AD NUMBER	
AD348726	
CLASSIFICATION CHANGES	
TO:	unclassified
FROM:	confidential
LIMITATION CHANGES	
TO:	Approved for public release, distribution unlimited
FROM:	Distribution authorized to U.S. Gov't. agencies and their contractors; Administrative/Operational Use; 30 NOV 1963. Other requests shall be referred to Office of Naval Research, One Liberty Center, 875 North Randolph Street, Arlington, VA 22203-1995.
AUTHORITY	
30 nov 1975, DoDD 5200.10; onr ltr, 4 may 1977	

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VERY-LOW-FREQUENCY PROPAGATION RESEARCH FINAL REPORT

30 November 1963

Submitted to

Office of Naval Research
Washington, D. C.

APPLIED RESEARCH LABORATORY

SYLVANIA ELECTRONIC SYSTEMS
Government Systems Management
for GENERAL TELEPHONE & ELECTRONICS

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VERY-LOW-FREQUENCY PROPAGATION RESEARCH

FINAL REPORT

Contract Nonr 3185(00)

NR 371-650

30 November 1963

Submitted to

Office of Naval Research
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Downgraded at 3 year intervals:
Declassified after 12 years.
DOD Dir 5200.10

APPLIED RESEARCH LABORATORY
SYLVANIA ELECTRONIC SYSTEMS
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INTRODUCTION

This is the second "final" report issued under this contract. It contains reports in summary form of investigations completed and new investigations initiated since the final report dated March 30, 1962. The aim of the program has remained as the undertaking of theoretical research to determine suitable electromagnetic models of the ionosphere (and earth) which can be used to predict terrestrial propagation observables at frequencies below 3 kc/s. (Extremely-Low-Frequency band).

Liaison has been maintained with experimental VLF/ELF propagation programs and related theoretical research at the National Bureau of Standards, Central Propagation Laboratory, Lincoln Laboratory of the Massachusetts Institute of Technology, Air Force Cambridge Research Laboratories, Radio Corporation of America, the U.S. Navy Electronics Laboratory, U.S. Navy Underwater Sound Laboratory and the Naval Research Laboratory, Stanford Research Institute and Stanford University, University of Rhode Island, Harvard University, University of Alaska, and the University of Texas.

Commencing in December 1962, a special study was undertaken to use the propagation models developed earlier together with thunderstorm activity maps to develop an ELF noise prediction technique. A schedule for simultaneous noise measurements at widely separated places by DECO Electronics was set up by agreement with Sylvania, DECO and ONR, NRL and USNUSL personnel. Some of the early data thus gathered was used to determine the normalization constant required in this technique. Unfortunately, funds on the contract were exhausted before this task could be completed.

At the request of ONR a brief study was made of the perturbation of an electromagnetic wave propagating over the sea caused by a submerged conducting sphere supposed to represent a submarine. The results of this study were presented in a letter to A. Shostak, ONR, Washington, dated 25 August 1962.

In June of 1962 Drs. H. Raemer and J. Galejs attended the NATO sponsored ELF meeting in Paris, and presented papers describing their work on the ELF noise spectrum in the cavity resonance region, and ELF propagation below an exponentially tapered ionosphere.

For two weeks in July of 1963 Dr. Galejs served as a faculty member at the NATO sponsored ELF Summer Institute in Bad Homburg, Germany, where he headed the panel on ELF propagation.

Five summary status reports covering the period 18 June 1962 to 30 September 1963 have been issued. Several verbal presentations to Navy personnel have been given and, since the March 30, 1962 final report, six technical reports have been issued bringing the total to 19 in addition to two interim letter reports on the ELF noise prediction study.

Most of the research completed on this contract has appeared in the open literature. To date two letters and eight full length papers have been published. These are listed at the end of this report.

This report consists in the main of summaries of the several individual researches carried out. With few exceptions the full details have been reported as indicated above.

EFFECT OF SEA SURFACE MOTION ON SUB-SURFACE FIELDS

This project, whose motivation was described in the final report of 30 March 1963, was completed with the issue of a report which appeared as a paper.[1] In this study attention was focused on the fluctuations in the subsurface horizontal electric field (pointing in the direction of wave motion) caused by surface waves. Extensive numerical computations of the mean square deviation of this field component were carried out for unidirectional surface waves of random height having an assumed Gaussian correlation function. The direction of wave travel, RMS wave height and correlation length, frequency of the source and depth of the observer were varied. With this many parameters the results cannot be presented succintly, however, a few general observations will be noted here. The mean square deviation (MSD) of the fluctuations decrease with increasing observer depth and frequency, and for small and large correlation distance.

ELF/VLF PROPAGATION BELOW A TAPERED ANISOTROPIC IONOSPHERE

In the final report dated 30 March 1962, mention was made of some possible effects of D-region ions on ELF propagation. A great deal of analytical work and numerical computation has been done since then. Attention has been directed to cases where the earth's magnetic field is horizontal. Two

1. Winter, D.F., "Low-Frequency Radio Propagation into a Moderately Rough Sea," Jour. Res. Nat. Bur. Stds. 67D, 551, Sept.-Oct. 1963.

reports have been issued and submitted for publication.[2,3] Figure 1 is a plot of the dominant waveguide mode attenuation constant for various directions of propagation in geomagnetic equatorial regions. Figures 2 and 3 show the normalized dominant mode propagation constants in the frequency region 5 to 50 cps. Sizeable non-reciprocity is evident between EN and WE directions of propagation. As seen from Figure 2, very large differences in attenuation rates are predicted for daytime propagation at frequencies from 5 to 15 cps. At the present time there is no direct experimental data available to check these predictions against. This predicted non-reciprocity may be the reason for the observed diurnal variations in the frequencies of the peaks in the ELF noise spectrum observed by Balser and Wagner and others. No detailed investigation has been made into this possibility. However, there is some reported data on non-reciprocity in WE and EW propagation at VLF. Figure 4 shows a plot of the predicted daytime rates from reference 3. The measured data are in general agreement with the predictions but exhibit about a half db/1000 km greater attenuation.

