DIURNAL VARIATIONS IN LORAN-C GROUNDWAVE PROPAGATION

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ABSTRACT

Measurements have been made of the time of arrival of Loran-C groundwave signals propagated over a 1000 km land path in which diurnal variations of several hundred nanoseconds are observed. These variations are well correlated with air temperature along the path, but show a negative correlation with refractive index. Correlation with simultaneous measurements at other locations confirms it to be a propagation rather than equipment-related phenomenon. A relationship with the "dry" component of the refractivity is established, and an empirical algorithm is developed using surface weather data which reduces variations by a factor of 2.5.

INTRODUCTION

Temporal variations in the apparent propagation velocity of Loran-C signals have been observed for over 20 years (Ref. 1-8). Many of these variations have a diurnal as well as a seasonal character. Early measurements involved measuring the difference in the time of arrival of two signals, making it difficult to identify the source of the apparent variations. Recent data, however, represents single paths, using cesium standards at the receivers.

Using two AN/BRN-5 Loran-C receivers for a U. S. Coast Guard field test program, recordings of time-of-arrival (TOA) data from the U. S. East Coast Loran-C chain, relative to a local cesium standard, were obtained in the spring of 1977. Most of the data analyzed concerns the TOA of the Master signal from Carolina Beach, N.C., propagated over an approximately 1000 km path to Fort Wayne, Ind. Records from the National Weather Service (NWS) were obtained from the National Climatic Center in Asheville, N.C., in an effort to identify phenomena which could explain observed TOA variations.

INSTRUMENTATION

The instrumentation used, called the Precision Loran Data Collection System (PLDCS) by the Coast Guard, consists of a prototype model AN/BRN-5 borrowed from the Navy, an HP 2808 computer, an HP 5061 Cesium Standard,

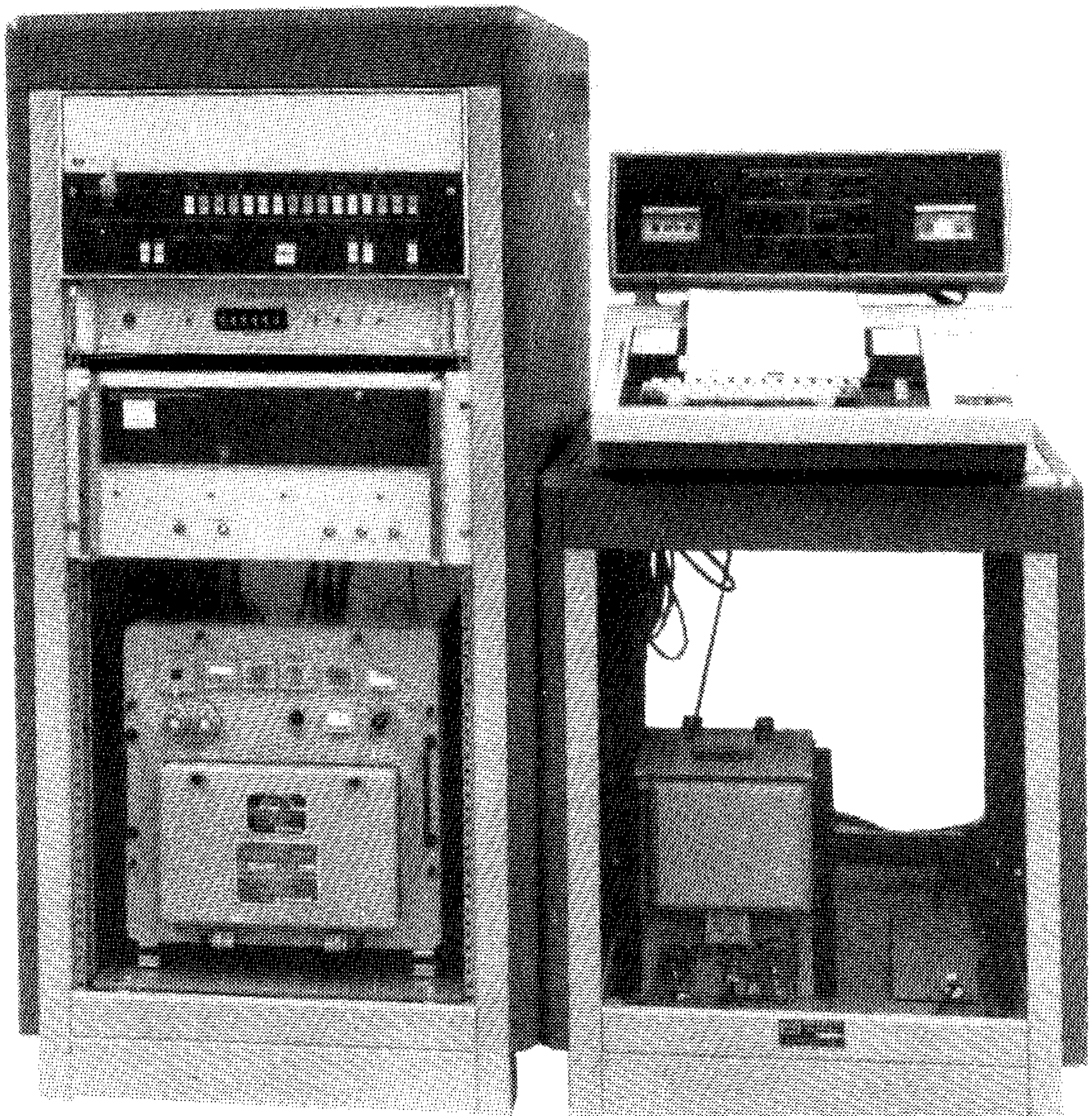

Fig. 1 - PLDCS Configuration

and a TI ASR 733 keyboard-printer and cassette recorder. Figure 1 shows how these equipments were mounted. The antenna consisted of a 1.3 meter whip with a ground plane and an untuned transformer matching twin-conductor leadin.

The PLDCS is programmed to record a variety of signal and receiver status parameters at periodic intervals. These include signal TOA for three stations, two time differences, signal amplitudes, signal-to-noise ratios, and pulse envelope measurements. Most of the data collected were at 15 minute intervals.

After being recorded on cassettes, the data were transferred to an in-house disk system, and selected data plotted for easier analysis.

Selected TOA data from the U.S. Naval Observatory (USNO) Washington, D.C. and Newark AF Station, Ohio, were read visually from strip chart recordings and plotted manually for comparison with local data.

