3 MHz. At lower frequencies, the limiting field strength values are held at the 3 MHz level to protect against shocks and RF burns. Almost none of the health effects research has been performed in the 10 - 100 kHz region except to determine electrical parameters of the body for shock and current density predictions. If shock hazards are eliminated or controlled, then higher exposures at these frequencies may be allowable from a thermal standpoint. As described earlier, very high field strengths are required to produce significant SARs. At 100 kHz, an rms electric field strength of about 2000 V/M is required to produce an SAR of even 0.04 W/kg. On this basis, it appears that field induced thermal effects are unlikely at either LORAN-C or OMEGA stations.

Shock hazards are important for a number of reasons. Most obvious is the possibility of tissue damage or heart fibrillation at high current levels, reducing to involuntary muscle control and startle phenomena at lower levels. Another consideration is the possibility of local or whole body SARs resulting from shock currents. These subjects have been addressed in two recent studies (10) (11) funded by U.S. Air Force School of Aerospace Medicine. Earlier studies by Dalziel (17) (18) (19) (20) (21) quantified human response to shock currents of frequencies up to 10 kHz. One important finding is that physiological sensation decreases with increasing frequency. According to Gandhi, et. al., (11), the threshold for perception increases from 3 - 5 mA at 10 kHz to 30 - 70 mA at 100 kHz. The threshold for pain increases from 6 -10 mA at 10 kHz to 50 - 60 mA at 100 kHz.

Shock currents are generally initiated when the subject contacts a large conductive object of elevated potential. As the size (extent in the field) increases, the electric field strength required to produce a given shock current decreases. Thus, shock standards are often based on the shock currents that can be generated on the largest normally occurring ungrounded conductors in the field. Two common examples are trucks and school buses. At 100 kHz, for example, an RF burn could be received by touching a compact car in a 700 V/M field, while only 350 V/M is required to produce the same effect with a school bus.

As shock currents pass through the body, the current density varies depending on the cross-sectional area through which the current passes. The highest current densities normally occur in wrists and ankles because of their small cross-sectional area. This effect can result in local SARs that exceed the limiting values for some standards. The Coast Guard (ACGIH) standard, for example, limits whole body SARs to 0.4 W/kg and local SARs (over any one gram of tissue) to 8 W/kg. At 10 kHz, the 8 W/kg limit can be exceeded by a current of about 35 mA or contact with a van in a 1000 V/M field. A current of about 60 - 70 mA is required to exceed the standard at 100 kHz which translates to contact with a van in a 250 V/M field (11). The whole body SAR limit of 0.4 W/kg can be exceeded at 2-3 times higher field strengths. All values presented above are for adult subjects and are presented as rms values. Substantially lower currents and field strengths are required to produce the same effects in children.

With sufficient shock effects data available, the question becomes what level of effects must be avoided. Obviously, the severe effects of respiratory constriction and heart fibrillation must be carefully guarded against as well as involuntary muscle control or "let-go" currents. Beyond these severe effects, however, the answer depends on the degree of care taken to avoid shock situations, which primarily consist of grounded personnel contacting ungrounded conductors. Avoiding shock perception entirely would require very low electric field limits if no other controls are employed, although such an approach may be useful in some situations where startle effects could result in a fall or other dangerous reaction. Field strength limits for avoiding shock are still under consideration, but Guy, et. al., (10) have suggested that electric field strengths may have to be limited to values less than 97 V/M to avoid exceeding the 8 W/kg SAR level under certain circumstances.

One of the most controversial issues in recent years has been in regard to the existence and importance of non-thermal effects. Although the 1982 ANSI subcommittee decided that only thermal effects were well documented and understood enough to serve as a basis for standards, the weight of evidence has steadily mounted since that time in favor of non-thermal effects. This term refers to biological responses to electromagnetic fields which are not intense enough to cause significant heating. In other words, the fields are interacting directly with the living system without the intermediary action of heat. The major objections to the existence of these effects by some investigators are that mechanisms for such interactions are not well understood and many of the research results have not been replicated. In at least one sense, it is not surprising that such effects may occur considering the numerous electrical and electrochemical processes underway in the body. On the other hand, electric field strengths inside the body, especially at low frequencies, are orders of magnitude lower than external fields.

At this point in time, the existence of non-thermal effects is well established although their importance is not well understood. A recent report by the National Research Council (NRC) acknowledges the abundance of non-thermal effects reports, but calls for a greater effort to reproduce results and relate them to theoretical mechanisms (22). Several mechanisms have been proposed, but none have been universally accepted, and verification is just beginning. The basic problem is utilization of the small amount of energy coupled from the fields to affect body systems. A review of many of the theories can be found in the recently published CRC Handbook of Biological Effects of Electromagnetic Fields (23).

The question of non-thermal effects at LORAN-C and OMEGA frequencies is particularly uncertain because of the lack of health effects research in this frequency range. Results of experiments at other frequency ranges may, however, be relevant. One of the most notable and reproducible non-thermal effects is the change in the efflux of calcium ions from the brain during exposure to weak, low frequency electric fields (24-28). An important finding of this research is that the effect occurs for both ELF fields as well as RF fields modulated at the same ELF frequencies. The implication is that some type of rectification is occurring within the system making the effect independent of carrier frequency over a wide range. This effect is important when considering LORAN-C and OMEGA fields because of the pulse modulation. The LORAN-C carrier frequency of 100 kHz is modulated with a pulse repetition rate of 1000 Hz within a train, and a train repetition rate ranging from 10 Hz to 20 Hz. The train repetition rate thus falls within the 9 Hz to 20 Hz range found to be effective in affecting calcium efflux. Maximum effect in this range occurs at 16 Hz which is most closely approximated by the LORAN-C GRI rate of 5990 having a train repetition frequency of 16.7 Hz.

The above correlation is interesting and indicates the need for detailed biological studies using LORAN-C waveforms, but does not imply that an effect is occurring. The calcium efflux result depends on specific exposure conditions or "windows" and the mechanisms have not been determined. Further investigation is warranted by the important role of calcium in central nervous system function. Blackman, et. al., report that an SAR of 1.3 mW/kg is most effective at a carrier frequency of 50 MHz, which corresponds to an average internal electric field of about 0.05 V/M (23). Using Equation 4, the ratio of external to internal electric field strength (23) at 100 KHz is about 27000.

$$E_{\perp 2} = \frac{\sigma_2 + j\omega \varepsilon_2}{\sigma_1 + j\omega \varepsilon_1} E_{\perp 1}$$ Equation 4

E_1 = Electric field strength in air
E_2 = Electric field strength inside the brain

$\sigma_2 \approx 0.15$ S/M (Ref. 23)
$\sigma_1 \approx 10^{-13}$ S/M
$\varepsilon_2 \approx 1250$ F/M
$\varepsilon_1 \approx 10^{-11}$ F/M

This result implies that an external electric field strength of 1350 V/M would be required to produce an internal field strength of 0.05 V/M. Such field levels were recorded at the LORAN-C stations, but only in areas very close to the antenna.

Internal electric fields can also be induced by magnetic fields, which are nearly equal inside and outside the body at these frequencies. Magnetic fields create an electric field along a circular path according to Equation 5.

$$E = \frac{wuHr}{2}$$ Equation 5

w = Angular frequency
u = Permeability
H = Magnetic field strength
r = Radius of the circular path

Using a path radius of 0.05 meters, Equation 5 implies that a magnetic field strength of 2.5 A/M is required to create an internal electric field strength of 0.05 V/M at 100 kHz. Peak magnetic field strengths of this magnitude and higher are found over relatively large areas around LORAN-C stations. It is important to recognize that these figures are crude approximations meant only to indicate the possibility of effects in the LORAN-C near field environment. The calcium efflux effect and other non-thermal effects are not well enough understood to make predictions at this point.

In reviewing the available data, it appears that only one bioeffects study has been performed thus far using LORAN-C type waveforms and carrier frequency. This study was funded by the Office of Naval Research and performed at Loma Linda University (29). Preliminary findings published in a July 29, 1986 annual report indicated field-related changes in the levels of certain neurotransmitter substances in the brains of exposed rats. The effects were not replicated, however, in subsequent trials. Data analysis is currently underway, and the results will be presented later this year in a final report.

OMEGA signals are more difficult to relate to existing results because of the non-uniform pulse repetition rate. Individual pulses range from 0.9 seconds to 1.2 seconds duration with 0.2 second silent intervals between. During a single pulse train, the repetition "frequency" thus ranges from 0.71 Hz to 0.91 Hz while the train repetition rate is 0.1 Hz. Possibly the best approach to determining bioeffects of OMEGA fields is to perform experiments using this specific waveform.

One non-thermal effect currently under scrutiny is the apparent effect of pulsed magnetic fields on the embryological development of fertilized chicken eggs. This effect was first reported by Delgado, et. al., (30) in 1982 and has since been studied by other investigators. The original study utilized square pulses at 10,100 and 1,000 Hz at magnetic fields of 0.12, 1.2, and 12 microtesla. These values correspond to field strengths of 0.096 A/M to 9.6 A/M. Malformations and abnormalities were seen with several combinations of field strength and frequency with the greatest effect occurring at 0.96A/M and 100 Hz. A later study at the same laboratory (31) examined the importance of pulse shape in producing the effect. Although several combinations produced effects, the greatest number was found when using a rise time of 42 microseconds and a field strength of 0.8 A/M.

Several attempts have been made to replicate these experiments because of their potential importance in regard to commonly encountered fields. Similar results were obtained in studies in Finland (32) (33), but two other replication attempts have failed (34) (35). In an attempt to clear up the controversy, the Office of Naval Research is sponsoring a multinational replication study in cooperation with the U.S. Environmental Protection Agency (36). A recent report by Leal (37) correlates the developmental effects with fluctuations in the geomagnetic field as recorded at the nearest National Geographic Institute post. If verified, the effect could help explain the variability in findings by different investigators. A recent Swedish study found implications of similar effects of pulsed magnetic fields on mice fetuses (38) although this report has also been surrounded by controversy.

The simplest model in attempting to explain the pulsed magnetic field effects is to determine the internal electric fields induced by the time rate of change of the magnetic fields. Using the 0.8 A/M and 42 microsecond values above, the time rate of change is about 2×10^4 A/M/S. The pulse envelope rise times for LORAN-C and OMEGA are 62.5 and 100 microseconds, respectively. Using these values, the above time rate of change is achieved for LORAN-C and OMEGA pulses ranging in intensity from 1 to 2 A/M. This model, however, does not explain many of the experimental findings. Other models have been proposed including cyclotron-type resonance (39) which occurs in a combination of oscillating and static fields. In one experiment with fields chosen to produce cyclotron resonance for lithium ions, operant behavior of rats was altered during exposure (40). A frequency of 60 Hz was used for this study, but other frequencies may be effective if the correct combination of field strengths is chosen. This model has also been suggested as a possible explanation of the calcium efflux effect.

Also under investigation at this time are the reports of correlation between power line (50-60 Hz) magnetic field and cancer rates. The earliest report of this effect was of an epidemiological study performed by Wertheimer and Leeper (41) in 1979. A subsequent replication study in Rhode Island (42) failed initially, but later showed positive results when the data was re-evaluated. A recent Swedish study (43) also supports the finding, as well as a U.S. study by Savitz, et. al., (44). Work at the Cancer Therapy and Research Foundation in San Antonio, TX, has demonstrated increased tumor growth rates during 60 Hz laboratory studies (45). These, and many other reports, have helped to form a consensus among the bioeffects community that there is some correlation between power frequency fields and cancer rates. A number of effects have also been noted among workers at high voltage substations (46) (47).

Numerous other non-thermal effects have been reported from the ELF to microwave frequency ranges. Rats exposed throughout their lifetimes to pulsed microwave radiation at an SAR of 0.4 W/kg have shown a number of effects including a higher incidence of malignancies (48). Studies in Poland have shown that carcinogenic action of certain chemicals is enhanced by exposure to microwaves (49). Reproductive and developmental effects in rats exposed to low levels of 27.12 MHz radiation have been reported by a research group in Italy (50) and recent multi-generational studies funded by the Electric Power Research Institute have shown that effects can occur in later generations (51). Regarding occupational exposures, a study of persons exposed occupationally to radio frequency and microwave fields showed significantly higher risks of developing cancers and was most pronounced for subjects at the age of 40 - 49 who were exposed for 5 - 15 years (52).

