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Field Intensity Measurements at 10.2 kc/s Over Reciprocal Paths

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Experimental data at 10.2 kc/s are presented which demonstrate nonreciprocity in attenuation rates for propagation in the east-west directions, and that reciprocity exists in the north-south direction along a magnetic meridian. The experimental evidence, recorded for propagation paths of 3,820, 7,830, and 8,450 kilometers, compares well with theoretical attenuation rates at 10 kc/s given by J. R. Wait and K. Spies.

1. Introduction

The purpose of this paper is to present measured VLF field intensities at 10.2 kc/s for signals propagated in both directions over three different paths. One of these paths corresponds closely to the geomagnetic equator; the second path is oblique to the geomagnetic meridian; the third path is in the direction of a geomagnetic meridian. The paper will demonstrate nonreciprocity in attenuation rates for propagation in the east-west and west-east directions, and that reciprocity is the case in the north-south direction.

The data reported herein were collected in development and evaluation of the Navy's experimental OMEGA VLF Navigation System.

The first substantial experimental evidence of nonreciprocity in attenuation of VLF signals, propagated over paths in the general east and west directions, is credited to Crombie in a paper published in 1958. Crombie's paper reviews the earlier observations [Barber, 1959; Wait, 1957; Budden, 1951 and 1954; Round, 1925] which led to the hypothesis of nonreciprocity in specific cases of VLF propagation. These prior works were mainly concerned with boundary value solutions representing models of the ionosphere with and without superimposed transverse magnetic fields. Two papers of note [Crombie, 1960; Wait and Spies, 1960] concern the special case solution for propagation along the magnetic equator.

The theoretical values for attenuation rates are compared with the experimental data reported herein.

2. Instrumentation

Upon establishment of an experimental OMEGA navigation station in the Canal Zone in February 1961, the field intensity of the received 10.2 kc/s signal at Oahu, Hawaii, was observed to be less than expected for the 8,450 km predominantly sea water path.

Subsequent to the initial observations, special narrowband field intensity measuring equipments were developed at the U.S. Navy Electronics Laboratory. These were to provide improved accuracy in quantitative measurement and continuous recording of each of the three transmitting stations.

Measurement of the field intensity of the three OMEGA transmitting stations, while in normal operation, is not possible with available radio field intensity equipment, for the following reasons:

1. All three stations operate, sequentially, on the same frequency;
2. the transmitting time of each station is approximately 1 sec, with 4 to 9 sec off. This does not allow enough time for ordinary field intensity measuring equipment to produce a reading, and;
3. the signal-to-noise ratio of the distant stations is so poor that an accurate rms subtraction of noise and signal is impossible.

Therefore, a field intensity recorder was developed which is capable of—

1. Identifying which station is being received;
2. detecting the amplitude of each signal without responding to noise; and,
3. storing and recording each signal without degradation due to its duty cycle.

This recorder is more completely described in an NEL Report [Hanselman, 1963].

Since these recorders are used with whip antennas, of indeterminant (until measured in the field) effective height, an external calibration procedure was used employing a loop antenna, loop calibration network, and meters of known accuracy. Then an internal calibration oscillator was calibrated, to be used daily to check the recorder. Since this is also a substitution method, plus or minus one decibel accuracy is realistic.

3. Recordings

Figure 1 illustrates geographical sitings of the three OMEGA transmitting stations and the propagation paths discussed in this paper.

The 3,820-km New York to Canal Zone path is essentially north-south and parallels the earth's magnetic lines of force.

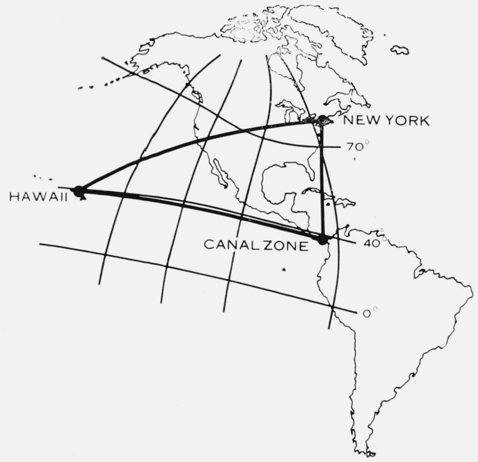

FIGURE 1. *Map of propagation paths recorded, and their orientation relative to geomagnetic field.*