An investigation into the correctness of using a plane wave surface impedance in the determination of the mode constants at VLF was initiated towards the end of this reporting period. It was hoped that this would shed some light on the problem of choosing a height for the lower edge of the ionosphere.

PREDICTION OF ELF NOISE LEVEL

The object of this study is to predict the diurnal and seasonal RMS noise level for any point on the earth in the ELF band (3 cps-3 kcs). The basis for the method devised was to use worldwide thunderstorm activity maps from the Geophysics Handbook for Air Force Designers, the diurnal thunder probability distribution which peaks about 1600 hours local time,[4] and the

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2. Galejs, J., R.V., Row, Propagation of ELF Waves Below an Inhomogeneous Anisotropic Ionosphere, Research Report 334, 10 April 1963, Applied Research Laboratory, Sylvania Electronic Systems. To appear in IEEE Transactions Prof. Tech. Grp. Antennas and Propagation, Jan. 1964.

3. Galejs, J., ELF and VLF Waves Below an Inhomogeneous Anisotropic Ionosphere, Research Report 350, 9 August 1963, Applied Research Laboratory, Sylvania Electronic Systems.

4. Williams, J.C., "Thunderstorms and Very-Low Frequency Noise", Ph.D. Thesis, Division of Engineering and Applied Physics, Harvard University, June 1959.

spectrum of the average return lightning stroke[5], together with Galejs[6] model of propagation below an exponentially tapered conductivity versus height profile of the ionosphere, to predict the RMS noise spectrum of the vertical electric field. Because there was interest in frequencies well above the resonance region (5-35 cps) it was necessary to extend the individual dipole moment stroke spectrum out to at least 1 kc. It was discovered in the course of attempting this that the available data on stroke current waveforms and statistics is insufficient. Consequently the stroke spectrum was taken arbitrarily to be flat out to 1 kc. Data from Ushuaia, Argentina and the Panama Canal Zone (averaged over several days) were used to normalize the absolute level of the noise at a frequency of 35 cps. Figure 5 shows a plot of the predicted spectrum at Ushuaia and Figure 6 the predicted spectrum at Malta. Originally it was intended to have DECO measure noise simultaneously at three widely separated sites and compare the predictions from one to the other. Such measurements were made in June 1963 at Malta, Boulder, Colorado and Fairbanks, Alaska. However, the data has not been processed up to this time.

It was recognized that sources near an observer or his antipode are incorrectly weighted by the usual simple asymptotic expansion of the function $P_\nu(-\cos\theta)$, which was used in the above computations. Work was initiated to develop a more satisfactory approximation in these regions. Lack of funds have not permitted the reworking of the numerical computations including this correction. A rough calculation has been made where the contribution of noise sources (lightning strokes) within 50 degrees of the observer and his antipode have been neglected. Figure 7 shows a plot of the calculated diurnal variation of the noise at frequencies of 8, 14 and 20 cps for an observer at Ipswich, Massachusetts. Figure 8 shows the corresponding experimental observations of Balser and Wagner. In view of the crudeness of the theoretical model the comparison is encouraging.

The thunderstorm activity maps used in this task are compiled from a variety of sources and refer only to thunder heard. It is not clear *a priori*

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5. Raemer, H.R., "On the Spectrum of Terrestrial Radio Noise at Extremely-Low-Frequencies," *Jour. Res. NBS* *65D*, 581, Nov. 1961.

6. Galejs, J., "Terrestrial Extremely-Low-Frequency Noise Spectrum in the Presence of Exponential Ionospheric Conductivity Profiles," *Jour. Geophys. Res.* *66*, 2787, Sept. 1961.

that there is a one-to-one correspondence between the surface density of the average vertical dipole moment strength of the initiating lightning strokes and thunder itself. If indeed lightning is the dominant source of ELF noise in the cavity resonance frequency region then it should be possible to work the prediction technique in reverse, so to speak, and to construct maps of lightning dipole density. Work was started on determining a suitable analytical - computational technique for processing measurements from a grid of observing stations which measure the RMS or average noise at the same frequencies simultaneously. This work is necessary to determine how many stations and frequencies would be necessary to achieve a given mapping coverage of the world. If such a scheme were feasible it could result in a much better picture of worldwide thunderstorm activity and serve as the basis of a better noise prediction service at VLF and possible HF. Unfortunately no conclusive results were available at the time of writing.

GUIDED WAVES NEAR THE AIR-IONOSPHERE BOUNDARY

A study was undertaken, by a consultant, into the possibility of launching guided ELF or VLF waves from a source near the air-ionosphere boundary. This would pertain to a transmitter in a low orbit satellite, to upward lightning strokes and possible to the propagation of micropulsations. The work is reported in two technical reports.[7,8]

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7. Seshadri, S.R., A. Hessel, Radiation from a Source Near a Plane Interface Between an Isotropic and a Gyrotropic Dielectric, Research Report 339, Applied Research Laboratory, Sylvania Electronic Systems, 27 May 1963.