Weather data for selected locations obtained from the NWS were used in a BASIC program to calculate the index of refraction. Both surface and upper air (radiosonde) data were processed.

DATA COLLECTED

Most of the data analyzed consists of TOA measurements of the Loran-C master station at Carolina Beach, N.C. (see Figure 2). The 1000 km path to Fort Wayne is a mixed one of high and low conductivities. TOA measurements were made over periods of several days taken in February, March and April 1977.

OBSERVATIONS

Variations in TOA of several hundred nanoseconds were observed which tended to have a diurnal character. Explanations for these effects have been put forward, including:

1. Temperature effects in the receiver
2. Temperature effects at the transmitter
3. Skywaves
4. Index of Refraction

The BRN-5 receiver contains an automatic calibration system which measures and compensates for changes in phase shift through the receiver, to an accuracy of one nanosecond. Additionally, a recording of room temperature showed no correlation with TOA variations. Receivers at different locations showed similar variations. It is concluded that the receiver is not the culprit.

Changes in antenna characteristics could cause changes in the phase of the transmitted signal. However, a servo control loop at each transmitter

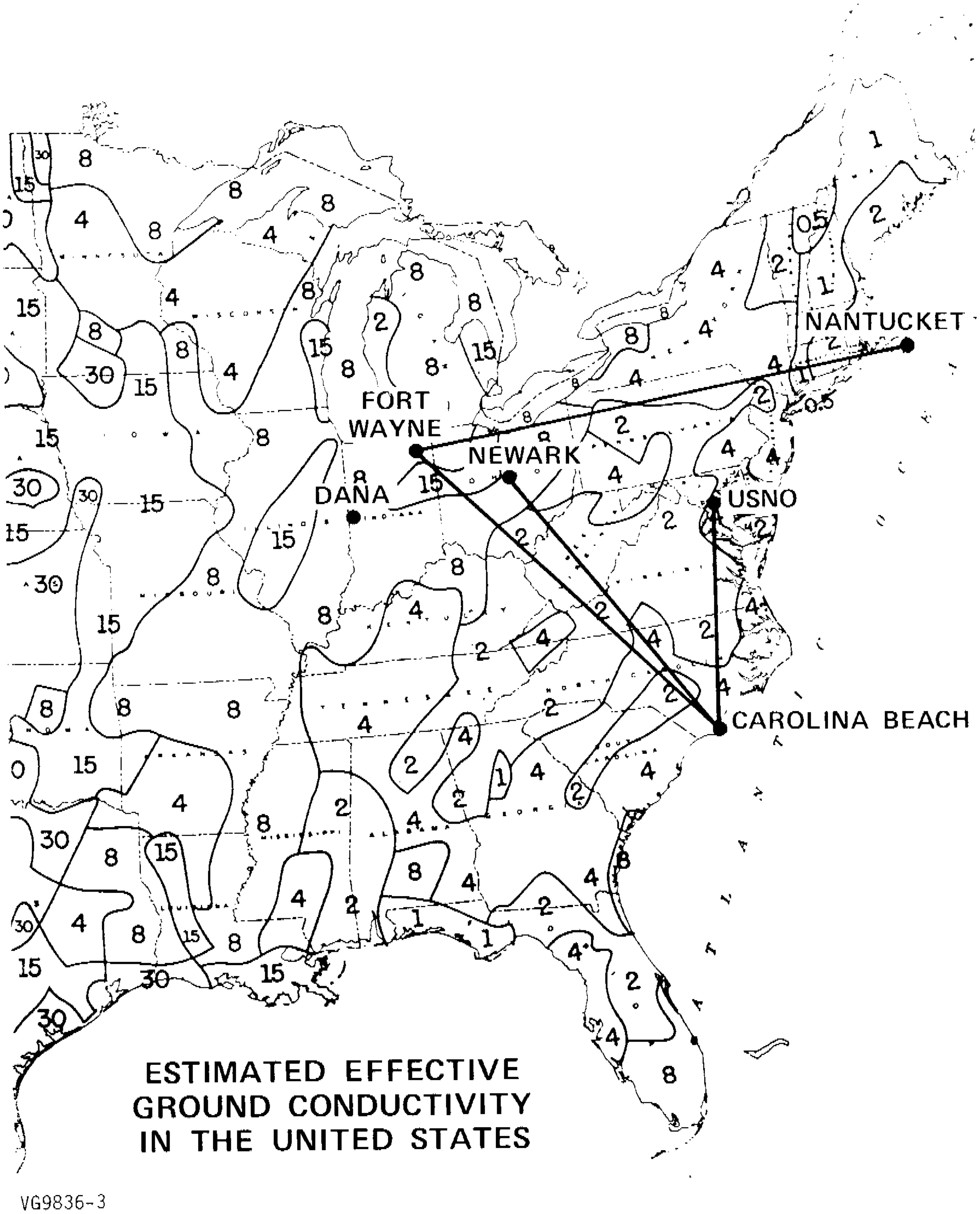

Fig. 2 - Measurement Area

continuously compares the phase of the transmitted signal with a local reference and adjusts the transmitter drive to maintain constant phase output. Also, if the variations were due to the transmitter, all receivers would see the same variation. Data from the USNO showed this not to be so. The transmitter is exonerated.

Skywaves have been suspected as the cause of the phase shift, but the tests proved this not to be so. The rationale is as follows.

Figure 3 shows the envelope of a Loran pulse, on a logarithmic amplitude scale, out of the BRN-5 receiver. Assuming an unheard-of worst case of a skywave delayed only 22 microseconds gives the dashed curve in Figure 3. Now, if a receiver is sampling at 45 μs, the skywave will be -20 dB, and a phase fluctuation of 317 ns could be encountered. If, simultaneously, a receiver is sampling at 50 μs, the skywave will be -60 dB, and fluctuations will be 3 ns.

Figure 4 shows the results of testing this hypothesis. The only apparent difference between the performance of the two receivers is the increased random fluctuations resulting from the 12 dB poorer signal-to-noise ratio of the receiver sampling at 50 μs. It follows that no skywaves are affecting the measurements at 45 μs.

To further test the hypothesis that the propagation velocity is varying, TOA data were obtained from two other locations, the U.S. Naval Observatory (USNO), Washington, D.C. and the Air Force Newark Air Station, Ohio. Figure 5 shows the Newark data compared with the Fort Wayne data. Figure 6 shows the measurements taken on two receivers at USNO compared to the Fort Wayne data. The degree of correlation is readily apparent. Also notable is the fact that the path to the USNO is approximately one-half the length of the path to Fort Wayne.