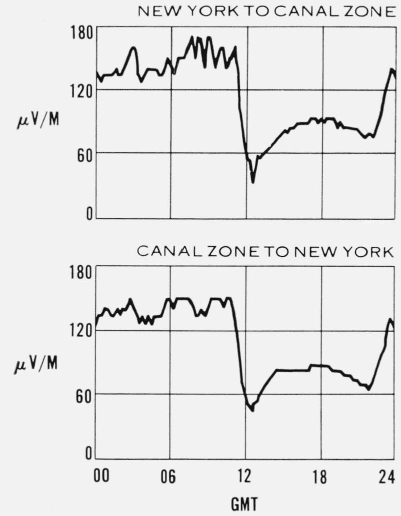

FIGURE 2. *A typical day for the north-south path.*

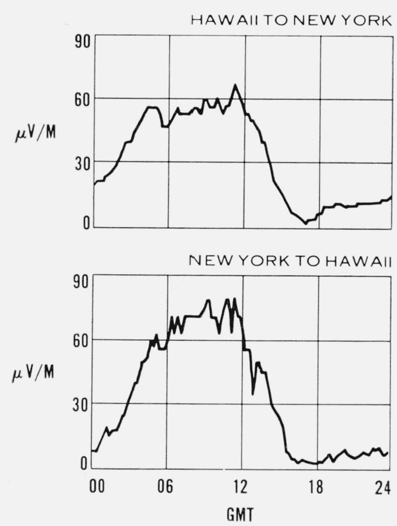

FIGURE 3. *A typical day for the northeast-southwest path.*

The 7,830-km New York to Hawaii path is northeast to southwest, cutting the earth's magnetic lines of force at an angle; the 8,450-km Canal Zone to Hawaii path is almost perpendicular to the earth field and nearly parallel to the geomagnetic equator.

Radiated powers from the Hawaii and Canal Zone transmitters are 4 and 1.4 kw respectively.

The transmitting antenna of the New York station is voltage limited because of the small insulators and varying weather conditions. Therefore, the radiated power varies between 5 and 165 w.

For the following graphs and charts, the received field intensity data have been normalized to indicate a radiated power of 1 kw. For the Hawaii and Canal Zone transmitters, constants are used to normalize, but for the New York transmitter, corrections are made from data collected by the local (Rome, N.Y.) Field Strength Recorder.

Figure 2 shows a typical day for the north-south path. The similarity of the night, day, sunrise and sunset portions of the curve are especially notable. Over these paths, reciprocal propagation exists.

Figure 3 shows a typical day over the northeast-southwest path. The nighttime fields are about the same for both directions but there is approximately a two-to-one difference during the day, with the east to west path having more attenuation.

Figure 4 shows a typical day over the east-west path which also is near and parallel to the geomagnetic equator. Over this path is the best example of nonreciprocity. During the night the field intensity varies markedly. On some occasions, over the east-west path, the field intensity has dropped to less than 1 μv/m for a period of half an hour during the night. This, and other irregular nighttime curves, indicates that, at this distance and over this path, some phase interference is being experienced. Sunrise and sunset over the east-west path are characterized by rapid and deep dips in field intensity which are also accompanied by rapid phase changes. The west-east path shows a small attenuation constant and only some of the vagaries of the reciprocal path.

Figure 5 shows, in tabular form, day and night average field intensities for propagation in both directions over the three reciprocal paths. They have all been normalized to indicate field intensity for 1 kw of radiated power. These measurements were made during late fall and early winter of 1962–63 and consist of averages of 14 to 20 days of operation. Only data taken simultaneously over each reciprocal path were considered.