In evaluating the potential for health effects resulting from exposures to electromagnetic fields near LORAN-C and OMEGA facilities, it is clear that there are far more questions than answers. One conclusion which can be drawn is that, in spite of the high field strengths, there is little probability of thermal effects because of the poor energy coupling with the body at these low frequencies. The question of non-thermal effects, however, is very much open. The references and approximations in this chapter are provided to illustrate that non-thermal effects are possible, but at the same time emphasize that the limited understanding of mechanisms and almost total lack of research in this frequency range make prediction impossible.

An important issue to consider in the case of LORAN-C signals is the large disparity between peak and rms values. While it is conventional to use the rms values in SAR calculations, the importance of peak field strengths in non-thermal effects has yet to be fully evaluated. Peak magnetic fields, for example, are obviously important in calculating induced electric fields, because at a given frequency the time rate of change is proportional to the signal amplitude. Present standards limit rms field strengths and thus present less problem in terms of compliance.

If peak fields are found to be significant, the standards will be exceeded over much larger areas, as the peak-to-rms ratios for LORAN-C stations range from 10.3 to 17.6.

A short questionnaire was distributed during the site visits to determine if station personnel perceive any unusual effects when working at the stations. Out of 128 questionnaires filled out, 25 reported some kind of effects ranging from mild shocks to fatigue and dizziness. Positive responses are broken down by type and number in Table 70. Of the 25 reported effects, 11 were related to shocks at OMEGA stations and only 1 reported shocks at a LORAN-C station.

Table 70. Questionnaire Results.

Response	Number
Shocks	12
Increased Irritability	3
Fatigue	2
Dizziness	4
Eye Irritation	2
Hearing Effects	2
Headaches	1

Chapter XI. Discussion of Study Findings

Interpretation of the modeling and measurement results in terms of personnel safety is difficult because of the limited health effects data available as described in Chapter X. Given the present state of knowledge in this area, it is impossible to predict with certainty whether significant health effects will or will not occur as a result of typical exposures to LORAN-C and OMEGA fields. In an effort to bracket the possibilities indicated by current knowledge, the study results are discussed from a number of viewpoints, ranging from thermal effects to the lowest EPA option. At the high end, thermal effects are known to be hazardous above certain levels based on health effects data and simple heat load considerations. Establishing a lower limit, below which exposures can be considered absolutely safe, is more difficult. The lowest EPA option was chosen for this purpose because its limiting values at LORAN-C and OMEGA frequencies are the lowest under consideration in the United States or western Europe (except for the 50 V/M limit for Air Force GWEN facilities). While there is no guarantee that this exposure limit will prevent non-thermal effects, few investigators are currently advocating a lower standard.

The probability of thermal effects at LORAN-C and OMEGA frequencies is low because of the poor coupling of the body with low frequency fields. Based on the study findings, the only areas where sufficient field strengths might occur at LORAN-C stations are above the tower top, very near the base insulator, and near the final tuning coils. Most of the tower climbers interviewed were aware of the high electric field strengths above the tower and stated that standing above the top rail was not routine. Standing in the high fields near the base insulator is extremely dangerous because of the possibility of lethal shock from contact with the tower. Exposure to these intense feedpoint fields occurs normally only when the climbers are mounting the tower. Once inside the tower, exposures are substantially reduced. Magnetic fields are several times less efficient at coupling energy into the body than electric fields (on a plane wave equivalence basis) and very high field strengths are required to induce significant heat in the body. Magnetic field strengths near some of the final tuning coils were so intense that they could not be measured with the instruments used for this study. It appeared that peak magnetic field strengths exceeded 800 A/M in some localized areas very near the coils, but further study is needed to investigate the possibility of substantial SARs.

The rms electric field strengths are much higher at OMEGA stations than at LORAN-C stations, but the even poorer coupling efficiency prevents the possibility of thermal effects in normally accessible areas. At the La Moure, ND, OMEGA station it is possible that sufficient electric field strengths (about 200 KV/m) could occur very near the base insulator, but station policy does not permit entry into the fenced area around the tower. A more likely source of thermal effects at OMEGA stations is high local SARs due to shock currents. RMS currents of only 25 to 30 mA are required to produce local SARs of 8 w/kg in the ankle (11). Measured currents from pick-up trucks at the two OMEGA stations were below these values, but shock currents from larger vehicles could easily exceed the 8 W/kg limit. Higher rms currents are required to produce the same SARs at 100 kHz; and considering the lower electric field strengths at LORAN-C stations, there is less probability of reaching the 8 W/kg limit at these facilities. Sufficient currents are possible, however, if large vehicles are positioned near the feedpoint.

The Coast Guard Occupational Standard, which is equivalent to the ACGIH guideline and the third EPA option, limits exposures at LORAN-C and OMEGA frequencies to 614 V/M and 1.63 A/M. These limits are intended to reduce shock hazards and are far lower than required to prevent field induced SARs above the 0.4 W/kg whole body and 8 W/kg local maximums. Because this is a thermally-based standard, higher exposures are permitted if measures are taken to prevent shocks, and the SARs are shown to be below the limiting values. The most straightforward approach, however, is to identify areas where the field strength limits are exceeded.

In general, magnetic fields exceed the standard over larger areas than electric fields at LORAN-C stations while the reverse is true at OMEGA stations. RMS electric field strengths above 614 V/M were seldom measured outside the feedpoint fences at LORAN-C stations. Some local electric fields near the tuning coils exceeded this level, but only in cases where the coils were protected by plexiglas rather than metal. RMS magnetic fields higher than 1.63 A/M sometimes extended a few feet past the tower fences but did not cover extensive areas. At stations such as Nantucket, where the tower is adjacent to parking areas and walkways, magnetic field exposures near the limiting value are a common occurrence. In cases where the tower is isolated from normal work areas, such exposures are rare. Local magnetic field strengths above 1.63 A/M are common around the various tuning coils in the transmitter or plenum rooms, even when the coils are behind metal enclosures. These fields drop off quickly with distance and are usually below the standard a few feet from the coils.

OMEGA stations produce electric fields above the standard over much larger areas. At the La Moure, ND OMEGA, electric field strengths above 614 V/M were measured to distances of 350 feet from the tower. Values nearly as high were measured as far as 550 feet. Fortunately, the tower at this station is located over 1500 feet from all buildings except the Helix building which is normally unmanned. More significant perhaps are the electric fields at the Kaneohe, HI OMEGA station where field strengths above the 614 V/M limit are encountered daily by all station personnel and visitors as they pass through the station parking lot and other areas around the building. Painful shocks are a common occurrence at both OMEGA stations.

More extensive areas are affected if the second EPA option is considered. This option limits electric field exposures to 275 V/M and magnetic field exposures to 0.73 A/M. In common with the Coast Guard limit, electric fields exceeding this standard are normally confined to the fenced area around LORAN-C towers with the exception of Station George where such exposures can occur 20 feet from the feedpoint. Meeting the magnetic field limit at LORAN-C stations requires maintaining distances of 25 feet to 70 feet from the feedpoints. Larger areas of the transmitter rooms would also be affected. At the La Moure, ND OMEGA station, electric field strengths greater than 275 V/M occur to distances of 1350 feet from the tower. Extensive areas around the Kaheohe, HI OMEGA station building would also be affected.

Meeting the lowest EPA option, 87 V/M and 0.23 A/M, would be considerably more difficult. Magnetic field strengths above this level occur over significant areas around all LORAN-C feedpoints. Required distances from the feedpoints to comply with this standard are typically 100 to 200 feet with a maximum of 225 feet in the case of Station George. At stations where the tower or feedpoint is near the buildings, parking lot exposures are above the standard. Significant areas within the transmitter rooms would have to be restricted to comply with the standard along with some other indoor areas in cases where the buildings are very close to the feedpoint. At the La Moure, ND OMEGA, electric field strengths above 87 V/M were measured to a distance of 2000 feet from the tower. Extensive areas of the Kaneohe, HI OMEGA would also be affected including the maintenance ladder which is currently open to the public.

An encouraging finding is that no field strengths in excess of even the lowest EPA option were found in or around any of the on-base barracks or family housing units. Except for the transmitter and plenum rooms, most other indoor exposures were also found to be far below this standard. Some very local fields around conduit and piping were relatively intense, but it is usually possible to avoid these areas. Field strengths at station property boundaries were also found to be below the lowest EPA option. A simple rule of thumb noted at all stations visited is that field strengths outside the top radial anchor points are below the 87 V/M and 0.23 A/M limit. This was true even at the La Moure, ND OMEGA station. The rule can be modified to include extended antenna systems (SLTs and the TIP) by using the extent of the antenna (grounded support towers) as the demarcation point rather than the top radial anchors. This guideline is overly conservative in most cases, but is significant because the Coast Guard typically owns or controls property at least to this extent. Thus, public exposures above the lowest EPA option can be prevented by restricting access to the antenna area. No additional property acquisition is necessary.

On-tower field strengths present a greater problem in terms of standards compliance. Magnetic field strengths inside the towers (climbing position) are above all the EPA options including the Coast Guard limit. Electric field strengths inside the towers are below the Coast Guard limit but typically above the lower EPA options. Compliance with the Coast Guard standard is possible, however, from a thermal viewpoint. Once the climber has mounted the tower, there is little probability of significant shocks occurring during the climb. In such cases, the Coast

Guard (ACGIH) guidelines limit maximum SARs rather than field exposures. As discussed earlier, there is little probability of substantial SARs occurring during the climbs.

The question of which standard to enforce at LORAN-C and OMEGA stations is a difficult one. A reasonable approach may be to apply the Coast Guard standard to on-duty exposures and one of the lower EPA options to off-duty and general public exposures. If this approach is chosen, then once the necessary precautions are taken to limit shock hazards, there should be no problem meeting the SAR limits during normal work routines. Public exposures could be held below one of the EPA options by restricting access to the station or antenna area. Such measures would have to include family members residing off-base or in on-base housing.

A slight modification of the above approach might be warranted in light of current health effects research results. The basis for this approach would be the "as low as reasonably achievable" (ALARA) concept which has been used for other types of exposures. Motivating this more conservative stance are the numerous reports of non-thermal effects as discussed in Chapter X. The frequent reference to rms field strengths in this report de-emphasizes the high peak field strengths measured near LORAN-C stations. An rms field strength of 1.0 A/M, for example, can indicate a peak field strength of 17.7 A/M, and it is possible that non-thermal effects depend on peak rather than rms values. There is not enough information available at present to develop a comprehensive standard based on non-thermal effects, but the abundance of reported effects justifies minimizing exposures. The main difference between this and the previous approach is that station personnel would be alerted to the high field strength areas near the feedpoints and tuning coils, and instructed avoid unnecessary exposures. In a few cases, simple measures for reducing exposures could be taken such as moving picnic tables away from the feedpoint area (Station George) or constructing a larger fence around the tower (Nantucket).

The most conservative approach which can be considered at this time is to follow the recent recommendations of the international committee assembled by the World Health Organization (WHO) and the International Radiation Protection Association (IRPA). This committee has concluded that current densities less than 10 mA/M^2 are unlikely to cause adverse health effects (53) and pointed out the importance of waveform, pulse shape, and the peak instantaneous current density. Meeting this criterion would require avoiding exposures to peak magnetic field strengths above about 0.25 A/M at LORAN-C frequencies and 2.5 A/M at OMEGA frequencies. Such (peak) field strengths occur at LORAN-C stations to distances of approximately 1000 feet from the feedpoint. In most cases, sufficient property is controlled around each station to prevent public exposures above these levels, but the issue of occupational exposures is not easily addressed. Several recent epidemiologic surveys of men occupationally exposed to electromagnetic fields have suggested an increased risk of leukemia (46). At present, the data is not sufficient to conclude that the electromagnetic field exposures are the cause of the increased risk. Furthermore, these studies span a wide range of occupations, do not qualify the exposure levels, and do not reveal any specific causal relationships between certain signal types and reported increases. They do, however, indicate the need for coordinated health monitoring of station personnel.

Whatever approach is taken to limiting personnel and public exposures, it should be possible to determine the necessary preventative measures by using the modeling and measurement data presented in this report. The modeling results, including the simplified models in Appendix E, are useful for determining distances from the antennas required to prevent exposures above specific limits. High field strength areas in and around the buildings and antenna structures are better approximated using the measurement data. It is important to note that compliance depends heavily on the type of standard considered. RMS field strengths, for example, depend not only on the stations power output, but the antenna radiation efficiency and particularly the GRI(s). A dual-rated station produces a greater rms field strength than a similar single-rated station. This increase is equivalent to doubling the power output. If a standard based on peak field strength is considered, then the GRIs are less important, and the extent of the affected areas will depend on power power and antenna configuration only.