INDEX OF REFRACTION

The natural phenomenon that experiences relatively rapid temporal changes and can affect radio wave propagation is the index of refraction. Doherty and Johler (5) correlate propagation variations with variations in N-dry, and associate the phenomenon with changes in the α factor. Other observers (6, 9) have variously referred to lapse rate, or α factor, without numerical confirmation. These hypotheses are examined in more detail.

Travel time of the groundwave Loran pulse is given by the expression

$$t = \frac{dn}{c} + t_c \qquad (1)$$

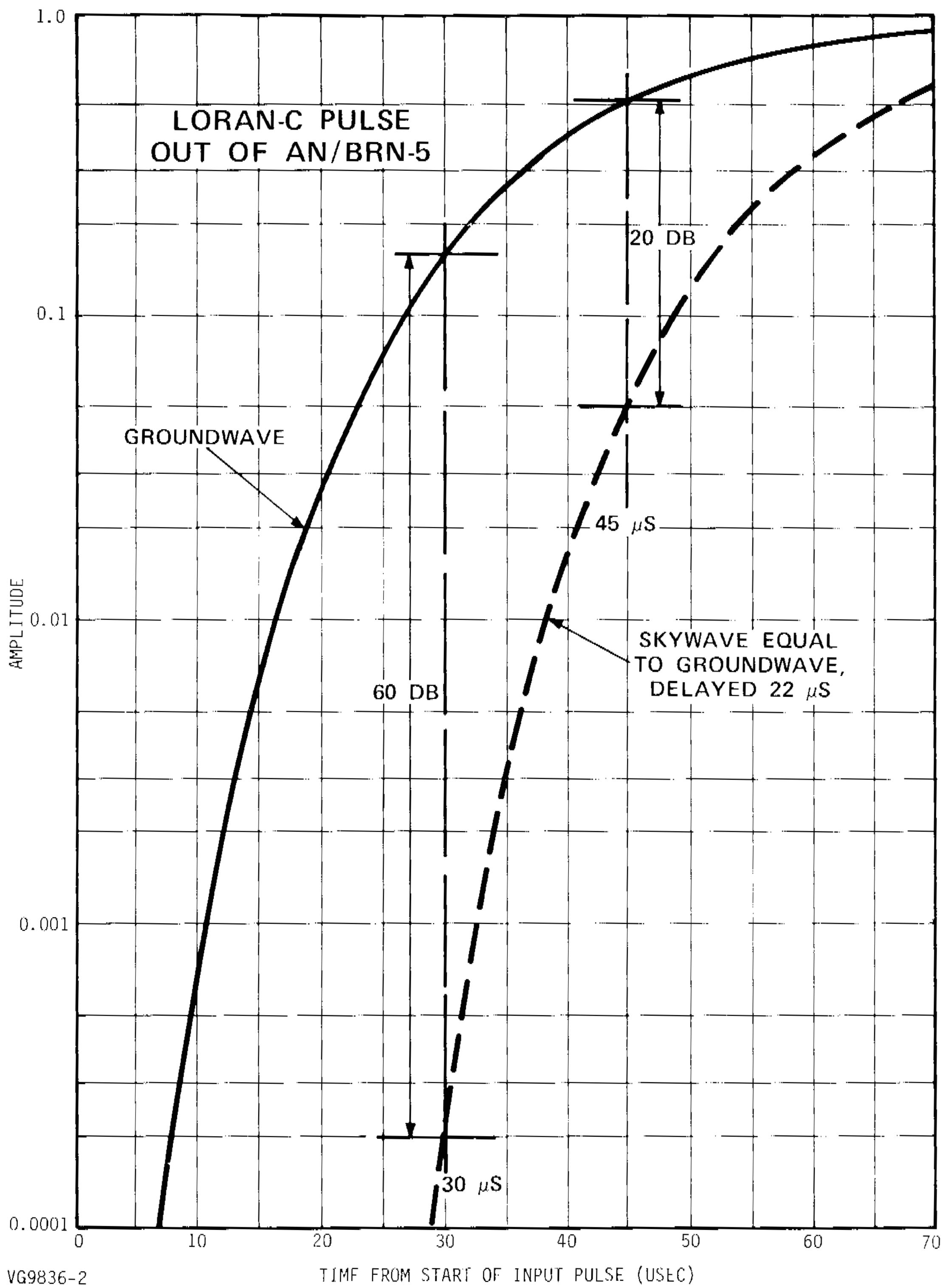

Fig. 3 - Loran Pulse Envelope

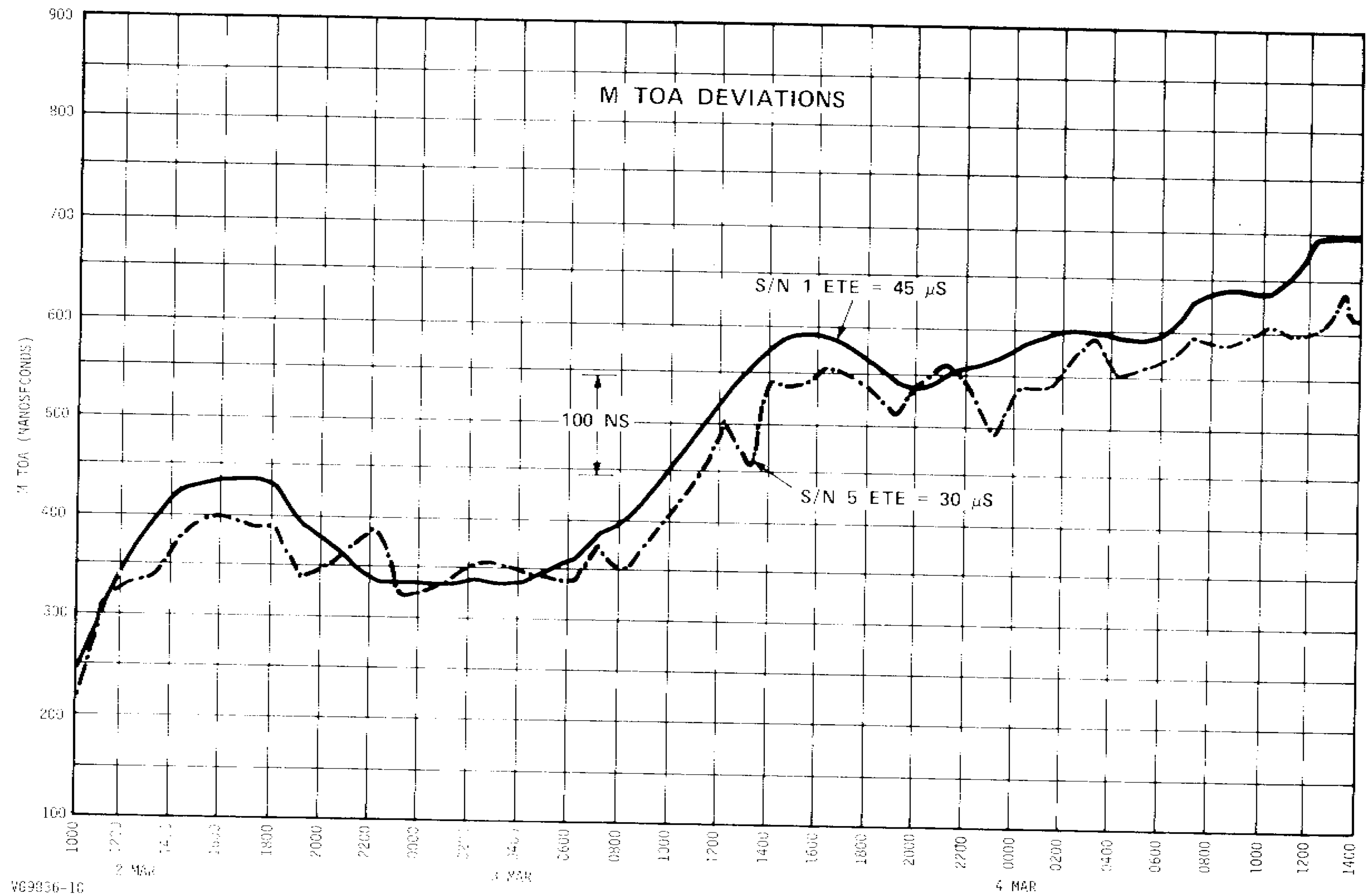

Fig. 4 - TOA Measured by Two References