8. Seshadri, S.R., Radiation from Electromagnetic Sources in a Plasma, Research Report 344, Applied Research Laboratory, Sylvania Electronic Systems, 5 June 1963.

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"Propagation of VLF and ELF Radio Waves Excited by a Horizontal Magnetic Dipole," 16 August 1960.

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"Low Frequency Slot Antennas," 9 September 1960.

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"The Effect of Induced Polarization on Propagation," 28 September 1960.

APPLIED RESEARCH MEMORANDUM 234 Part I, H. Raemer

"On the Spectrum of Terrestrial Radio Noise at Extremely Low Frequency," 7 February 1961.

APPLIED RESEARCH MEMORANDUM 240, J. Galejs

"ELF Waves in the Presence of Exponential Ionospheric Conductivity Profiles," 11 April 1961.

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"On the Resonant Frequencies of the Schmann Modes," 30 June 1961.

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"Tensor Conductivity and ELF/VLF Indices of Refraction for the D-Region," 31 July 1961.

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"Further Note of Terrestrial ELF Propagation in the Presence of an Isotropic Ionosphere with an Exponential Conductivity Height Profile," 7 December 1961.

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"Low Frequency Radio Propagation into a Moderately Rough Sea," 5 March 1963.

RESEARCH REPORT 334, J. Galejs and R. Row

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Work partially supported under Nonr 3185(00)
Research Report 339, S. R. Seshadri, A. Hessel

"Radiation from a Source Near a Plane Interfact Between an Isotropic and a Gyrotropic Dielectric," 27 May 1963.

RESEARCH REPORT 344, S. R. Seshadri

"Radiation from Electromagnetic Sources in a Plasma," 5 June 1963.

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2. "Effect of Underground Induced Polarization of ELF Propagation," H. Raemer, Jour. Geophys. Res. 66, 1596, May 1961.
3. "On the Extremely Low Frequency Spectrum of Earth-Ionosphere Cavity Response to Electrical Storms," H. R. Raemer, Jour. Geophys. Res. 66, 1580, May 1961.
4. "ELF Waves in the Presence of Exponential Ionospheric Conductivity Profiles," J. Galejs, IRE Trans. Ant. Prop. AP-9, 554, November 1961.
5. "On the Spectrum of Terrestrial Radio Noise at Extremely Low Frequencies," H. R. Raemer, Jour. Res. NBS, 65D, 581, November-December 1961.
6. "Terrestrial Extremely Low Frequency Noise Spectrum in the Presence of Exponential Ionospheric Conductivity Profiles," J. Galejs, Jour. Geophys. Res., 66, 2787, September 1961.

7. "A Further Note on Terrestrial Extremely Low Frequency Propagation in the Presence of an Isotropic Ionosphere with an Exponential Conductivity Height Profile," J. Galejs, Jour. Geophys. Res. 67, 2715, July 1962.

8. "Terrestrial Extremely Low Frequency Propagation in the Presence of an Isotropic Ionosphere with an Exponential Conductivity Height Profile," J. Galejs, Proceedings of the International Conference on the Ionosphere, London, July 1962.

9. "On the Electromagnetic Resonant Frequencies of the Earth Ionosphere Cavity," R. Row, IRE Trans. Ant. Prop. AP-10, 766, November 1962.

10. "Low Frequency Radio Propagation into a Moderately Rough Sea," D. F. Winter, Jour. Res. NBS, 67D, 551, September-October 1963.