Chapter XII. Recommendations.

Specific recommendations based on the study results and current health effects data are listed below. Some of the items overlap but are listed separately for emphasis. The fundamental premise of the recommendations is that typical exposures to LORAN-C and OMEGA fields are not expected to produce harmful effects but that based on the suggestive bioeffects data base, it is wise to minimize exposures until more information is available. All recommendations are subject to re-evaluation as new research findings are reported.

1. Minimize Personnel Exposures

Exposures can be reduced by educating station personnel to provide a better understanding of electromagnetic field distributions and by specifically identifying high field strength areas. Observation of work procedures during the study revealed that most personnel do not enter high field strength areas as a part of normal routines. Deliberate avoidance of high field strength areas such as near the feedpoint and tuning coils should not significantly impact station operation. The general rule is to stay as far as possible from the tower base or feedpoint and re-route traffic patterns to avoid passing through transmitter or plenum rooms unnecessarily. These guidelines are useful even at stations such as Nantucket where the tower is adjacent to the parking lot, as field strengths drop off quickly with distance near the tower. Maintaining 30 feet rather than 20 feet from the tower can reduce exposures by several times. Recreational areas should not be located near the feedpoints, and warning signs should be posted as reminders of high field strength areas.

2. Reduce On-Tower Exposures

Some of the highest prolonged exposures at LORAN-C stations occur during tower climbs. Climbers are exposed to high magnetic fields and substantial electric fields inside the towers. Ground personnel who stand near the tower base during the climb (inside the fence) are often exposed to comparable magnetic field strengths and much higher electric field strengths. At the time of this study, climbs on the La Moure, ND OMEGA tower were restricted to the de-energized condition. It is recommended that this practice be continued and consideration be given to instituting a similar policy for LORAN-C stations. The health effects data does not indicate that such a move is required, but it would follow the principle of reducing exposures wherever possible. Alternatively, climbers should be instructed to not tarry on the insulated (climb-on) ladder, stay inside the tower during the climb, and not elevate themselves above the top rail. The number of climbs should be minimized and ground personnel should position themselves well outside the tower fence once their assistance inside is no longer required. Similar precautions are not required for climbing grounded towers except that climbers should stay below the top rail.

3. Reduce Risks to Pregnant Women or Those Planning Pregnancy

Because of the research results indicating possible developmental effects, it is recommended that even further precautions be taken in the case of pregnant women or those planning pregnancy. These personnel should be restricted from entry into transmitter and plenum rooms and should avoid outdoor areas near the feedpoints.

4. Reduce Exposures to Tuning Coil Fields

The high magnetic field strengths near the tuning coils should be avoided to the extent possible. Significantly higher field strengths were measured near coils which were protected only by plexiglas, rather than steel. A useful approach would be to replace all plexiglas shielding with steel plates to attenuate the fields. Another helpful measure would be to paint caution lines on the floor indicating areas which should not be entered while the transmitter is active. A distance of as little as 2 to 3 feet can reduce exposures by more than an order of magnitude. Tuning coils inside standby transmitters sometimes couple with the active transmitter producing substantial field strengths and should also be avoided when possible. A better understanding of the tuning coil fields can be gained by applying the equations developed in Appendix C to the specific dimensions of the tuning coils.

5. Reduce Shock Hazards

Although the only shocks encountered at LORAN-C stations resulted from contact with ungrounded guy wire sections, more serious shocks could result if large vehicles or other ungrounded conductors are positioned near the feedpoints. Such situations can be easily avoided by alerting personnel to the potential dangers and posting warning signs referring to shock hazards. In the event that large vehicles are required near the feedpoints, shock hazards can be avoided by carefully grounding the vehicles during the operation. Guy wire shocks can be eliminated by positioning the lowest insulator above reach, or in cases where the insulator is already too low, by running a jumper across the insulator. Personnel should also be alerted to the possibility of shocks from broken ground radials. Ground straps on support towers (SLTs and TIP) should be periodically inspected to prevent a potentially lethal ungrounded condition.

Shock hazards at the two OMEGA stations are more widespread and difficult to deal with. At the La Moure, ND OMEGA, the best approach is probably to institute a station policy requiring approval before any large metal objects or vehicles are permitted near the tower. Warning signs should be posted and station personnel should be informed that the magnitude of the shock hazard depends on the size of the ungrounded conductor. Safety shoes and gloves may be useful during extended activities near the tower as long as weather conditions are dry. Similar recommendations apply to the Kaneohe, HI OMEGA station with the additional suggestion of considering some type of shield over the parking lot. The shield could consist of a series of grounded wires suspended above or a large metal awning which would also serve as a rain shield. If cables are used, they should run perpendicular to the feedline to reduce magnetic field coupling. Any such design should be carefully evaluated to avoid affecting antenna performance. Alternatively, warning signs could be posted and personnel alerted to take precautions (isolate themselves from ground) before contacting large vehicles.

6. Improve Health Monitoring System

The ability to detect exposure related health effects among personnel could be improved by upgrading and standardizing the health monitoring program. One approach is to consult several bioeffects researchers for assistance in choosing the tests to be performed as part of the program. An important feature would be that the same health parameters were monitored uniformly among all Coast Guard personnel. Records from each station should be compiled in a central location to facilitate processing and analysis.

7. Conduct Health Effects Studies

Because few other sources operate in the LORAN-C and OMEGA frequency range, there is a serious lack of directly applicable health effects data. Studies could be conducted using these specific waveforms to investigate the possibility of effects. Another approach is to use existing or new health data on the station personnel to perform epidemiological studies. Such studies are needed to improve the credibility of any safety program instituted. Although no adverse effects are expected, there is currently little assurance that exposures to the electromagnetic fields around these stations are without consequence.

8. Minimize Public Exposures

Public exposures should be minimized by restricting access to the station property or extent of the antenna system (top radial anchor points or grounded support towers). In cases where family housing units are located at the station, family members should maintain the maximum possible distance from the feedpoint and, if possible, stay outside the top radial anchors. Such measures should limit exposures to values below all existing and proposed western standards including the WHO-IRPA guidelines for induced currents. As in the case of occupational exposures, the health effects research results should be continuously monitored to determine the possible need for revising this stance.

At the time of the site visit to the Kaneohe, HI OMEGA station (November 1986), the public was allowed access to the station building to sign in before climbing the maintenance ladder up the side of the valley. If the ladder remains open to the public, visitors should be re-routed so as not to pass by the station building where high field strengths exist. Consideration should also be given to discontinuing public access to the ladder. Weather conditions prevented measurements along the entire extent of the ladder, but field strengths at three points on the ladder were found to be above the lowest EPA option. More thorough measurements along the ladder should be taken leading to, at most, closure to the public or, at least, informing visitors of the exposure levels.

9. Improve Fences Around Feedpoints

During the site visits, many of the feedpoint fences were found to be either inadequate or in a state of disrepair. The Port Clarence tower, for example, is surrounded by a fence made of ropes tied to posts. The Native Americans who inhabit the area have been warned to stay away from the tower, but considering the consequences of touching the tower (death), it is recommended that a more substantial fence be constructed. A similar recommendation applies to all LORAN-C stations. The station boundaries are not guarded, and adequate fences should be provided around all feedpoints to prevent unauthorized entry by curious children or adults. Enlarging the radius of the fences would have the beneficial effect of reducing maximum possible exposures outside fenced areas. This approach would be useful at stations where the feedpoint is located near the main station buildings by serving to enforce traffic patterns away from the high field strength areas.

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Appendix A. Root Mean Square Calculations For LORAN-C Signals

The LORAN-C signal consists of a train of 8 or 9 pulses with a carrier frequency of 100 KHz. The ideal or desired pulse shape is given by the expression:

$$A(t) = A_p\left[\left(\frac{t}{t_p}\right) \exp\left(1-\frac{t}{t_p}\right)\right]^2 \sin wt \qquad \text{Equation A1}$$

where A(t) is the waveform amplitude at time t
Ap is the peak value of the pulse
tp is the time of the peak (62.5μS)
and W is the angular frequency (2π 100 KHz).

These pulses repeat each 1 millisecond during the pulse train (see Figure 45). The pulse train repeats with a time period specified by the group repetition interval (GRI) of the chain. Values of the GRI range from 49.9 to 99.9 milliseconds although the Coast Guard designation is given as 100 times these values (e.g., 49.9 milliseconds is designated as a GRI of 4990).

Pulsed waveforms such as LORAN-C present some difficulties in hazard assessment because most safety standards limit root mean square (rms) values of field strength rather than peak values. The rms value of a waveform is related to the power which it is capable of delivering. The rms of an ordinary sine wave signal is 0.707 times the peak value. Another quantity used to describe the relationship between peak and rms is the crest factor given by:

$$\text{Crest factor} = \frac{\text{peak value of waveform}}{\text{rms value of waveform}} \qquad \text{Equation A2}$$

The crest factor of a sine wave is 1.414 while crest factors for LORAN-C signals can range from about 10 to over 17. These high and variable crest factors make measurements difficult because the detection circuitry must perform true rms conversion at 100KHz over varying time periods and a wide dynamic range. This difficulty was avoided in the study reported here by only measuring the peak values of electric and magnetic field strength at each measurement location. RMS values of field strength were then calculated based on the rms-to-peak ratio for the individual station. There are also problems with this technique because the actual LORAN-C pulse often differs from the ideal theoretical shape given above. However, as a first approximation, an analysis based on the ideal pulse shape is presented below. A detailed evaluation of actual pulse shapes will be presented later.

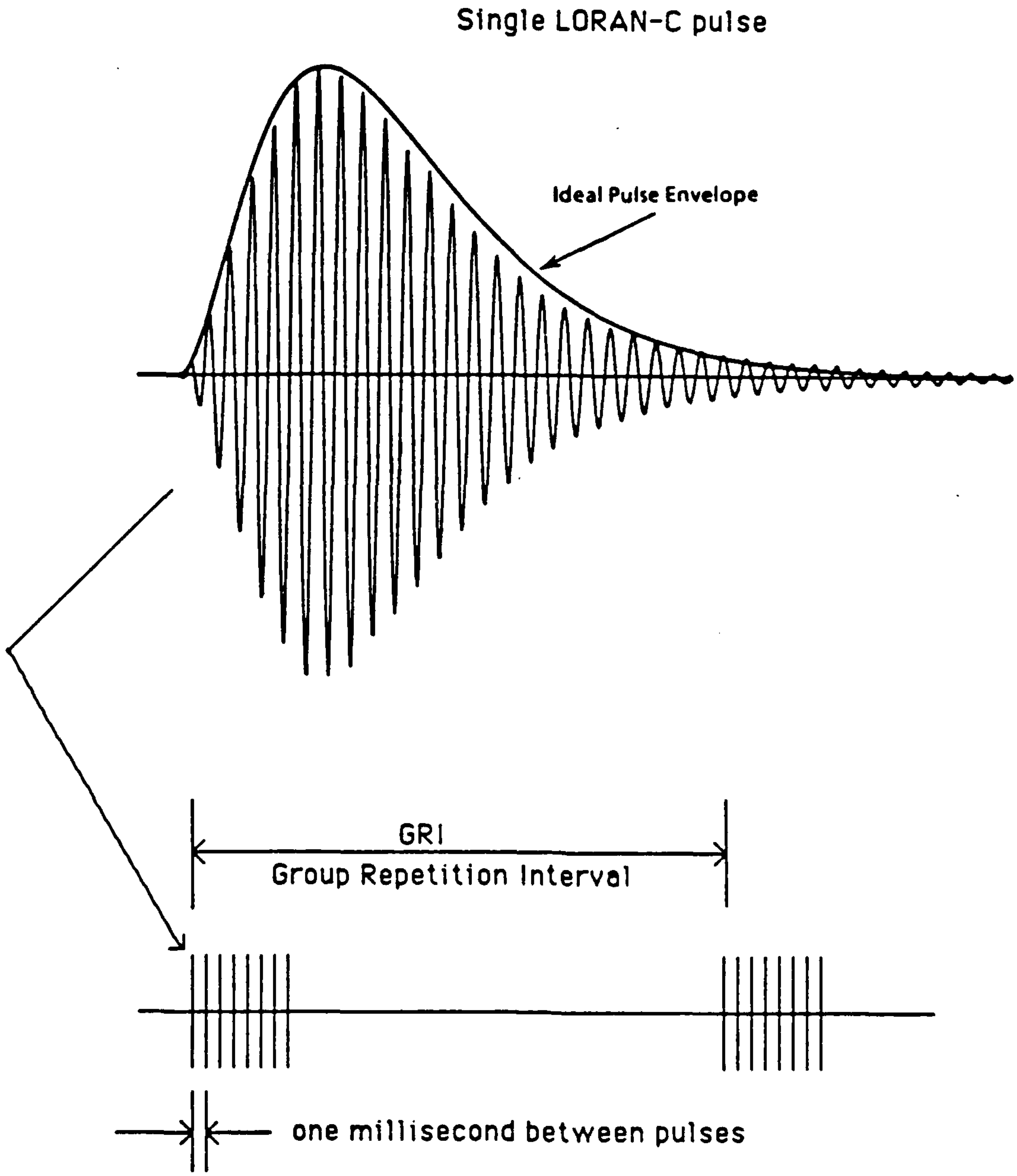


Figure 45. LORAN-C pulse modulation

The rms value of a waveform is given by the following expression:

$$A_{rms} = \sqrt{\frac{1}{T}\int_0^T A^2(t)\ dt} \qquad \text{Equation A3}$$

where T is the period over which the rms is to be determined. Since the formula for the LORAN-C signal given in Eq A1 refers to only a single pulse, the first step in deriving an rms value is to perform equation A3 over the pulse repetition time within a pulse train, that is, T = 1 millisecond. The rms-to-peak ratio for this time period is:

$$\frac{rms}{peak} = \frac{1}{A_p}\sqrt{\frac{1}{T}\int_0^T A_p^2\ \frac{t^4}{t_p^4}\exp(4-\frac{4t}{t_p})\sin^2 wt\ dt} \qquad \text{Equation A4}$$

or more simply

$$\frac{rms}{peak} = \sqrt{\frac{e^4}{T\,t_p^4}\int_0^T t^4\ \exp(-\frac{4t}{t_p})\sin^2 wt\ dt} \qquad \text{Equation A5}$$