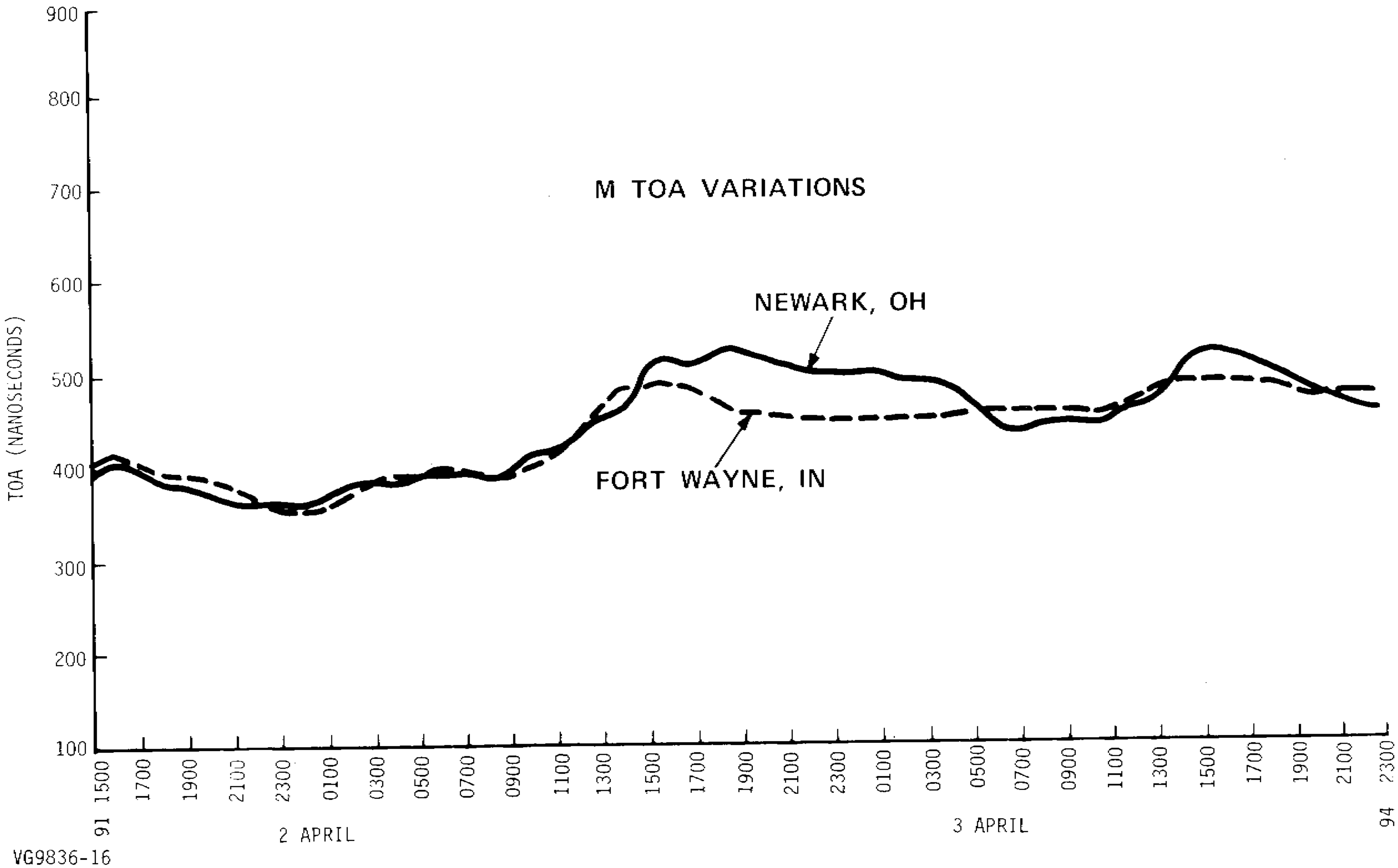

Fig. 5 - MTOA at Newark and Fort Wayne

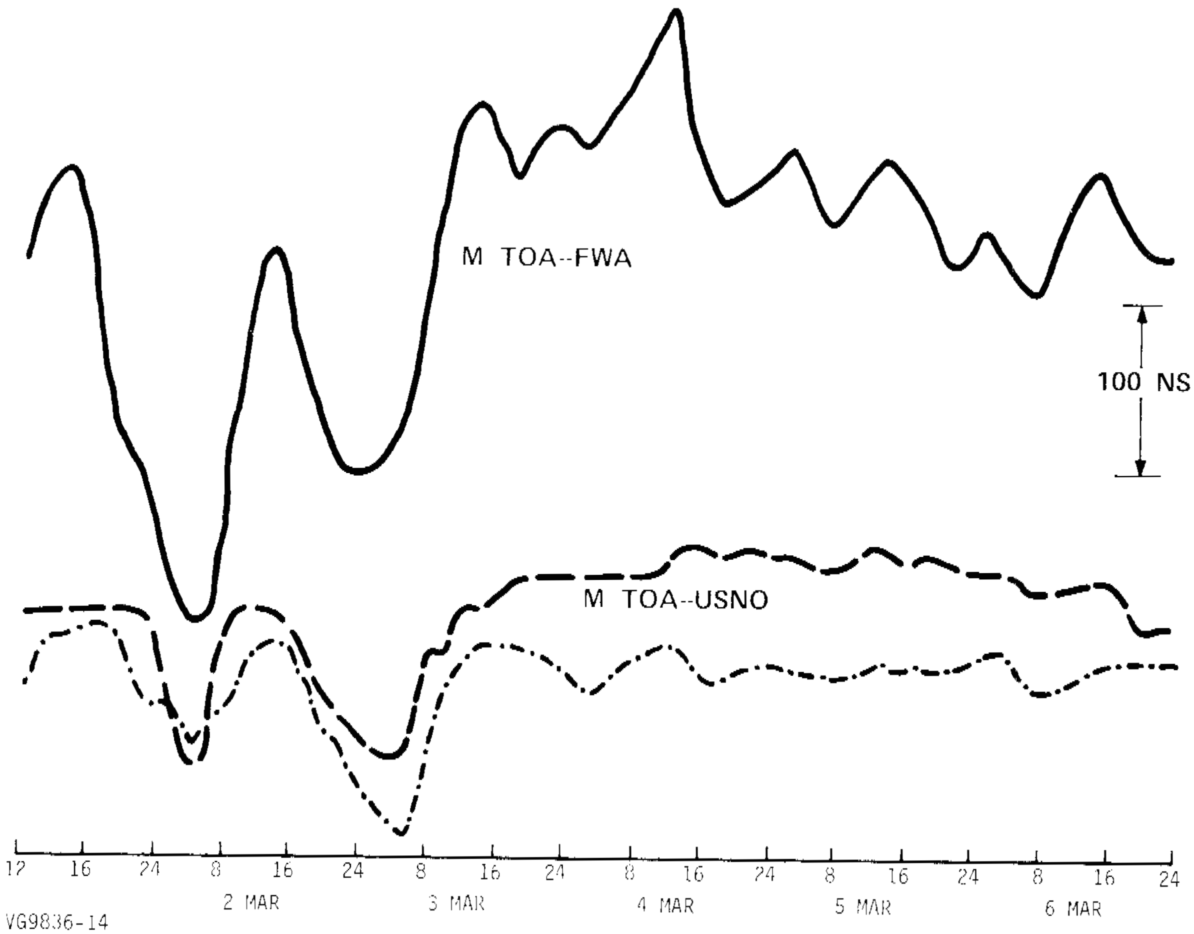

Fig. 6 - MTOA at NOBS and Fort Wayne

where τ = travel time in microseconds

d = distance in kilometers

c = velocity of light in kilometers per microsecond

n = index of refraction

t_c = secondary phase factor

Values of t_c as a function of earth conductivity, taken from NBS Circular 573, (10) are shown in Figure 7. Index of refraction is derived from climatological data as follows:

$$N = \frac{77.6\ P}{T} + \frac{3.76 \times 10^5\ e_S\ RH}{T^2} \qquad (2)$$

where N = refractivity = $(n - 1)\ 10^6$

P = atmospheric pressure

T = temperature, ^oK