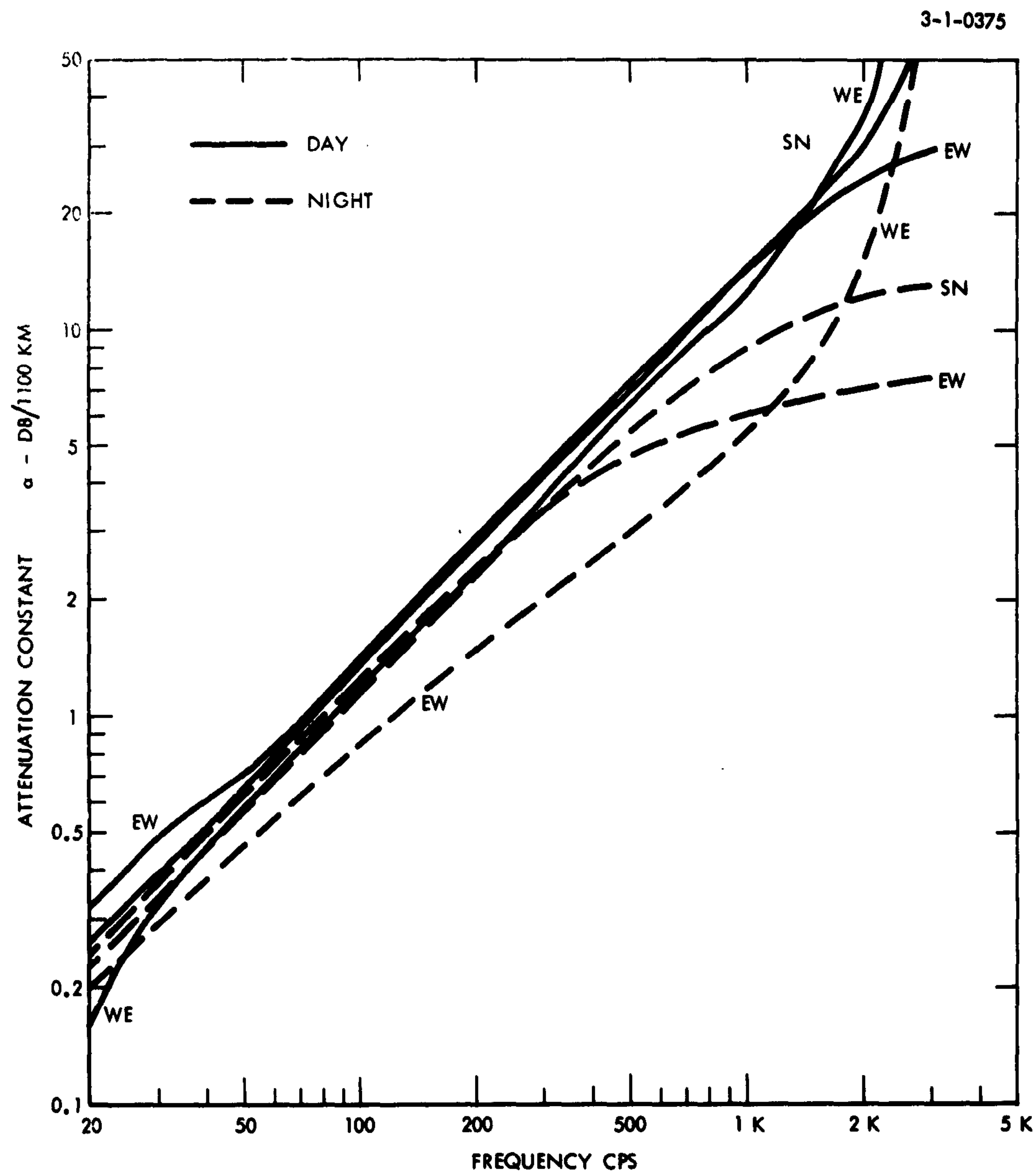

Figure 1. ELF Attenuation Constants

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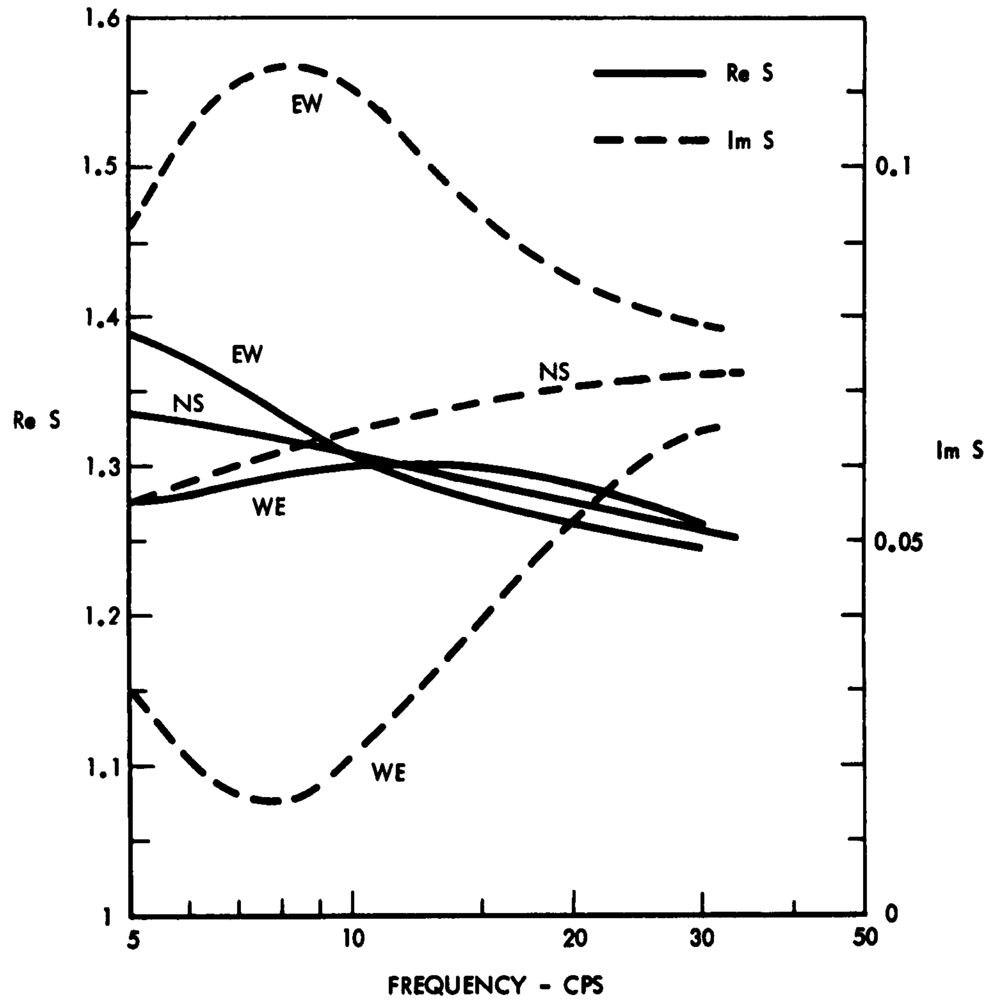