After extensive manipulation, a closed form solution to equation A5 can be obtained. The solution is shown below:

$$\frac{rms}{peak} = \left[\frac{e^{at+4}}{2Tt_p^4}\left(\frac{t^4}{a}-\frac{4t^3}{a^2}-\frac{12t^2}{a^3}-\frac{24t}{a^4}-\frac{24}{a^5}-\frac{t^4}{\rho}\cos(2wt-\alpha)\right.\right.$$

$$+\frac{4t^3}{\rho^2}\cos(2wt-2\alpha) - \frac{12t^2}{\rho^3}\cos(2wt-3\alpha)+\frac{24t}{\rho^4}\cos(2wt-4\alpha)$$

$$\left.\left.-\frac{24}{\rho^5}\cos(2wt-5\alpha)\right)\right]^{1/2} \qquad \text{Equation A6}$$

where $a = -\frac{4}{t_p}$

$\rho = \sqrt{a^2 + 4w^2}$

$\alpha = \cos^{-1}(\frac{a}{\rho})$

Evaluation of this expression at T = 1 millisecond yields the following result:

$$\frac{\text{rms}}{\text{peak}} = 0.1999722 \qquad (T = 0.001 \text{ seconds})$$

This result was checked by performing a numerical integration of Equation A5. Numerical integration involves evaluation of a function at equally separated points along the X-axis and constructing a rectangle or trapezoid to approximate the area under the curve in that region. The areas are then summed over the limits of integration to yield an approximation to the integral of the function. The separation of the calculation points can be reduced to achieve a desired accuracy. Since the advent of readily accessible personal computers, it is frequently easier and faster to solve an integral using numerical integration than attempting an exact solution. In the present case, both methods were used to insure reliability of the result. The numerical integration in this case agreed with the closed form result to six decimal places. This excellent agreement is considered verification of the result. For practical purposes, an rms-to-peak ratio of 0.2 can be considered the result of the theoretical analysis.

Another method of approximating the rms-to-peak ratio will also be discussed because of its usefulness in analyzing actual LORAN pulses. Application of the technique to the theoretical pulse shape will serve as a check of the method's accuracy. The rms-to-peak ratio of a sine wave is 0.707 as stated earlier. In this approach, the LORAN-C pulse is thought of as a series of sine waves of varying amplitude. This is approximately true in the sense that the pulse is an amplitude modulation of the 100 KHz carrier frequency. However, the instantaneous value of the carrier varies continuously with time -- not just at the cycle peaks. In other words, the pulse modulation deforms the carrier wave such that each cycle is not exactly sine wave shaped.

The method is applied by computing or measuring the amplitude of each cycle within the LORAN-C pulse. The rms value of each cycle is then approximated by multiplying the amplitude by 0.707 and taking the square root of the sum of the squares. The mathematical formulation is shown below:

$$\frac{\text{rms}}{\text{peak}} = \sqrt{\frac{1}{100} \cdot \frac{1}{2} \cdot \sum_{n=1}^{100} A_n^2} \qquad \text{Equation A7}$$

where An = the amplitude of cycle n and the factor of 100 is the time period (each cycle lasts 10 microseconds so that 100 cycles occur in 1 millisecond).

The cycle amplitudes, An, can be computed for the theoretical pulse shape by evaluating the envelope portion of Equation A1 at cycle peak times. In a LORAN-C pulse, cycle peaks occur at 2.5 microseconds and every 10 microseconds thereafter during the pulse.

The envelope portion of Equation A1 is:

$$A(t) = A_p \left[\left(\frac{t}{t_p}\right) \exp\left(1 - \frac{t}{t_p}\right) \right]^2 \qquad \text{Equation A8}$$

Evaluation of Equation A7 yields the result:

$$\frac{rms}{peak} = 0.199974$$

which agrees with the closed form solution to five decimal places. The result is surprising because the high degree of accuracy was not expected. Even better accuracy can be obtained by computing the negative as well as positive cycle amplitudes before summing.

The overall rms-to-peak ratio of a given LORAN-C station can now be determined by multiplying the pulse rms value (0.2) by the square root of the duty cycle. In this case, the signal "on time" is the number of pulses in a train times one millisecond and the repetition rate is the GRI divided by 100 (also in milliseconds). The number of pulses, N, is nine for Master and eight for secondary stations. For a single-rated station, the overall rms-to-peak ratio is:

$$\frac{rms}{peak} = (0.2) \sqrt{\frac{100\,N}{GRI}} \qquad \text{Equation A9}$$

Dual-rated stations transmit pulses at two different GRIs. The resulting rms values are higher because more pulses occur within the same time period. The overall rms-to-peak ratio for dual-rated stations is:

$$\frac{rms}{peak} = (0.2) \left[\sqrt{\frac{100\,N_1}{GRI_1} + \frac{100\,N_2}{GRI_2}} \right] \qquad \text{Equation A10}$$

The above equation slightly overestimates the rms-to-peak ratio for dual-rated stations because of a process called blanking. At times when pulses from the two different GRIs would overlap, one of the pulses is eliminated or "blanked" to avoid interference. A short computer program was written to calculate the effect of blanking on the amount of pulse energy emitted. The LORAN-C station on Nantucket Island, for example, transmits at GRIs of 9960 and 5930, and the computer program predicts that about 5.7% of the pulses are blanked. This result translates to about a 3% reduction in rms-to-peak ratio. In the interest of erring on the conservative side (that is, overestimating rather than underestimating field strengths), the effect of blanking has been ignored in the data analysis.

A more important effect is the deviation of actual LORAN-C pulse shapes from the theoretical shape. Because the pulse shapes differ from one station to the next in an unpredictable way, no functional shapes for the pulses are known and closed form solutions for the rms-to-peak ratio are not possible. For this reason, it is recommended that true rms reading meters be constructed for future studies. In order to estimate the rms-to-peak ratio for actual pulses, the method described by Equation A7 was used. Cycle amplitudes within a pulse were measured directly on an oscilloscope or on a scope photograph. Any convenient scale can be used as the values are normalized to one (the highest peak value) before the application of equation A7. Below is a table of rms-to-peak ratios derived using the above method:

Table A1. RMS-to-Peak Ratios for LORAN-C Pulses

Station	Pulse $\frac{rms}{peak}$	Fraction of Theoretical Value (0.2)
Jupiter	0.192	0.960
Carolina Beach	0.153	0.765
Nantucket	0.194	0.970
Port Clarence	0.176	0.880
Dana	0.193	0.965
George	0.187	0.935
Upolu Pt.	0.163	0.815
Seneca	0.188*	0.940
Searchlight	0.205*	1.025

* These values were derived from Coast Guard test reports (54) (55).

Table A1 illustrates the deviation of actual LORAN-C pulse shapes from the theoretical rms-to-peak ratio of 0.2. It should be pointed out that these values are based on a single oscilloscope photograph or observation and do not account for variations with time, transmitter repair, weather conditions (which sometimes affects antenna impedance) or the different pulses within a train. As a check of the variation with time, pulse data taken by the U.S. Department of Transportation of Station George in October 1984 (56) was compared to the September 1986 data taken for this study. The 1986 analysis showed an rms-to-peak ratio of 0.187 while analysis of the 1984 data resulted in an rms-to-peak ratio of 0.196, representing about a 5% difference. A methodology check was performed by comparing the rms-to-peak value for Upolu Pt. to the rms current reading for that station. Some LORAN-C stations such as Upolu Pt. measure current output through a thermal current meter in addition to the standard Pearson current transformer which permits observation of the waveform and peak value. At Upolu Pt., the measured rms current was 32.5 amps compared with a peak current of 500 amps.

$$\text{Overall } \frac{\text{rms}}{\text{peak}} = \frac{32.5\text{A}}{500\text{A}} = 0.065$$

The single pulse rms-to-peak value can be derived by dividing by the square root of the duty cycle which for this case is 0.4004.

$$\text{Pulse } \frac{\text{rms}}{\text{peak}} = \frac{0.065}{0.4004} = 0.162$$

This result compares very favorably with the value derived using Equation A7 (Table A1) agreeing within 1%. Only two other stations surveyed, Port Clarence and Carolina Beach, employed the rms current meters. Table A2 shows the pulse rms-to-peak ratios derived using the two methods.

Table A2: Comparison of pulse rms-to-peak ratios using two methods

Station	$\frac{\text{rms}}{\text{peak}}$ from Eq. A7	$\frac{\text{rms}}{\text{peak}}$ from rms current meter	% Difference
Upolu Pt	0.163	0.162	0.6
Port Clarence	0.176	0.141	19.9
Carolina Beach	0.153	0.143	6.5

Table A2 indicates that at least one of the methods described above can produce substantial errors. The cause of the error is unknown at this time but may be due to differences in physical sampling points (between the rms and Pearson monitors) or device inaccuracies.

When all the influencing factors and uncertainties are considered, it appears that accurate, long-term values for the rms-to-peak ratios of the various stations cannot be obtained. Reasons for this assertion include equipment changes, weather effects, variations between pulses in a train, device inaccuracies, and near-field distortion, to name a few. Near-field distortion has been occasionally noted when the waveform was observed using a loop and oscilloscope, and probably results from the superposition of the primary field with delayed secondary fields generated by induced currents. This uncertainty and variability of the waveform indicates that measurement of rms as well as peak field strengths should be included in future studies. The decision to measure peak fields was made before this study was initiated and could not be changed during the study because the instrumentation had already been specified and built.

Determination of rms field strengths from the peak fields strength data taken in this study is accomplished using the theoretical pulse rms value of 0.2. By using this value, the field strengths will be overestimated in nearly all cases, improving the safety of any precautionary measures based on the results. Typical overestimation errors are less than 20% (1.6 dB) but could rarely be as high as 40% (2.9 dB) based on Tables A1 and A2. The net result of these errors is that distances to which a given standard is predicted to be exceeded will be larger by a factor roughly equivalent to the overestimation error (because magnetic fields drop off approximately as 1/r). The possible exception is Searchlight which according to Department of Transportation data has a pulse rms-to-peak ratio of 0.205. Applying a 0.2 ratio to the Searchlight measurement data results in field predictions that may be 2.5% too low. An error of 2.5% (0.2 dB), however, is less than the measurement accuracy and can be safely ignored. The rest of the stations for which the DOT has pulse data (not surveyed for this study) show rms-to-peak ratios of less than 0.2.

Appendix B. Root Mean Square Calculations for OMEGA Signals

The OMEGA signal consists of a continuously repeating train of eight pulses with carrier frequencies ranging from 10.2 KHz to 13.6 KHz. Pulse lengths range from 0.9 to 1.2 seconds with 0.2 second separations between pulses. The entire sequence lasts 10 seconds with each of the eight worldwide stations transmitting a unique pattern of carrier frequencies (see Figure 46). In contrast with LORAN-C pulses, the OMEGA pulses are simple square wave modulations of the carrier sine wave. In other words, the carrier signal is either on or off with no complex functional pulse shape as in the case of LORAN-C.