e_s = saturation pressure of water

RH = relative humidity

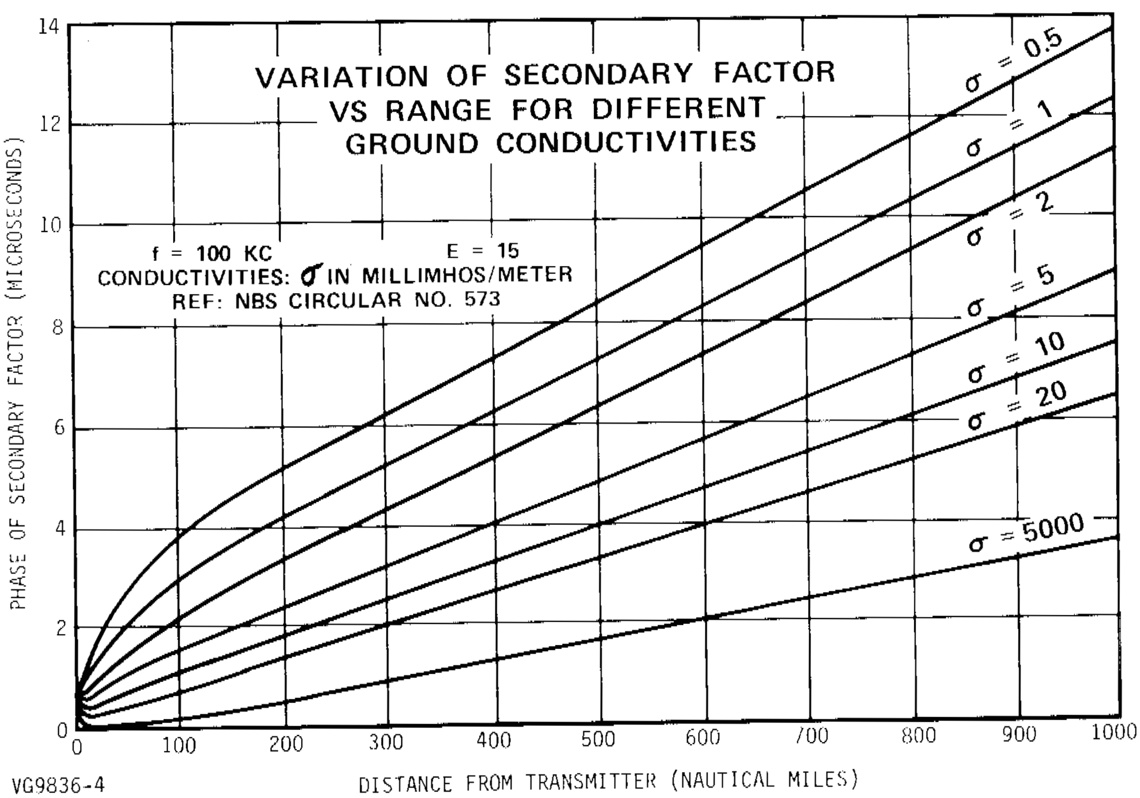

Fig. 7 - Variation of Secondary Factor vs Range for Different Ground Conductivities

The first term, sometimes called the "dry" term, represents 90 - 95% of the refractivity, while the second, the "wet" term represents the remainder. To test the correlation between N and the observed variation, consider the period 0800 - 1800 on 2 March 1977. The value of N along the path of propagation decreased 20 N units. According to equation 1, the propagation velocity should go up by 20 x 10^{-6}, and the propagation time from Carolina Beach to Fort Wayne should decrease 67 nanoseconds. Instead it increased 220 nanoseconds.