Figure 2. Normalized Propagation Constants - Daytime - With Ions Considered

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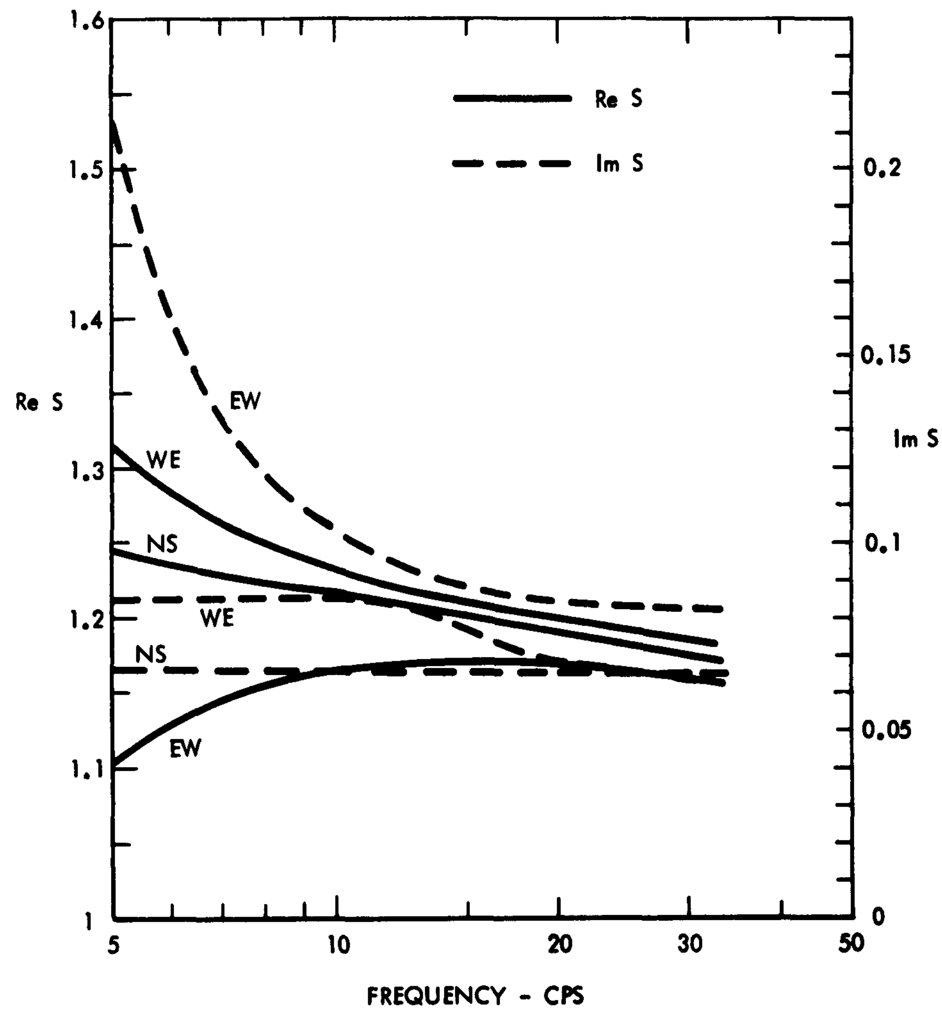

Figure 3. Normalized Propagation Constants - Nighttime - With Ions Considered

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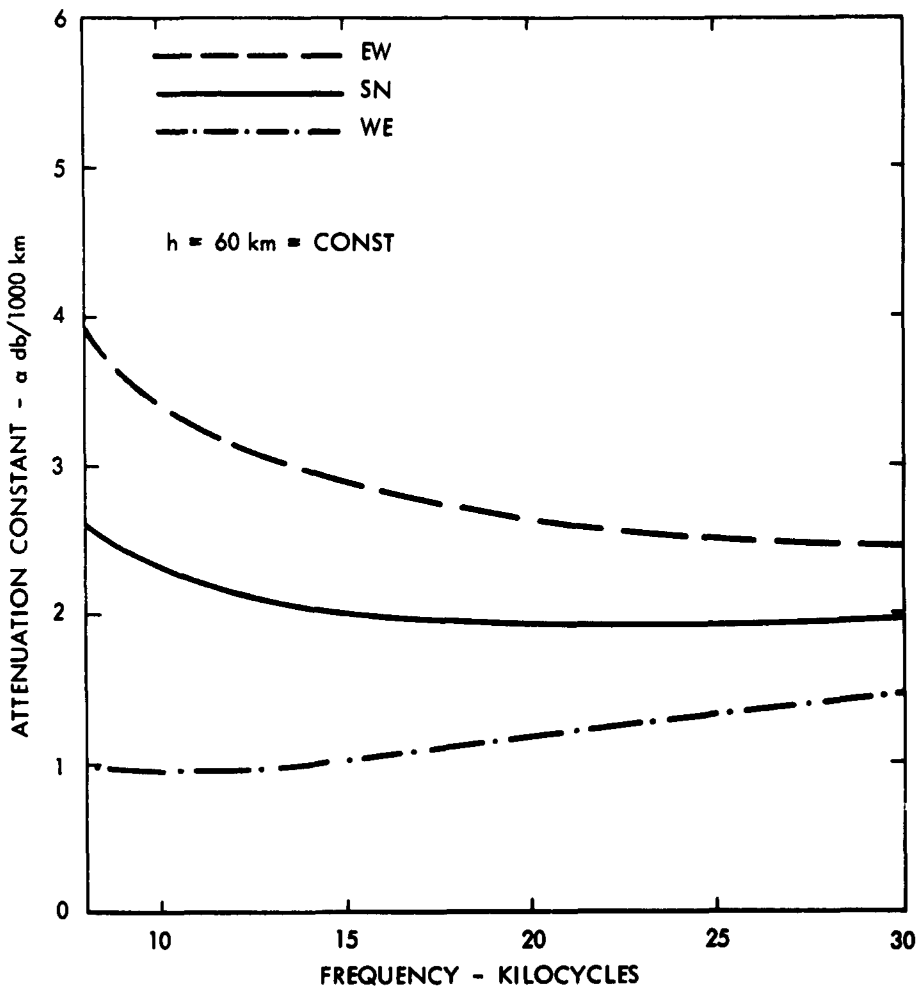