RMS calculations for OMEGA signals would be straightforward except for the fact that each pulse is not of the same amplitude. Instead, the OMEGA stations are configured to maintain constant power output at each frequency. The effect of this constraint on pulse amplitudes is discussed below. As in the case of LORAN-C signals, only the peak field strength was measured for this study, and an rms-to-peak ratio for each station is required to determine rms field strength values.

OMEGA antennas are electrically short with a mostly capacitive impedance. Thus, most of the current in the antenna is imaginary or out-of-phase with the applied voltage. Holding power constant, the real current increases as the square of frequency (due to greater radiation efficiency), but represents only a small fraction of the total current. Imaginary current, on the other hand, decreases with the inverse of frequency. Voltage decreases as the inverse square of frequency.

OMEGA stations transmit constant power (10 kW) at all frequencies. Therefore, the imaginary current (representing over 99% of the total current) at 10.2 KHz is greater than that at 13.6 KHz by the factor of 13.6/10.2 or 1.33. Near magnetic fields are directly proportional to antenna current and, thus, also obey the above relationship at the two frequencies. Near electric fields are directly proportional to the excitation voltage thereby decreasing as the inverse square of frequency. Electric fields produced at 10.2 KHz are $(13.6/10.2)^2$ or 1.78 times greater than those produced at 13.6 KHz.

In short, both the electric and magnetic fields produced by OMEGA stations vary in a predictable way as the station changes frequency. Highest fields occur at the lowest frequency which is 10.2 KHz. The fact that field levels are lower at the other (higher) frequencies will affect the relationship between peak and rms fields used in data analysis. Shown below is a table of the LaMoure, North Dakota, OMEGA frequencies and the relative field strengths expected to occur based on a value of one for fields at 10.2 KHz.

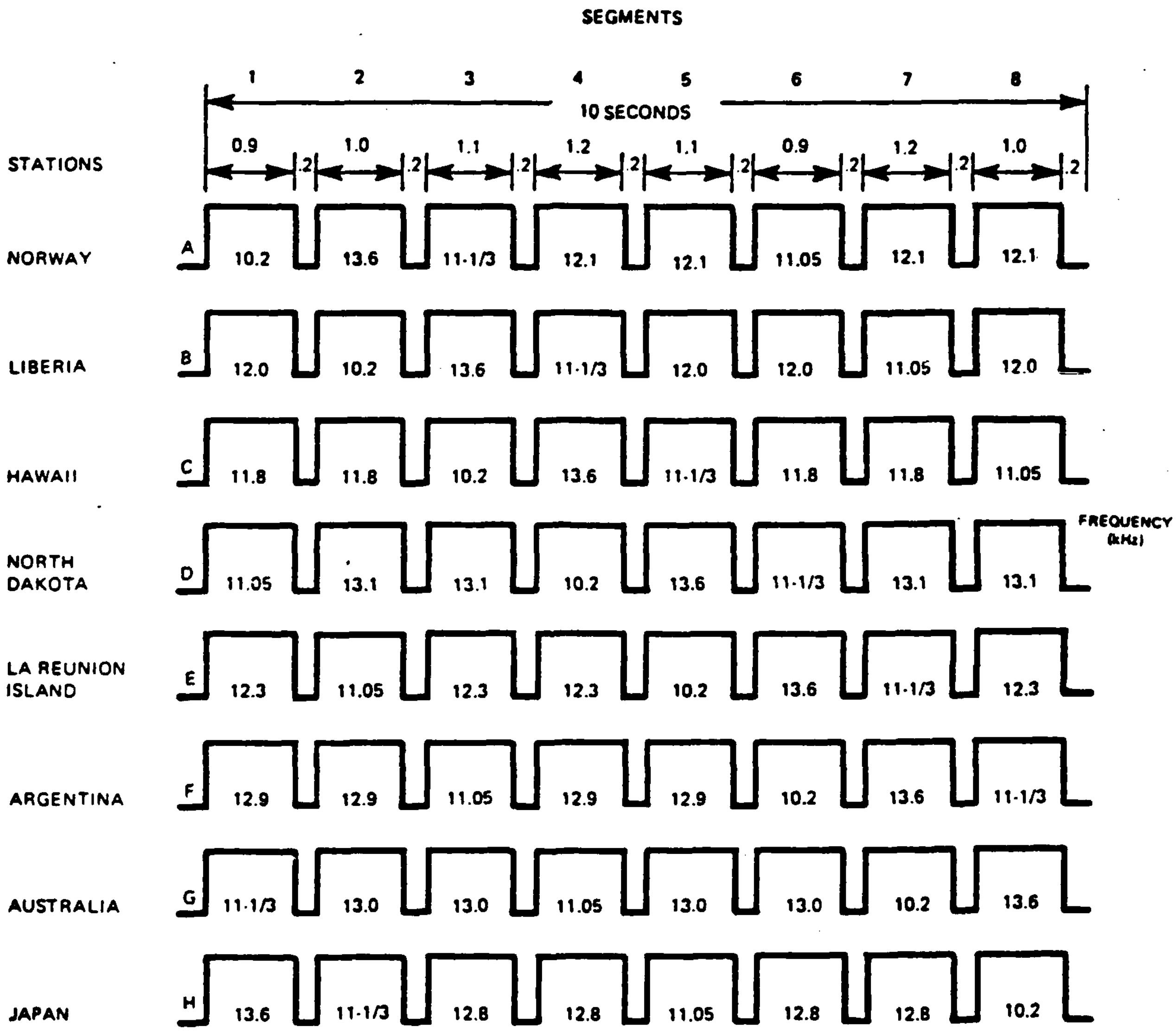


Figure 46. OMEGA modulation

Table B1. Theoretical Relative Field Strength Amplitudes for La Moure, ND, OMEGA

Frequency	Magnetic Fields (10.2/F)	Electric Fields $(10.2/F)^2$
10.2 KHz	1.000	1.000
11.05 KHz	0.923	0.852
11.33 KHz	0.900	0.810
13.10 KHz	0.779	0.606
13.60 KHz	0.750	0.563

An attempt was made to experimentally determine the relative field strengths during the field study at LaMoure, ND. Magnetic fields were examined by observing the output of the Ailtech loop antenna on the Tektronix 212 oscilloscope which was shielded from electric fields by a metal enclosure. Response to each frequency was identical which confirms the above relationship. This response is explained by the fact that loop response is directly proportional to frequency and thus exactly compensates for the field reductions at higher frequencies.

Relative electric field strength was observed by simply extending a short monopole element from the oscilloscope feed through the top of the shielded enclosure. This configuration is not calibrated for absolute field measurements, but can be used to examine relative field strengths. When the scope was adjusted such that the weakest signal had a peak value of one division, the strongest signal appeared to reach about 1.6 divisions. This reading compares with the calculated ratio of 1.78 described above. Considering the small screen size of the Tektronix 212 oscilloscope (1.25" x 2.0") and resulting reading error, the two values show reasonable agreement.

A more careful attempt to test the amplitude versus frequency relationships was performed at the Kaneohe, Hawaii, OMEGA station. Here, a larger screen oscilloscope belonging to the station was used to examine relative amplitudes. The various transmission frequencies were determined by writing down the pulse sequence and synchronizing with the OMEGA signal during the 10.2 KHz pulse. In the parking lot next to the station building, all the frequencies are audible because of vibrations induced in the coils and feed lines. The 10.2 KHz signal is the loudest and lowest pitched tone. Verification of the frequency was possible by observing the wavelength of the signals on the oscilloscope. Once the procedure was mastered, multiple amplitude readings were taken until repeatable results were obtained. Electric field amplitudes were observed by attaching a short coaxial cable to the scope with one connector removed. At this end, the center conductor was extended a short distance beyond the shield to create an electric field probe. Magnetic fields were measured using the Ailtech loop, which because of its frequency dependent response, performs the inverse operation of the station's frequency response.

Tables B2 and B3 show the results of this experiment along with the theoretical response and percent difference.

Table B2. Theoretical and Experimental Electric Field Pulse Amplitudes for Kaneohe, Hawaii, OMEGA

Freq (KHz)	Theoretical Amplitude $(10.2/F)^2$	Raw Data (Arbitrary Units)	Measured Amplitude (Scaled to one at 10.2 KHz)	% Diff.
10.2	1.000	4.0	1.000	--
11.05	0.852	3.5	0.875	2.7
11.3	0.815	3.4	0.850	4.3
11.8	0.747	3.1	0.775	3.7
13.6	0.563	2.2	0.550	2.3

Table B3. Theoretical and Experimental Magnetic Field Pulse Amplitudes for Kaneohe, Hawaii, OMEGA

Freq (KHz)	Theoretical Amplitude (10.2/F)	Raw Data (Arbitrary Units)	Measured Amplitude*	% Diff.
10.2	1.000	3.0	1.000	--
11.05	0.923	3.1	0.893	3.2
11.3	0.903	3.1	0.874	3.2
11.8	0.864	3.1	0.836	3.2
13.6	0.750	3.0	0.750	--

*Scaled to one at 10.2 KHz and corrected for loop response

The above results demonstrate good agreement between the theoretical analysis and experimental check. Differences between theoretical and measured values are all less than 0.4 dB and may be due to reading errors on the oscilloscope. This good agreement indicates that the theoretical values may be used to calculate rms-to-peak ratios for the OMEGA stations. The mathematical formulation for these ratios is derived below:

In general,

$$rms = \sqrt{\frac{1}{T}\int_0^t A^2(t)\,dt} \qquad \text{Equation B1}$$

where A(t) is the signal amplitude as a function of time.

The OMEGA pulse train repeats every 10 seconds and consists of 8 square pulse envelopes of varying carrier frequency (10.2 - 13.6 KHz) and duration (0.9 - 1.2 seconds) separated by "no transmission" intervals of 0.2 seconds. Using the magnitude dependence on frequency of the magnetic fields (10.2/F) and electric fields $(10.2/F)^2$ described above, the rms integral can be separated into pulse intervals.

Normalized to a peak value of one at 10.2 KHz:

$$A(t) = \left(\frac{10.2}{F}\right) \sin(wt)$$ for magnetic fields (H) Equation B2

$$A(t) = \left(\frac{10.2}{F}\right)^2 \sin wt$$ for electric fields (E) Equation B3

$$\int_0^t A^2(t)\,dt = \int_0^{t_1} \left(\frac{10.2}{f}\right)^2 \sin^2(wt)\,dt + \int_{t_1}^{t_2} \left(\frac{10.2}{f}\right)^2 \sin^2(wt)\,dt + \ldots$$ Equation B4

$$= \sum_{n=1}^{8} \left[\int_0^{t_n} \left(\frac{10.2}{f_n}\right)^2 \sin^2(wt)\,dt \right]$$ for H fields Equation B5

$$= \sum_{n=1}^{8} \left[\int_0^{t_n} \left(\frac{10.2}{f_n}\right)^4 \sin^2(wt)\,dt \right]$$ for E fields

Equation B6

where tn = duration of pulse n
and fn = frequency of pulse n.

Evaluating the integral yields:

$$\int_0^t A^2(t)\,dt = \frac{1}{2}\sum_{n=1}^{8} t_n \left(\frac{10.2}{f_n}\right)^2$$ for H fields Equation B7

$$\int_0^t A^2(t)\,dt = \frac{1}{2}\sum_{n=1}^{8} t_n \left(\frac{10.2}{f_n}\right)^4$$ for E fields Equation B8

For T = 10 seconds, the rms-to-peak ratios are:

$$\frac{\text{rms}}{\text{peak}} = \sqrt{\frac{1}{20}\sum_{n=1}^{8} t_n \left(\frac{10.2}{f_n} \right)^2} \quad \text{for H fields} \qquad \text{Equation B9}$$

$$\frac{\text{rms}}{\text{peak}} = \sqrt{\frac{1}{20}\sum_{n=1}^{8} t_n \left(\frac{10.2}{f_n} \right)^4} \quad \text{for E fields} \qquad \text{Equation B10}$$

These formulas can be applied to the OMEGA frequencies and pulse durations shown in Table B4 and B5 to calculate the numerical rms-to-peak ratios.