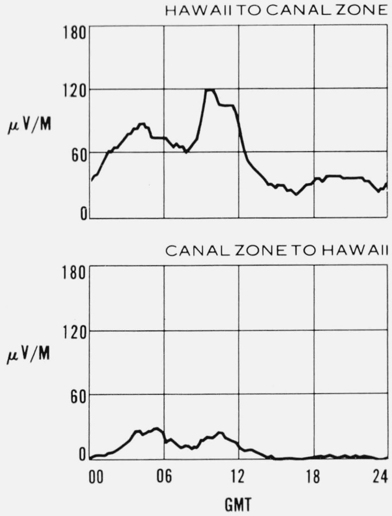

FIGURE 4. *A typical day for the east-west path.*

transmitter	*receiver*	*day*	*night*
HAWAII	CANAL ZONE	37	70
CANAL ZONE	HAWAII	3	20
NEW YORK	CANAL ZONE	83	140
CANAL ZONE	NEW YORK	81	135
NEW YORK	HAWAII	8	63
HAWAII	NEW YORK	15	61

FIGURE 5. *Fall-winter average field intensity.*
(In μv/m, for 1 kw radiated power)

<table>
<tr><td colspan="4">CALCULATED $\frac{\alpha(E\text{-}W)}{\alpha(W\text{-}E)}$, 10 KC/S DAYTIME
WAIT & SPIES (1960)</td><td colspan="6">NEL * MEASUREMENTS, 10.2 KC/S</td></tr>
<tr><td colspan="4"></td><td colspan="4">$\frac{\alpha(E\text{-}W)}{\alpha(W\text{-}E)}$</td><td colspan="2">$\frac{\alpha(S\text{-}N)}{\alpha(N\text{-}S)}$</td></tr>
<tr><td rowspan="2">N</td><td rowspan="2">I</td><td rowspan="2">ϕ_a</td><td rowspan="2">$\frac{\alpha(E\text{-}W)}{\alpha(W\text{-}E)}$</td><td colspan="2">HAWAII - CANAL ZONE</td><td colspan="2">NEW YORK - HAWAII</td><td colspan="2">NEW YORK - CANAL ZONE</td></tr>
<tr><td>DAY</td><td>NIGHT</td><td>DAY</td><td>NIGHT</td><td>DAY</td><td>NIGHT</td></tr>
<tr><td>1×10^3</td><td>0°</td><td>90° & 270°</td><td>1.75</td><td>2.25</td><td>2.1</td><td></td><td></td><td></td><td></td></tr>
<tr><td>3×10^3</td><td>0°</td><td>90° & 270°</td><td>1.50</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>1×10^3</td><td>45°</td><td>45° & 225°</td><td>1.3</td><td></td><td></td><td>1.22</td><td>0.98</td><td></td><td></td></tr>
<tr><td>1×10^3</td><td>–</td><td>0° & 180°</td><td>1.0</td><td></td><td></td><td></td><td></td><td>1.03</td><td>1.05</td></tr>
</table>

**Night-Time Per Watt & Plush 1959*
**Daytime Per Watt 1963*

FIGURE 6. *A comparison between calculated and measured values.*

4. Comparison of Results

The foregoing 10.2 kc/s field intensity measurements were converted to attenuation rates, using (2) by Watt and Plush [1959] and a 1963 revised form of this equation by Watt and Croghan [1963].

The attenuation rates thus determined are compared in figure 6 with the theoretical values of Wait and Spies [1960] (their figs. 3 and 4). Their values were calculated from mode theory equations with—

N=ionosphere electron density; calculated for 1,000 and 3,000 per cubic centimeter
I=dip angle of magnetic field; 0° and 45°
n=mode order, n=1, the dominant mode at long ranges
ν=ion collision frequency, 2×10^7

Close agreement is indicated between the experimental and theoretical attenuation rates.

5. Conclusions

Approximately 1 year of experience in recording 10.2 kc/s field intensities on various propagation paths has demonstrated that quantitative results with a high order of repeatability can be obtained.

Measurements reported herein confirm the existence of nonreciprocity of 10.2 kc/s attenuation rates in the east and west directions. The ratio of attenuations rates, E to W/W to E, is a maximum for daytime propagation in the direction of the geomagnetic equator. Reciprocity in attenuation rate appears to hold for propagation in the north-south direction. The small order of discrepancy from absolute reciprocity listed for the New York-Canal Zone path is attributed to instrumental error.

The authors express their gratitude to Mr. F. X. Dell for calculation of attenuation rates from the experimental data, and to Mr. A. D. Watt for additional attenuation rate information [Watt and Croghan, 1963].

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