Figure 4. VLF Daytime Attenuation Rates - Electronic Plus Ionic Conductivity

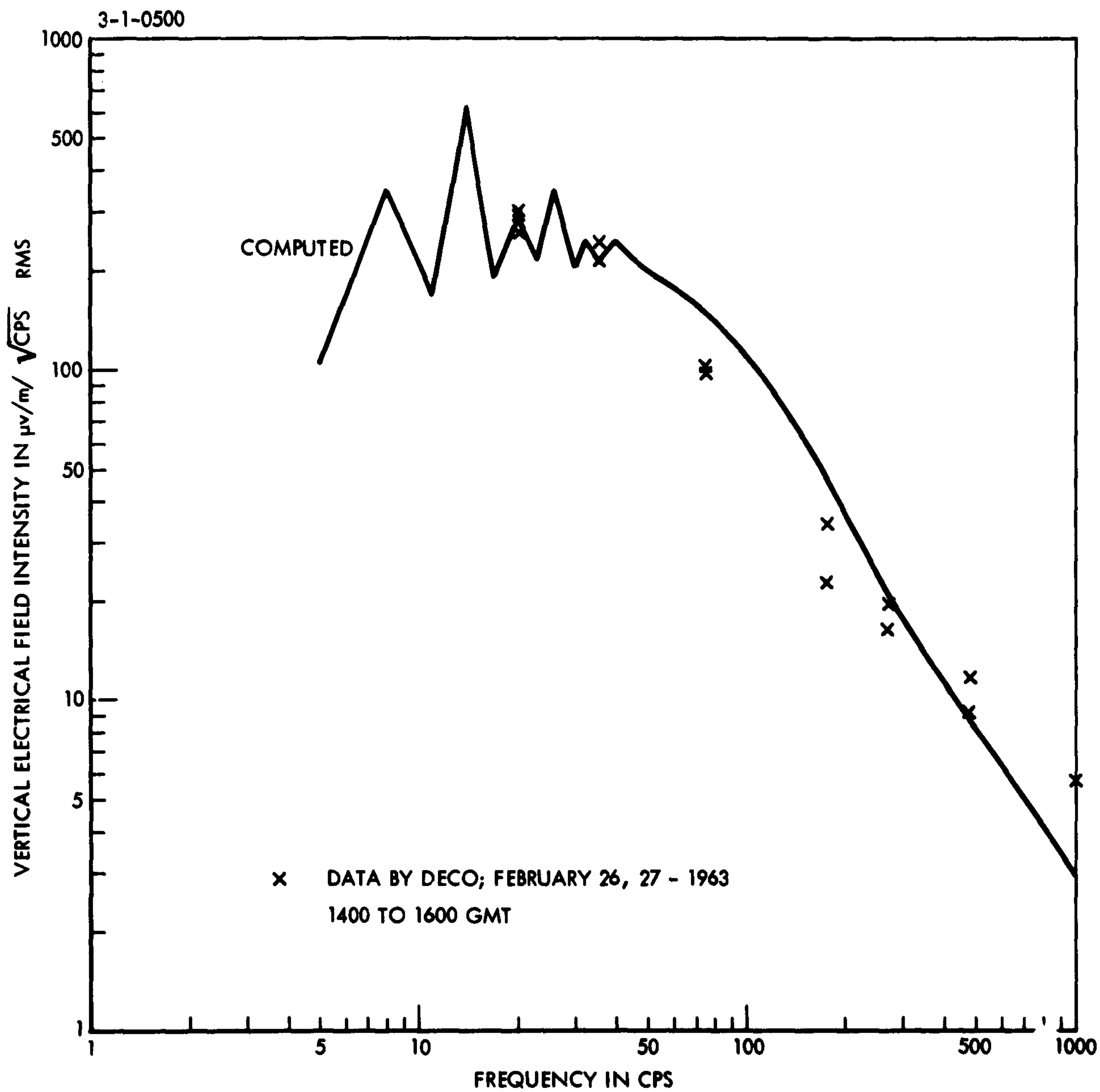

Figure 5. ELF RMS Noise Field - Ushuaia, Argentina - 1500 GMT

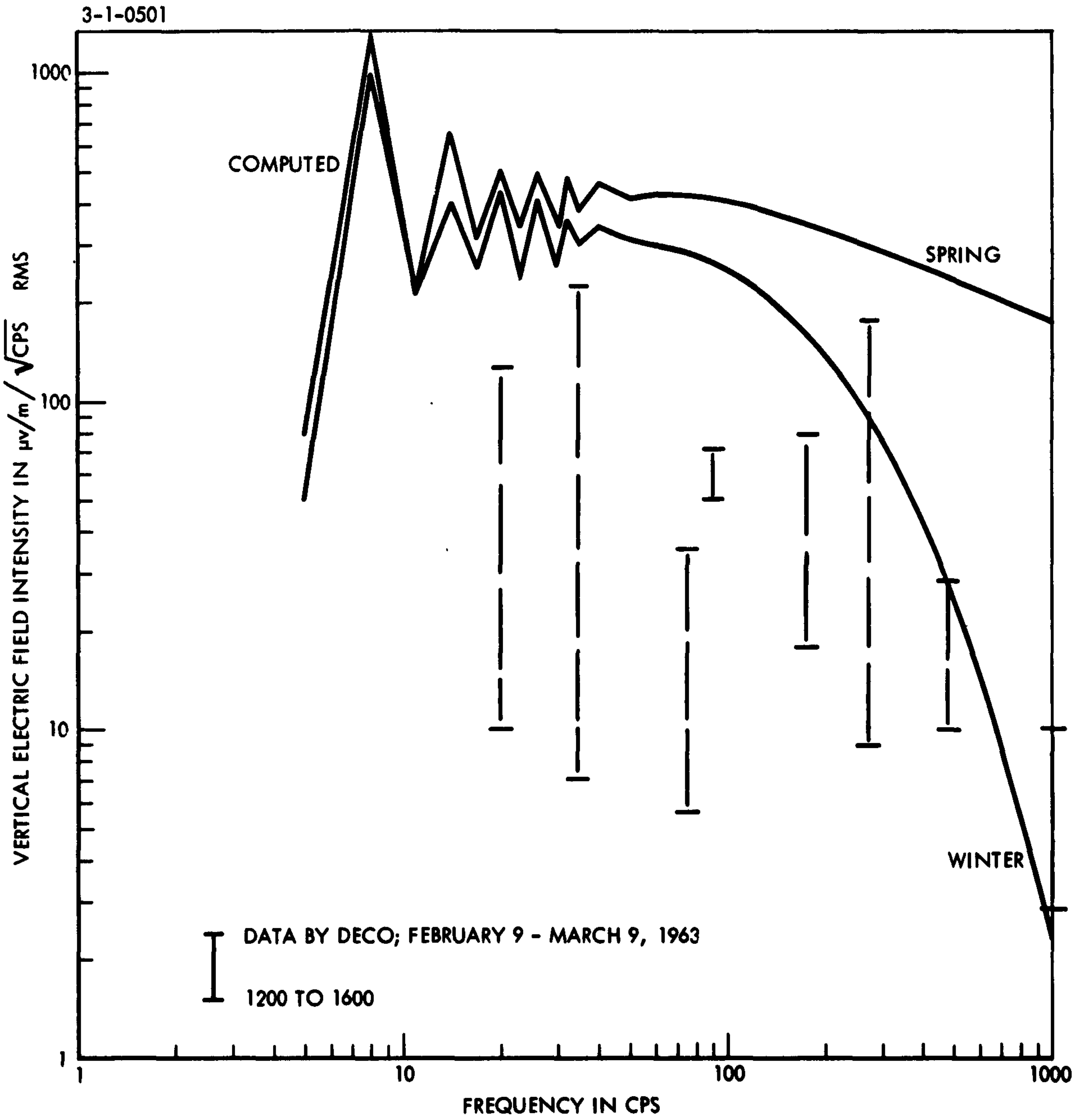