Table B4. Frequencies and Pulse Durations for LaMoure, North Dakota, OMEGA

Frequency (KHz)	Duration (seconds)
11.05	0.9
13.1	1.0
13.1	1.1
10.2	1.2
13.6	1.1
11.33	0.9
13.1	1.2
13.1	1.0

Table B5. Frequencies and Pulse Durations for Kaneohe, Hawaii, OMEGA

Frequency (KHz)	Duration (seconds)
11.8	0.9
11.8	1.0
10.2	1.1
13.6	1.2
11.3	1.1
11.8	0.9
11.8	1.2
11.05	1.0

Equations B9 and B10 are expanded below to illustrate the calculations for LaMoure, North Dakota, OMEGA:

$$\frac{\text{rms}}{\text{peak}} = \left[\frac{1}{20} \left((0.9)\left(\frac{10.2}{11.05}\right)^2 + (1.0)\left(\frac{10.2}{13.1}\right)^2 + (1.1)\left(\frac{10.2}{13.1}\right)^2 + (1.2)\left(\frac{10.2}{10.2}\right)^2 + \right.\right.$$

$$\left.\left. (1.1)\left(\frac{10.2}{13.6}\right)^2 + (0.9)\left(\frac{10.2}{11.33}\right)^2 + (1.2)\left(\frac{10.2}{13.1}\right)^2 + (1.0)\left(\frac{10.2}{13.1}\right)^2 \right) \right]^{1/2}$$

$$= 0.544 \text{ for H fields}$$

$$\frac{\text{rms}}{\text{peak}} = \left[\frac{1}{20} \left((0.9)\left(\frac{10.2}{11.05}\right)^4 + (1.0)\left(\frac{10.2}{13.1}\right)^4 + (1.1)\left(\frac{10.2}{13.1}\right)^4 + (1.2)\left(\frac{10.2}{10.2}\right)^4 + \right.\right.$$

$$\left.\left. (1.1)\left(\frac{10.2}{13.6}\right)^4 + (0.9)\left(\frac{10.2}{11.33}\right)^4 + (1.2)\left(\frac{10.2}{13.1}\right)^4 + (1.0)\left(\frac{10.2}{13.1}\right)^4 \right) \right]^{1/2}$$

$$= 0.468 \text{ for E fields}$$

The rms-to-peak ratios for both OMEGA stations surveyed are summarized in Table B6. Multiplying the measured peak field strength values by these ratios gives the rms field strengths.

Table B6. RMS-to-Peak Ratios for Surveyed OMEGA Stations

Station	RMS-to-Peak ratio for Electric Fields	RMS-to-Peak Ratio for Magnetic Fields
LaMoure, ND	0.468	0.544
Kaneohe, HI	0.507	0.570

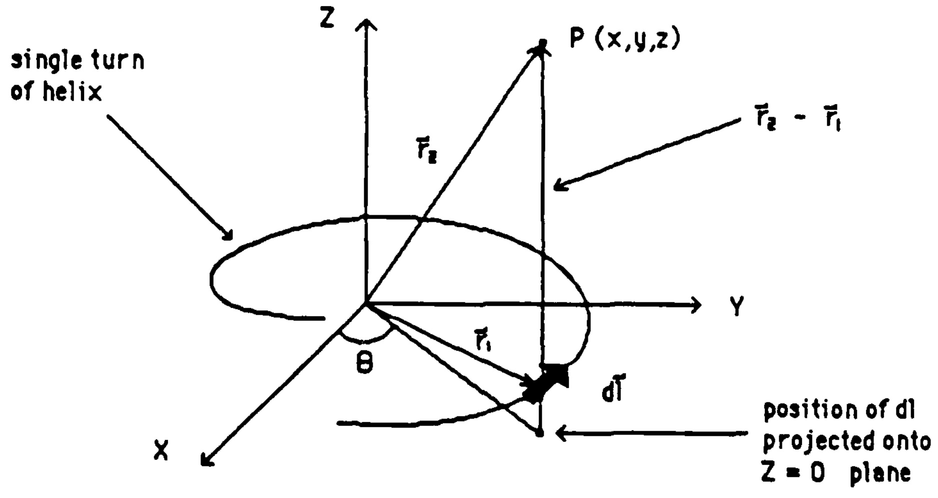
Appendix C. Helix Equations

Magnetic field strengths near some of the LORAN-C tuning coils were found to be too intense for the measurement instrumentation used in this study. In order to calculate the field strengths, the following helix equations were derived. The resulting expressions are elliptical integrals and are best solved by numerical integration on a computer. Application of the equations to the tuning coils requires knowledge of the current, radius, and pitch of the coils. The derivation is shown below.

a = coil radius
L = length of coil
n = number of turns/unit length

Coil centered on z - axis with one end at z = 0
Calculate magnetic field components at x,y,z

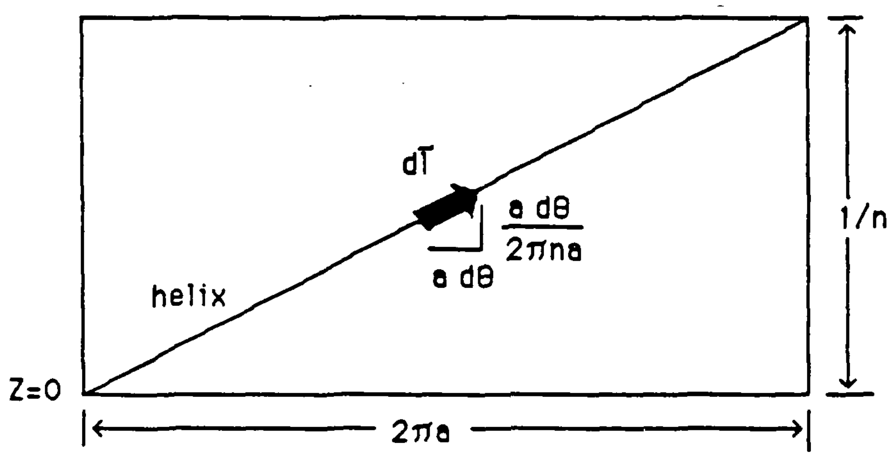
$$\vec{B}(\vec{r}) = \frac{\mu_0 I}{4\pi} \oint \frac{d\vec{l} \times (\vec{r}_2 - \vec{r}_1)}{|\vec{r}_2 - \vec{r}_1|^3}$$ Biot - Savart Law



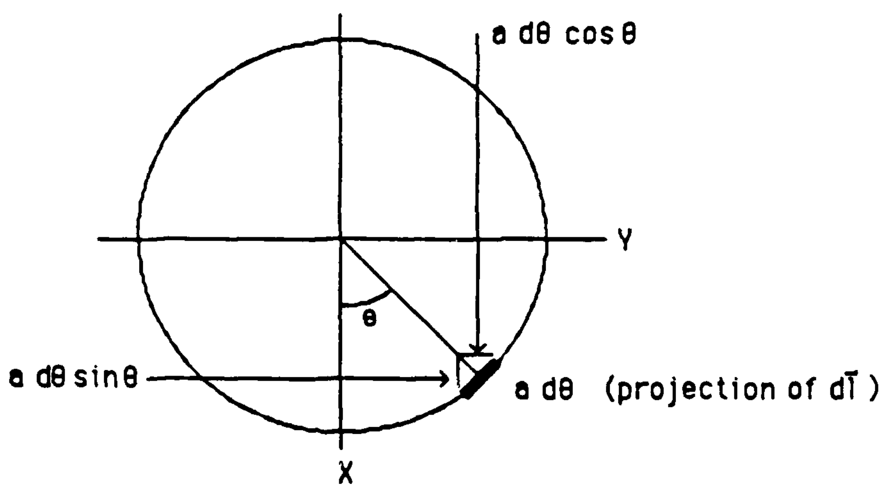
- Imagine a sheet of paper wrapped around a cylinder of radius a

- Draw one turn of the helix on the paper

- Unwrap the paper and lay it on a flat surface



Looking down the Z-axis (Z = 0 plane)



- $d\bar{l} = -a\sin\theta \, d\theta \, \hat{i} + a\cos\theta \, d\theta \, \hat{j} + \dfrac{d\theta}{2\pi n} \hat{k}$

- The helix rises a distance of $1/n$ for each revolution around the z-axis ($\theta = 2\pi$)

- $d\bar{l}$ is located at an angle θ and has therefore traversed the fraction $\theta/2\pi$ of a turn

- $\vec{r}_1$, the position vector for $d\bar{l}$, has a z component of $\theta/2\pi n$

$$\vec{r}_1 = a\cos\theta\,\hat{\imath} + a\sin\theta\,\hat{\jmath} + (\theta/2\pi n)\,\hat{k}$$

$$\vec{r}_2 = x\hat{\imath} + y\hat{\jmath} + z\hat{k}$$

$$\vec{r}_2 - \vec{r}_1 = (x - a\cos\theta)\,\hat{\imath} + (y - a\sin\theta)\,\hat{\jmath} + (z - \theta/2\pi n)\,\hat{k}$$

$$|\vec{r}_2 - \vec{r}_1| = \Big(x^2 - 2ax\cos\theta + a^2\cos^2\theta + y^2 - 2ay\sin\theta + a^2\sin^2\theta + z^2 - \theta z/\pi n + \theta^2/4\pi^2 n^2\Big)^{1/2}$$

$$|\vec{r}_2 - \vec{r}_1| = \Big(x^2 + y^2 + z^2 + a^2 - 2ax\cos\theta - 2ay\sin\theta - \theta z/\pi n + \theta^2/4\pi^2 n^2\Big)^{1/2}$$

$$d\vec{l} \times (\vec{r}_2 - \vec{r}_1) =$$

$$\begin{vmatrix} \hat{i} & \hat{j} & \hat{k} \\ -a\sin\theta\, d\theta & a\cos\theta\, d\theta & \dfrac{a\, d\theta}{2\pi n a} \\ (x - a\cos\theta) & (y - a\sin\theta) & (z - \dfrac{\theta}{2\pi n}) \end{vmatrix}$$

$$= \left[\, a(z - \frac{\theta}{2\pi n})\cos\theta\, d\theta \; - \frac{a d\theta}{2\pi n a}(y \; - \; a\sin\theta) \,\right] \; \hat{i} \; +$$

$$\left[\, a(z \; - \frac{\theta}{2\pi n})\sin\theta\, d\theta \; + \frac{a d\theta}{2\pi n a}(x \; - \; a\cos\theta) \,\right] \; \hat{j} \; +$$

$$\left[\, a(a\sin\theta \; - \; y)\sin\theta\, d\theta \; + \; a(a\cos\theta \; - \; x)\cos\theta\, d\theta \,\right] \; \hat{k}$$

The z component simplifies to

$$(a^2\sin^2\theta \; - \; ay\sin\theta \; + \; a^2\cos^2\theta \; - \; ax\cos\theta\,)\, d\theta \; \hat{k}$$

$$= (\, a^2 \; - \; ay\sin\theta \; - \; ax\cos\theta\,)\, d\theta \; \hat{k}$$

For a current I,

$$B_x = \frac{\mu_0 I}{4\pi} \int_0^{2\pi n L} \frac{\left[a\left(z - \frac{\theta}{2\pi n}\right) \cos\theta - \frac{1}{2\pi n}(y - a\sin\theta)\right]}{D} \, d\theta$$

$$B_y = \frac{\mu_0 I}{4\pi} \int_0^{2\pi n L} \frac{\left[a\left(z - \frac{\theta}{2\pi n}\right) \sin\theta - \frac{1}{2\pi n}(x - a\cos\theta)\right]}{D} \, d\theta$$

$$B_z = \frac{\mu_0 I}{4\pi} \int_0^{2\pi n L} \frac{\left[a^2 - ay\sin\theta - ax\cos\theta\right]}{D} \, d\theta$$

$$D = \left(a^2 + x^2 + y^2 - 2ax\cos\theta - 2ay\sin\theta + z^2 - \frac{\theta z}{\pi n} + \frac{\theta^2}{4\pi^2 n^2}\right)^{3/2}$$

The z component simplifies to

$$B_z = \frac{\mu_0 I n}{2} \left[\frac{z}{(a^2 + (L-z)^2)^{1/2}} - \frac{L}{(a^2 + (L-z)^2)^{1/2}} - \frac{z}{(a^2 + z^2)^{1/2}} \right]$$

Appendix D. Proposed Highway H3 Construction in Hawaii

A new highway (H3) has been proposed on the island of Oahu, Hawaii, which will pass under the Kaneohe OMEGA antenna. This project has been the subject of much controversy over the past several years for a number of reasons including electromagnetic effects from the OMEGA facility. The following discussion will address these effects on the basis of measurement results at this station and simplified electromagnetic theory.