The explanation for this discrepancy is found in NBS 573, which indicates that the secondary factor t_c is also a function of the lapse rate of the refractivity.

Figure 10 of NBS 573 shows the variation of t_c with lapse rate in ΔN units per kilometer, for various distances over good earth (σ = 5 millimhos/meter). This shows that, as the lapse rate increases, t_c decreases. Re-plotting the data we find a linear relationship between the rate at which the change in lapse rate causes a decrease in t_c, and the distance. This is shown in Figure 8. On the assumption, to be discussed later, that the lapse rate is directly related to the surface value of N, a second curve is shown in Figure 8 representing the net phase delay correction taking into account the effect of refractivity on wave velocity.

Lapse rate of the refractivity can be calculated from data collected by radiosonde by NWS. Unfortunately, these measurements are made, because of the cost, only at relatively few selected places and times.

Examples of refractivity lapse rates calculated from data taken twice daily at Dayton, Ohio are shown in Figure 9. It had been hoped that some relationship between refractivity at the surface and the lapse rate would be observed, but none is obvious. A plot of the lapse rate of temperature, Figure 10, shows another erratic pattern.

The dry term of the refractivity, however, is something else. Figure 11 shows the lapse rate of N-dry for the same period as Figures 9 and 10. The value of N-dry at one kilometer above the ground is approximately equal to 250, independent of the value at the ground. Data at other stations and times confirm this. This means that an estimate of the lapse rate of N-dry for the first kilometer of height can be obtained from the value of N-dry at the surface by the simple relationship

$$\frac{\Delta N}{km} = N\text{-dry} - 250 \qquad (3)$$

Having found a convenient way to find the lapse rate of N-dry, it is relevant to test the hypothesis that it is this change in lapse rate of N-dry which causes the variation in propagation time. Variations in propagation time from Carolina Beach to Fort Wayne (MTOA) during the period 1 -

6 March 1977 are shown in Figure 12 along with variations in air temperature at a point near the propagation path, Roanoke, Va. A high degree of correlation is apparent. This correlation between propagation time and temperature has been observed many times over the past 20 years.