Figure 6. ELF RMS Noise Field - Island of Malta - 1500 GMT

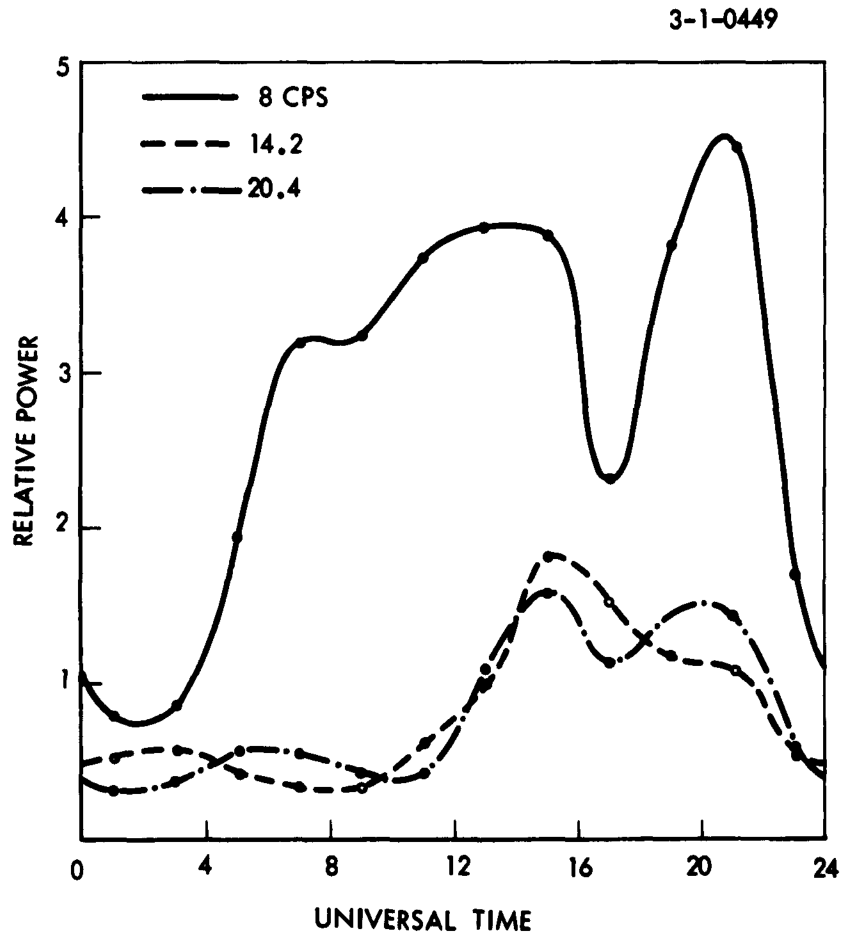

Figure 7. Calculated Diurnal Variation of Noise Power at the Peak of the Resonance Modes - Wintertime - Boston, Massachusetts