There are three major areas of consideration regarding passage of the highway under the OMEGA antenna. These are as follows:

1. Effect of the highway on the antenna performance
2. Effects of the electromagnetic fields on highway construction.
3. Exposure of the public to electromagnetic fields when traveling on the highway.

Experiments performed during the site visit to the station provide data which may be useful in predicting the field strengths and shock potentials expected to occur. Using this data and the physical and electrical parameters of the station, it is possible to estimate certain effects.

An antenna's performance can, in general, be affected by large conductive objects located in the near-field. The interference is caused by induced currents on the object which can change the antenna's impedance and re-radiate signals which interfere with the primary signal due to phase differences. Interference is greatest when the conductor is a significant fraction of the antenna (or a wavelength) in length, and is aligned with the field polarization. In spite of its horizontal dimensions, the OMEGA antenna is essentially a vertically polarized monopole with extensive top loading. This means that large currents will be induced on vertical conductors which may then cause an interference. An additional mode of coupling with an antenna occurs when closed loops are aligned perpendicularly to the near-magnetic field. This condition also causes current induction.

The proposed route for H-3 takes it under the antenna at about a 40 degree angle with the horizontal direction of the antenna spans and then turns so that it is nearly perpendicular to the spans. The highway will rest on piers about 115 feet above the ground. Because of the steel beams and reinforcement, the highway can be thought of as a several thousand foot horizontal conductor elevated something more than a hundred feet above ground.

The OMEGA antenna employs an extensive ground radial system to improve the ground conductivity and provide a more stable load to the transmitter. The ground system consists of copper wires spaced 1 to 2 degrees apart radiating outward several hundred feet. Ground radials are typically buried a few inches under the ground but can migrate to the surface due to weather and soil conditions. The integrity of this system is crucial to the proper functioning of the station.

There are several issues with regard to grounding which may affect station performance. First of all, the ground radial system must not be broken. Excavation for pier footings will require cutting the radials, but even the movement of heavy machinery over buried radials will likely cause breakage. To prevent ground system degradation, the radials should be located and unearthed for some distance around the construction site. Broken radials must then be repaired as soon as possible. Presumably, the highway will be grounded and perhaps tied in with the ground radial system.

Grounding the highway will deform the existing ground plane shape by raising electrical ground to the highway surface. Because the highway represents over 100 feet of vertical extent, large currents will be induced on the piers (or ground straps attached to them) by the vertical electric fields under the antenna. This coupling will probably cause a small change in antenna impedance. However, the ground plane already follows the valley's terrain features and any effect of the highway should be easy to compensate for by the transmitter.

Other coupling modes exist which will also induce current flow on the highway. Changes in the elevation of the highway with respect to the antenna spans will introduce another vertical component parallel to the field lines. Currents will, thus, be induced along the length of the highway which extends about 1/20 of a wavelength in the antenna field. These currents could result in some re-radiation, especially if the highway were ungrounded. A common technique to reduce such effects is to break the conductor into smaller sections using insulators, but this technique may not be practical in the case of a highway where structural steel is used.

A third coupling mode will result from the interaction of the magnetic field with the rectangular loops formed by highway, ground, and piers. The magnitude of the current depends on the magnetic field strength, the area and inductance of the loops, and their orientation with respect to the field polarization. A rough estimate of the current in a single loop can be made using the relationship:

$$I = \frac{U_o H A}{L} \qquad \text{Equation D1}$$

Where U_o = the permeability of free space,
H = the magnetic field strength,
A = the area of the loop, and
L = the inductance of the loop.

If the average rms magnetic field strength across the loop area is estimated to be 0.4 A/m, the highway height is 115 feet, the pier separation is 275 feet and the inductance is estimated at 1.0 mH, an rms current of 1.5 amps is predicted. In terms of the rms antenna current of about 240 amps, the induced current from this mode is relatively small.

Prediction of the total effect of all interaction modes is not practical, but order of magnitude estimates can be made based on the highway dimensions and simplified electromagnetic theory. Considering that the highway height represents only one-tenth of the antenna height, it is not expected to substantially impair the antenna performance. Grounding the highway will make it act as a proturbance in the ground plane of which many already exist. The ground radial system, however, must be maintained.

The second major topic of consideration is the electromagnetic field effects expected to occur during road construction. Even a cursory analysis is enough to reveal that significant shock and field exposure hazards will exist during the construction phase. Reasonable estimations of induced voltages and field strengths can be made using the highway's physical dimensions and the OMEGA station's electrical parameters.

Because the OMEGA antenna is electrically short, very high voltages and currents are required in order to radiate the required power output. Antenna current is monitored constantly, but antenna voltage is not a measured quantity. The OMEGA antenna voltage is reported to be between 150,000 and 250,000 volts peak. Electric fields and induced voltages between large, closely spaced parallel plates can be simply calculated at low frequencies. This model is useful in predicting effects under the OMEGA antenna because the multiple spans form an upper "plate" above the ground plane. Reasonable approximations can be made using the antenna height above ground at the location of interest. The results will be more accurate near the middle of the antenna with field strength reductions occurring around the edges.

The best way to approximate voltages on the highway is to regard it as an electrically short antenna. An important parameter for an electrically short antenna is the effective height, He. The induced open-circuit voltage is then

$$V_{oc} = H_e * E \qquad \text{Equation D2}$$

where E is the magnitude of the electric field strength parallel to the antenna. The effective height of an antenna depends on its geometry as well as physical dimensions. A vertical thin wire above a ground plane has an effective height of approximately one-half its physical height, while closely spaced parallel plates have an effective height equal to their separation. The highway, with its road surface elevated 115 feet above ground falls somewhere between these two cases. An effective height of 0.7 times the physical height is likely a good approximation because of the capacitive top-loading by the flat highway surface.

The next step is to estimate the average (spatial) electric field strength in the region of the highway. Using the parallel plate approximation, the electric field is

$$E = \frac{V}{D} \qquad \text{Equation D3}$$

where V is the antenna voltage and D is the height of the antenna spans above the ground plane. When values of 250,000 volts peak for V and 300 meters for D (near the proposed highway location) are assumed, 833 V/m is estimated for the peak electric field strength before the highway is constructed. This result can be compared with a peak electric field strength of 465 V/m measured near the proposed highway site at 1.5 meters above ground (see Chapter VII). Electric field strengths around low frequency antennas are normally less intense near the ground than at several meters above ground due to terrain features and other reasons, so the measured values are in reasonable agreement with the predictions. These two values can also be considered as upper and lower bounds of the ambient electric fields to be expected before construction.

Voltages expected between the highway and ground can now be predicted using Equation D2. The effective height of the highway is approximated as 0.7 times the physical height of 35 meters or 24.5 meters. Thus, the peak open-circuit voltage between the highway and ground should be from 11,000 to 20,000 volts. These figures apply to the ungrounded case. Once the highway is grounded, the voltage will drop to zero, and a short-circuit current, Isc, will be induced on the grounding straps. The magnitude of Isc depends on the capacitance of the highway with respect to ground. Capacitance is difficult to calculate exactly, but an approximation can be made using the data derived by Baum (57). For a highway section 60 feet wide by 275 long, the capacitance should be at least 1000 pf. This value implies a source impedance of about 16 kilohms and a peak short-circuit current between 0.69 and 1.25 amperes.

Before discussing specific shock hazards, it is useful to consider the relationship between the peak voltages and currents, and the corresponding rms values. The peak values described above refer to the maximum amplitudes reached during a single cycle. Most safety standards refer to rms values. The rms-to-peak ratio of a sine wave is about 0.707, but OMEGA signals are pulsed sine waves and have different ratios (see Appendix B). Standards based on specific absorption rate (SAR) require true rms values which can be obtained by multiplying the peak electric fields by 0.507 in the case of the Kaneohe OMEGA. The situation is more complex in regard to shocks because the electric field strengths (and corresponding induced voltages) are lower at higher frequencies (F) by a factor of $1/F^2$, but the impedance decreases as 1/F. Thus, induced currents have an rms-to-peak ratio equivalent to the one for magnetic field (0.570) which also follows the 1/F relationship. These true rms values relate to the heating ability of the signal over periods of time greater than 10 seconds (6 minutes is a common averaging time).

Shock perception and damage is not necessarily dependent on the true rms current. OMEGA pulse trains consist of eight pulses, each lasting from 0.9 to 1.2 seconds. During a single pulse, the amplitude is constant and the rms-to-peak ratio is the sine wave value of 0.707. The effects of this particular pulse modulation on shock hazards may differ from that of a continuous signal, but it is reasonable to assume that most physiological responses will begin during a single pulse. Thus, the single pulse rms-to-peak ratio of 0.707 should be used when evaluating shock hazards (21).

Shock currents and body impedances at OMEGA frequencies have been investigated in two recent studies funded by the U. S. Air Force School of Aerospace Medicine (10) (11). Earlier work by Dalziel also extends up to frequencies of 10 KHz (17-21). Shock perception at OMEGA frequencies begins at a few milliamps, with pain and muscle control occurring between 37 and 55 mA for adults. Let go current, the value above which an individual loses ability to release the conductor, ranges from about 50 to 75 mA. Body currents of 94 mA in adult men are considered to be severe shocks, and the possibility of fibrillation is predicted to occur in humans at values of about 500 mA depending on body weight and duration of the shock. It should be noted that no direct evidence is available to validate the threshold for fibrillation, and that other severe effects including respiratory inhibition can occur at lower current levels.

Much useful data concerning body impedance under a variety of conditions has been presented in the recent studies cited above. At 10 kHz, the lower limit is about 500 ohms for a grounded individual grasping a conductive rod. Electrical safety shoes or gloves increase the impedance to over 100 kilohms depending on the contact area. For single finger contact with safety gloves, the impedance can reach 2.5 megohms. These values have a direct bearing on the amount of current an individual will experience when contacting a charged conductor. An important question to consider is which of the above values should be used to predict shock hazards. It is presumed that precautions such as safety shoes and gloves will be taken, but the possibility of shocks through contact of other body parts still exists. The climate of the OMEGA station is rainy and often humid, and it is reasonable to assume that workers will frequently be wet with either rain or perspiration. There has been some suggestion of using full-body conductive suits, but the practicality and effectiveness of these garments have not, to the author's knowledge, been tested under these conditions and frequencies. The following estimates will, therefore, be based on body impedances ranging from 500 ohms to 100 kilohms.

Electrical shocks to construction workers may occur under a wide variety of circumstances. The most severe case would result from contact with the full potential induced on a highway section before it is grounded, such as might occur during the grounding process. Using the open-circuit voltages and source impedance derived previously, this condition could result in body currents ranging from 67 to 860 milliamps rms (single pulse), or let-go to possible death. Less severe shocks could result from contact of a grounded individual with a large ungrounded vehicle. Guy and Chou (10) indicate that let-go current can be exceeded by contacting an ungrounded truck in fields greater than 300 V/m, as is the case on the ground near the highway site. Mild shocks are possible when an ungrounded individual touches a grounded object. If the individual is physically elevated above ground, the shocks can be more severe.

Another series of shock hazards result from the highly concentrated electric fields immediately above a vertical conductor. The resulting field strengths depend on the specific structure and are difficult to predict, but a good estimate of values expected above the highway surface are possible from the results of experiments performed at the OMEGA station. During the site visit to this station, electric and magnetic field strength meters were taken to the top of the counterweight tower. This grounded metal tower is about 120 feet high and represents the best available approximation to the highway surface. The counterweight cable connects to the bottom of the tower and extends at an angle to the feed line which is horizontally several hundred feet away. Thus, the tower is the highest grounded object in its immediate vicinity and is sufficiently removed from the feedline so that the ambient antenna fields (from the spans) dominate. The tower top is lower in elevation than the proposed highway surface due to terrain features, and the measured fields are therefore probably lower than would occur on the highway. Peak electric field strengths of 2000 V/m were measured near the middle of the tower top, and values of 3900 V/m to 5200 V/m were measured near the sides and corners. The pulse rms value of 2000 V/m peak is 1414 V/m which can be used to predict nominal shock effects. There are, however, some differences between these fields and the plane wave fields used as the basis of safety standards. An individual standing on top of the flat tower top becomes the highest electric ground in the area and serves a field concentration point. Induced currents will, in general, be greater for this case than the plane wave case, and field strengths several feet above the highway will be greater than the measured values above.