3-1-0502

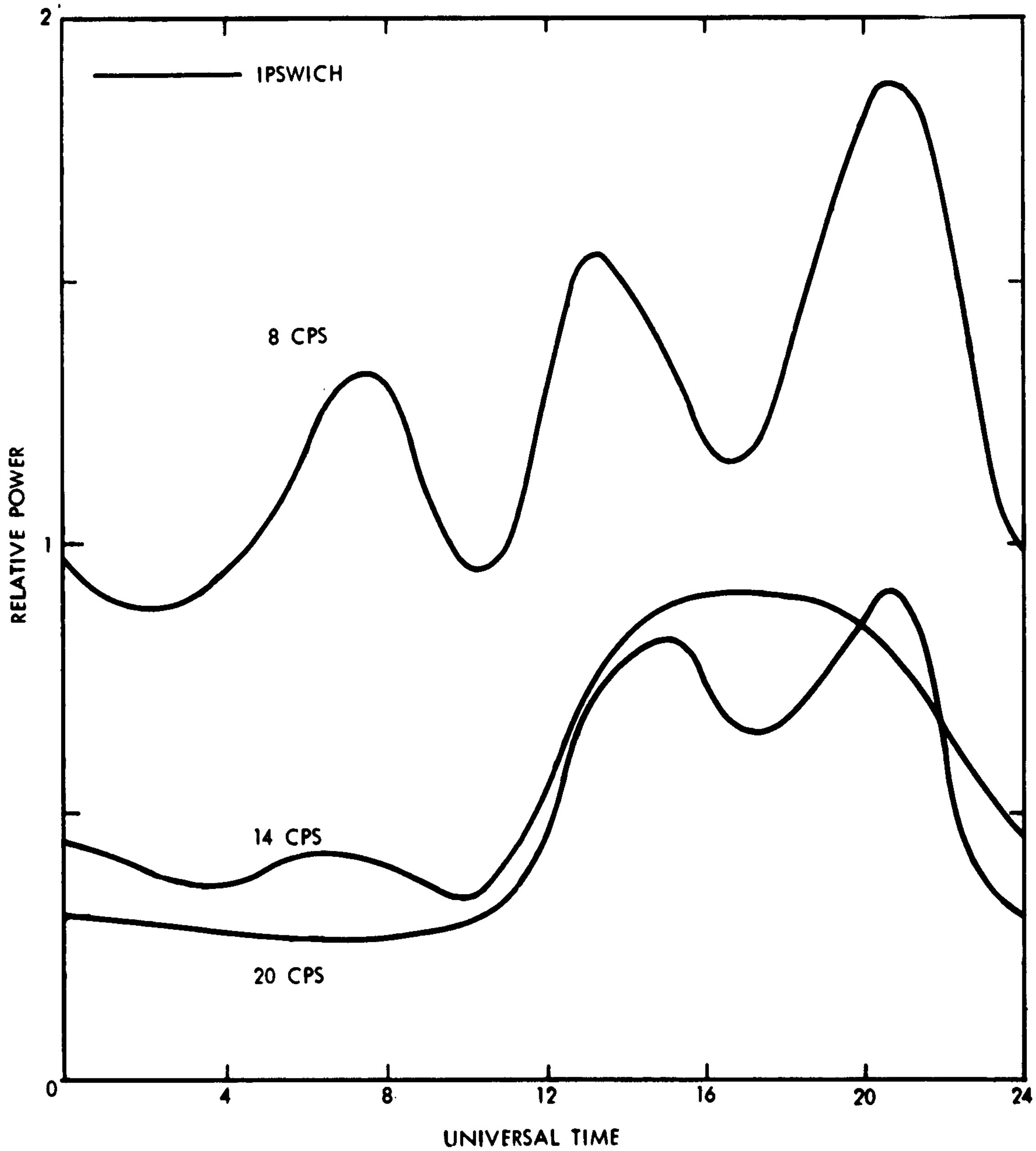

Figure 8. Measured Diurnal Variation of Noise Power at the Peak of the Resonance Modes - Ipswich, Massachusetts - February, 1961