Shock hazards will be greater on the highway surface because of the enhanced field strengths. During the counterweight tower experiments, numerous shocks were encountered by the investigator when contacting the tower structure. This effect was due to induced voltages on the body (insulated by rubber sole shoes) finding a current path to the grounded tower. The shocks occurred through clothing when brushing against a conductive surface and were startling and painful. More severe shocks will be experienced if grounded workers contact insulated vehicles. Under these conditions and field strength levels, touching any sizeable ungrounded conductor, such as vehicles or suspended construction girders, can result in severe shocks. Because of the capacitive effects at these frequencies, electrical safety shoes provide only limited protection (i.e., impedances of about 100 kilohms), and let-go currents can be exceeded by objects with induced potentials of over 7,500 volts. At the field strengths expected above the highway, an object with an effective height of between 10 and 20 feet could produce the required voltage. Major shock potentials are also expected between highway sections due to the other voltage and current induction modes described earlier.

Electric and magnetic field lines around the highway will be complex and it is also possible to induce voltages on horizontal conductors. This effect was experienced at the LaMoure, ND, OMEGA station where very painful shocks occurred when stretching a metal tape measure horizontally more than about 20 feet. In general, shocks will occur any time the body contacts a conductor of sufficiently different potential to force several milliamps or more through the body impedance. On the highway surface, where fields are intense and complex, this condition can be expected to occur frequently unless all personnel, equipment, construction materials, and the highway itself are grounded, and large conducting loops are avoided.

Another issue in regard to construction is exposure of the workers to electric and magnetic fields. Most safety standards refer to rms field strengths, so the overall rms-to-peak ratios discussed in Appendix B must be applied to any peak field predictions or measurements. On the counterweight tower, the overall rms values away from edges and corners were about 1000 V/m for electric fields and 0.3 A/m for magnetic fields. This electric field strength is above the ACGIH occupational standard of 614 V/m, and the USAF standard of 434 V/m. It is equivalent to the NATO standard and less than the West German standard of 1500 V/m. Magnetic fields are below most existing standards (e.g., ACGIH which is 1.58 A/m) but can be expected to increase on the highway because of horizontal currents running along the length. Higher magnetic fields are also expected near any vertical conductor such as cranes and grounding straps as a result of induced currents. Some standards also limit SAR which according to Gandhi et al (11) can be exceeded for the ACGIH guide by ankle or wrist currents greater than 35 mA. The U. S. Environmental Protection Agency is evaluating general population exposure limits ranging from 87 V/m to 614 V/m for electric fields and 0.23 A/m to 1.63 A/m for magnetic fields (16), but no action has been taken yet. As stated earlier in reference to shock hazards, it is not clear that conductive suits will provide adequate field protection at OMEGA frequencies. It can be dangerous to assume that protective clothing which functions effectively at one frequency will also be effective at another frequency. For example, conductive garments which have been used successfully to safeguard against microwave signals can function as resonant chambers at lower radio frequencies creating hot spots and field intensification inside the suit. This particular effect is not expected at OMEGA frequencies, but capacitive effects may cause a difference in performance than experienced at power line frequencies where conductive suits have also been used. A conductive garment that does not also cover the head may concentrate the electric fields in the region of the head and neck. Research into the effectiveness and practicality of these suits is required before a reasonable evaluation can be made. Without protection, however, it is clear that workers will be exposed to electric field strengths in excess of existing U. S. standards.

Consideration must also be given to other construction practices which may be affected by the fields. Cables carrying 60 Hz power from the ground to the highway surface or even along the surface are likely to experience induced OMEGA currents. These currents may damage equipment or result in shocks unless filtering techniques are used. Flammable substances will have to be guarded against ignition by arcing and special precautionary measures will be required if explosives are used. Care must be exercised when cutting the ground radials to prevent shocks and arcing.

Exposure of the public to electromagnetic fields and shock hazards must also be considered if the highway is built. It is clear from the preceding discussion that field strengths on the highway surface will exceed existing occupational standards and present unacceptable exposures to the public. Electric field strengths can be reduced by placing metal cables over the highway and connecting them to electrical ground as has been suggested. The degree of field attenuation will depend on the height of the cables above the highway surface and their spacing. Experimentation to determine the optimum shield configuration will probably be necessary after an acceptable exposure level is established. Electric field shielding will not provide equivalent shielding for magnetic fields. In fact, induced currents on the shielding cables may enhance magnetic field strengths. The textbook case of zero magnetic fields inside a hollow conductor does not apply in this situation because of the uneven current distribution. This effect has been noted during field measurements inside energized LORAN-C towers. A substantial fraction of the magnetic field strength measured outside the tower was also measured on the inside. RMS values of magnetic field strength ranged from 0.3 A/m to 0.9 A/m over the surface and sides of the counterweight tower which has only a few meters of horizontal extent. The highway will conduct more current horizontally as described earlier, and currents in the vertical portions of the shielding cables will also add to magnetic field strengths on the surface. The rms magnetic field strengths on the highway will probably range from 0.3 A/m to 1.0 A/m with the shielding in place except for local concentrations which will occur near certain conductors. These values can be compared with the general population standards proposed by EPA which range from 0.23 A/m to 1.63 A/m for OMEGA frequencies. Reduction of magnetic fields is more difficult than electric fields because of current distributions as described above. Overhead cables placed 10 feet apart may significantly reduce electric fields but have little effect on magnetic fields. Continuous shielding such as sheeting or wire mesh is more effective especially if the material used has a high relative permeability.

The question of acceptable exposure levels is a difficult one, especially when planning for the future. Most existing U. S. standards are based on thermal effects and shock hazards. Electromagnetic fields deposit heat energy in the body depending on frequency, field strength, and polarization. Exposure limits are presently set at the field strengths capable of inducing only small amounts of heat energy which are easily compensated for by the body's thermoregulatory system. If this criterion is used to set exposure limits on the highway, then it may be possible to design a shield to meet the standard. Both energy deposition and shock hazards could be reduced to minimal levels by keeping the electric field strengths below 100 V/m. Magnetic fields would not be an issue because they couple poorly with the body and deposit only about one-sixth as much energy as the equivalent (plane wave) electric field.

The situation becomes more complex, however, if non-thermal effects are considered. Non-thermal effects refer to changes in living systems resulting from exposures to electromagnetic fields which are not intense enough to cause significant heating. There has been widespread disagreement in the past concerning the existence of non-thermal effects, but the weight of evidence is apparently leaning in their favor. A recent National Research Council report (22) acknowledges the abundance of reported non-thermal effects. This field of investigation is still in its infancy and can at present offer no specific guidelines. However, efforts are now being made to replicate and quantify some of the experiments. One example is the finding that weak pulsed magnetic fields can induce embroyological changes in chicken eggs (30) (31). Some of the results have been replicated in Finland (32) 33), but other attempts to reproduce the effect have failed (34) (35). The Office of Naval Research is currently funding a multi-national effort to verify the effect (36). Studies similar to these are being carried out by various agencies, but it is likely to be some time before mechanisms and threshold limits are well understood. Unfortunately, little effort has been made to study biological effects at OMEGA frequencies because they are not commonly used elsewhere. No general recommendations based on non-thermal effects can be made at this time, but it is clear that the final word concerning safe exposure levels is not yet in.

The choice of exposure limits for the highway should include consideration of the EPA proposals and the health effects literature. Although no enforceable standards exist at present, the enforcement of a future standard such as the lowest EPA proposal could present serious technical problems and legal issues. Experiments should be performed before building the highway to determine the practicality of shielding to acceptable public exposure levels. The lowest EPA proposal of 87 V/m and 0.23 A/m could serve as a guideline for this purpose.

In summary, construction of the proposed H-3 highway under the OMEGA station would, at best, be hazardous and expensive. Failure to anticipate and mitigate shock hazards could result in serious injuries or death to construction workers. The effects of exposing workers to OMEGA field strengths of 1000 V/m or more for extended periods are not known, and protection methods have not been proven under these circumstances. Designing an effective shield would require experimentation to determine the configuration and quantity of materials to be used. The problems outlined above are not insurmountable, but could present serious difficulties if they are not thoroughly studied and resolved.

Appendix E. Simplified Model for Prediction of LORAN-C Field Strengths

Magnetic fields are generally easier to calculate analytically than electric fields for most configurations as long as the antenna current is known. A simple model for predicting magnetic field strengths around LORAN-C stations is presented here to facilitate determination of the requirements for standards compliance at new or modified stations. Development of such a model is possible because the antenna current for each station is measured and recorded as a part of normal operations. The model is useful because in nearly all cases, the magnetic field strengths near LORAN-C stations are higher than the electric field strengths on a plane wave equivalence basis. Thus, magnetic fields are the important quantity in determining areas in which the standard is exceeded.

The magnetic field strength created by an infinite wire is simply

$$H = \frac{I}{2*PI*Dm} \qquad \text{Equation E1}$$

Where I is the current and Dm is the perpendicular distance to the calculation point in meters. LORAN-C antennas are not infinite conductors, but considering that the apparent length is double the physical height because of the image reflected in the ground plane, they are large compared to most distances of interest. This formula is surprisingly accurate for calculating peak magnetic field strength at a distance Dm from the tower using the antenna current for I.

The antenna current is measured using a Pearson current transformer which outputs one volt for every ten amps of current. The Pearson voltage, Vp, rather than the current, is the recorded quantity. Expressed in terms of Pearson voltage and distance from the tower in feet, Df, Equation E1 becomes

$$H\ peak = \frac{10\ Vp}{1.92\ Df} = (5.22)\ \frac{Vp}{Df} \qquad \text{Equation E2}$$

Most exposure standards are stated in terms of rms rather than peak field strengths. The rms magnetic field strength can be calculated by incorporating the rms-to-peak ratio into Equation E2.

$$H_{rms} = (1.044)\left[\sqrt{\frac{100\ N_1}{GRI_1} + \frac{100\ N_2}{GRI_2}}\right]\frac{V_P}{D_f} \qquad \text{Equation E3}$$

In this equation, both Group Repetition Intervals (GRIs) can be included for dual-rated stations or one of the radicals can be left out for single rated stations. N is the number of pulses per train which is equal to 8 for secondary stations and 9 for master stations. This formula is based on ideal LORAN-C pulse shapes and will slightly overestimate rms values in most cases.

Equation E3 can be modified to calculate the distance from a station required to comply with a given magnetic field strength limit, HL.

$$D_f = (1.044)\left[\sqrt{\frac{100\,N_1}{GRI_1} + \frac{100\,N_2}{GRI_2}}\right]\frac{V_p}{H_{rms}} \qquad \text{Equation E4}$$

Equation E4 can be applied by inserting the parameters for the desired station, along with the magnetic field strength limit of interest. The parameters for the Dana, IN LORAN-C station are

N_1 = 9
N_2 = 8
GRI_1 = 8970
GRI_2 = 9960
Vp = 65 volts

Table E1 shows the results of Equation E4 along with modeling and measurement results for the station. As expected, the results are more accurate close to the tower.

Table E1. Simplified Model Results for Dana, IN.

Magnetic Field Strength Limit (A/m)	NEC Modeling Results (feet)	Measurement Results (feet)	Simplified Model Results (feet)
0.23	115	97	125
0.73	38	38	40
1.63	16	19	18

Appendix F. Recommendations for Future Stations.

Electromagnetic field exposures at future LORAN-C facilities can be reduced by incorporating a few design considerations based on the study findings. The most obvious recommendation is to locate the towers as far as possible from the station buildings and work areas. An example is the Dana, IN station which has the antenna tower separated from the rest of the buildings by several hundred feet. Except for maintenance operations at the tower, personnel exposures are normally very low. A slightly less effective configuration consists of the tower located next to the transmitter building with other station buildings much further away. The Jupiter, FL station is an example. Here, only a few station personnel regularly pass by the antenna. These individuals spend most of their time indoors watching signal generation equipment.

Positioning the antenna tower a long distance from the transmitters leads to line losses and higher construction costs and may not be possible in all cases. However, even a separation of 50-100 feet significantly reduces exposures. As a minimum, towers should be positioned behind the buildings and opposite the incoming road and parking lot. All towers should be surrounded by substantial fences preventing approach closer than 25 feet (or more if possible).

Transmitter rooms should be designed to separate normal work activities from the final tuning coils. All coils should be shielded by steel enclosures to attenuate the fields. If the transmitter building is positioned next to the antenna tower, then efforts should be made to avoid the area near the adjacent wall where field strengths are high.

New stations should be located in remote areas whenever possible. As a minimum, the Coast Guard should control and prevent access to areas inside the top radial anchor points. The lowest guy wire insulators should be out of reach, and warning signs should be posted to remind the public and station personnel to observe necessary precautions.