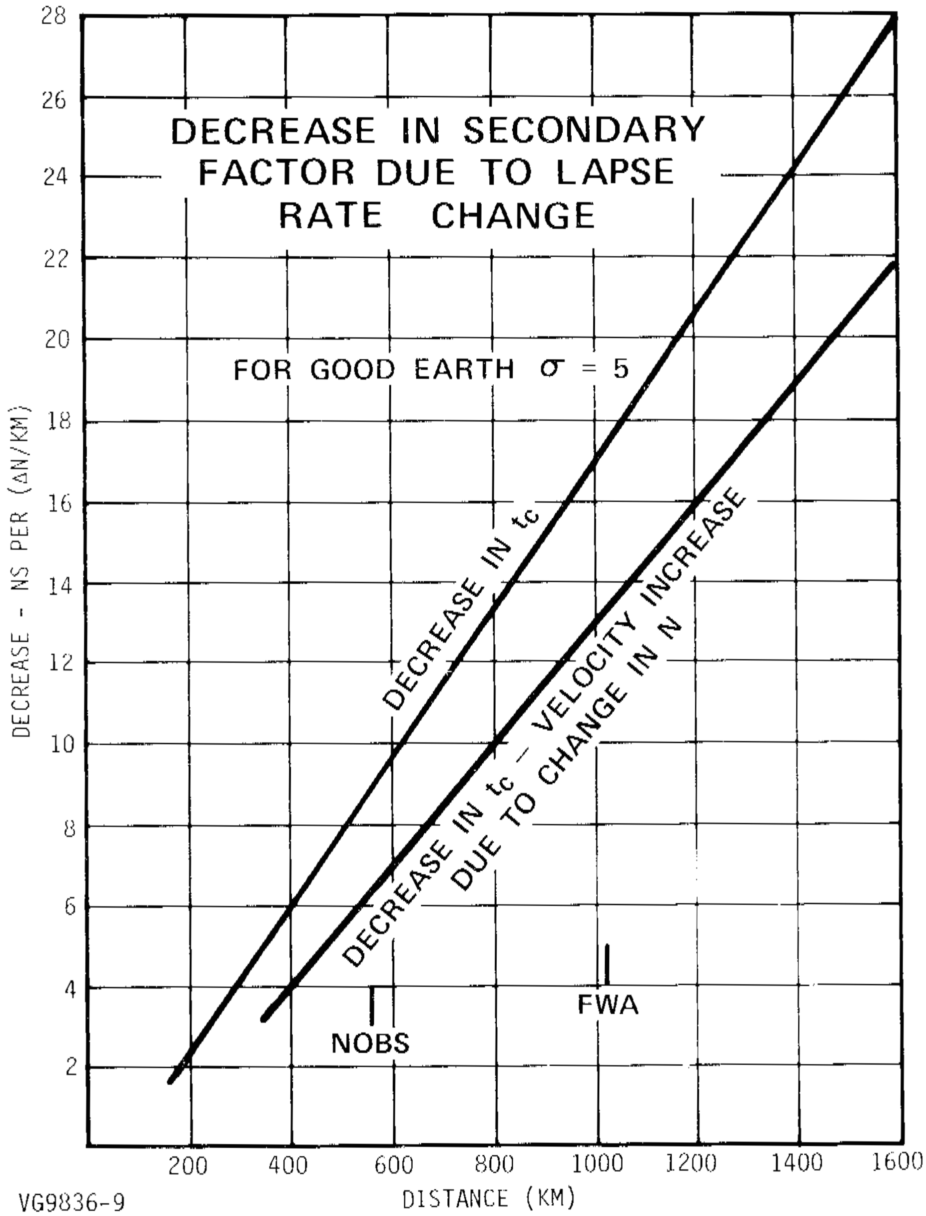

Fig. 8 - Decrease in Secondary Factor due to Lapse Rate Change

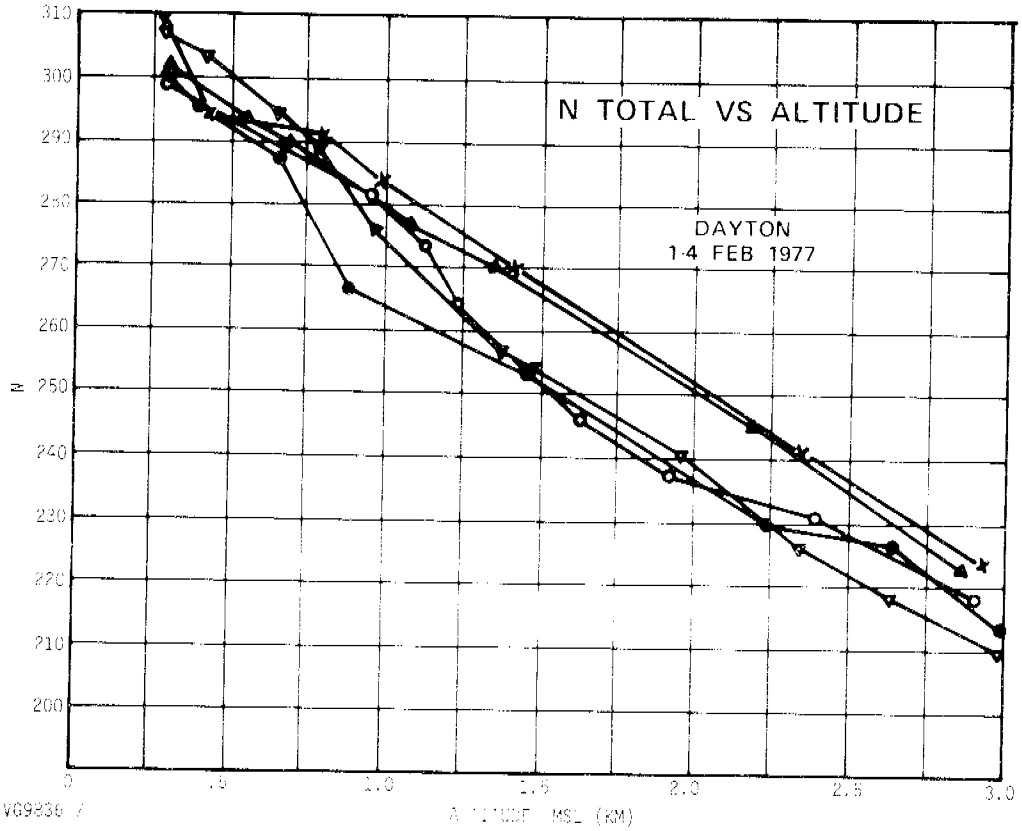

Fig. 9 - Lapse Rate of N at Dayton

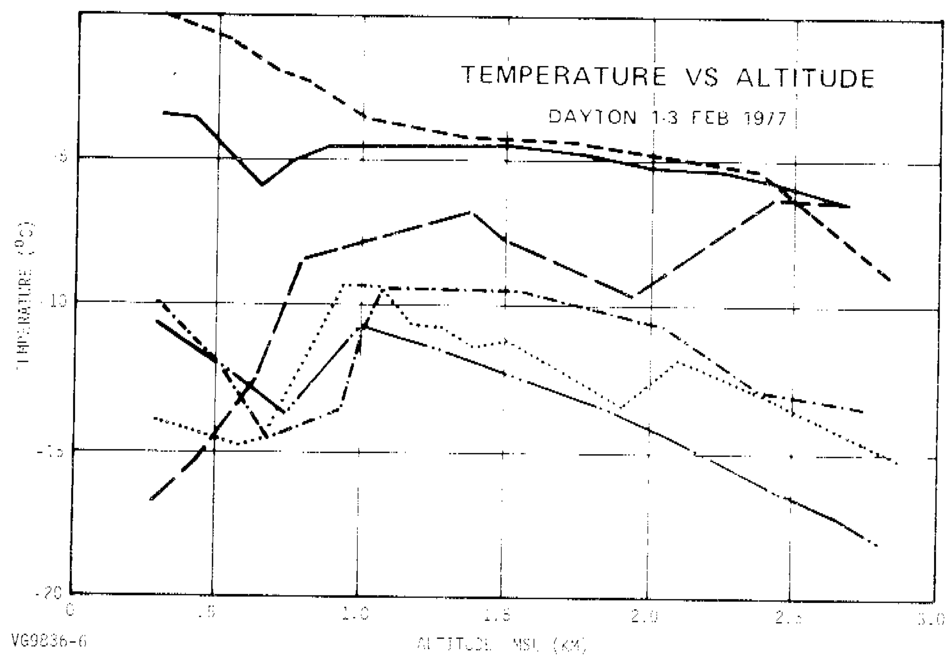

Fig. 10 - Lapse Rate of Temperature at Dayton

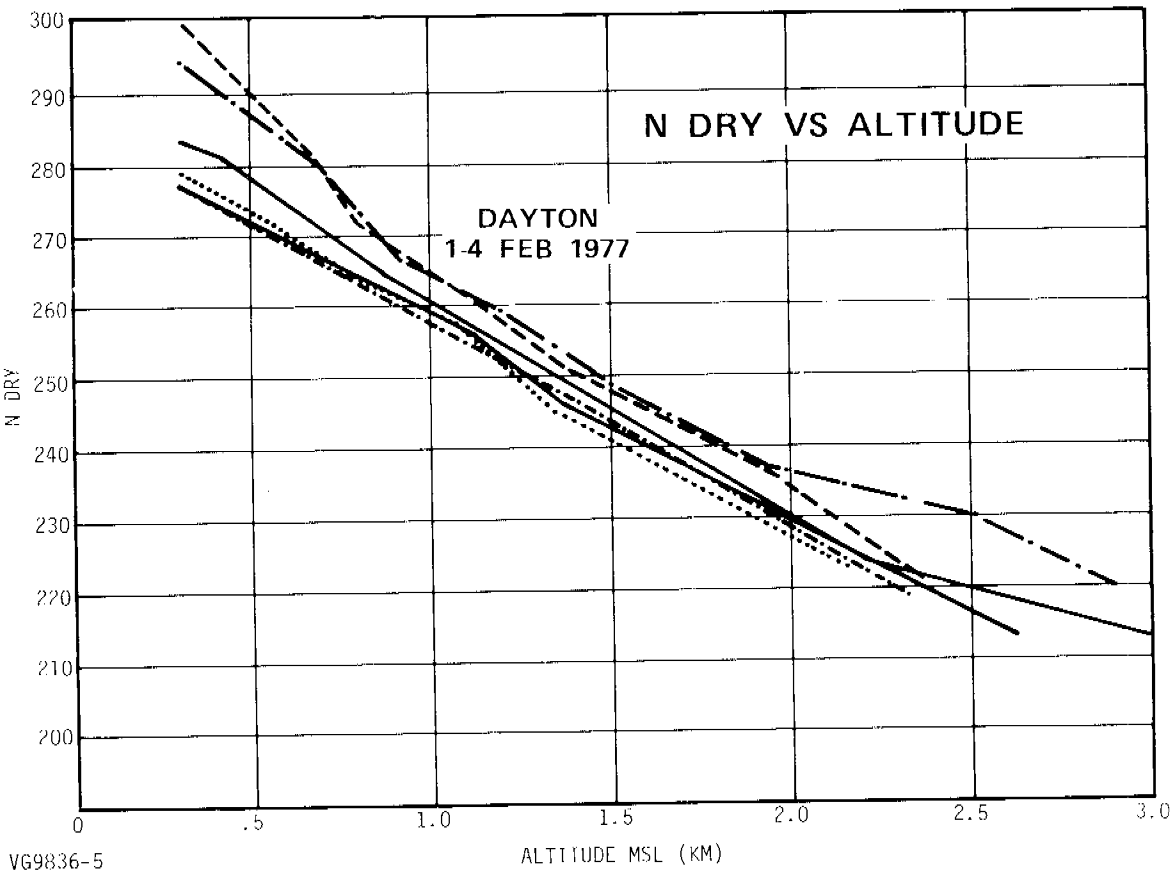

Fig. 11 - Lapse Rate of N-Dry at Dayton

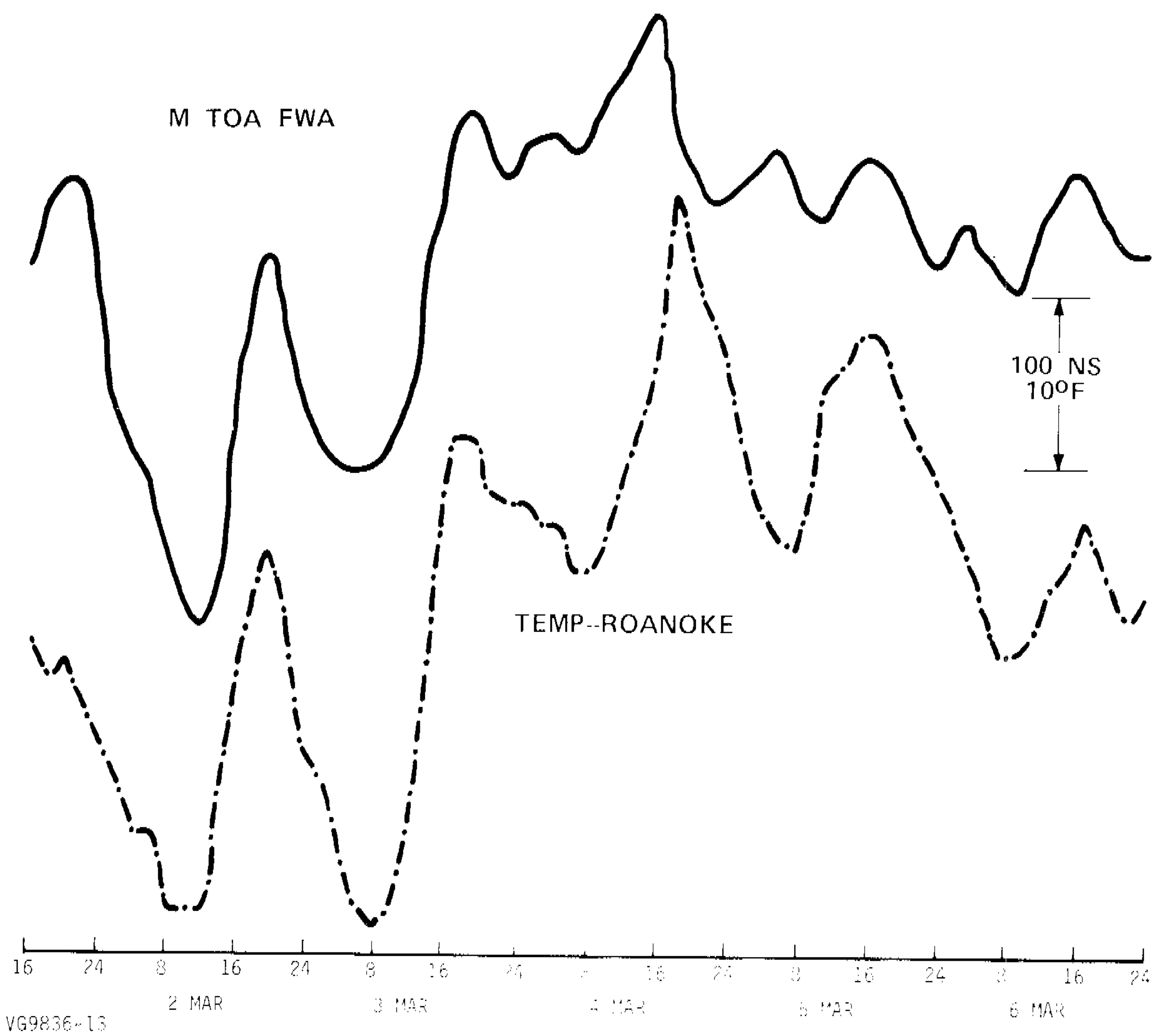

Fig. 12 - MTOA at Fort Wayne and Roanoke Temperature

Figure 13 shows the same variation in arrival time and the variation of refractivity (N-total) at Roanoke. It is obvious that the correlation of N-total is not nearly as good as that of temperature. Figure 14 shows the same MTOA data with N-dry at Roanoke. The high degree of (negative) correlation is obvious.

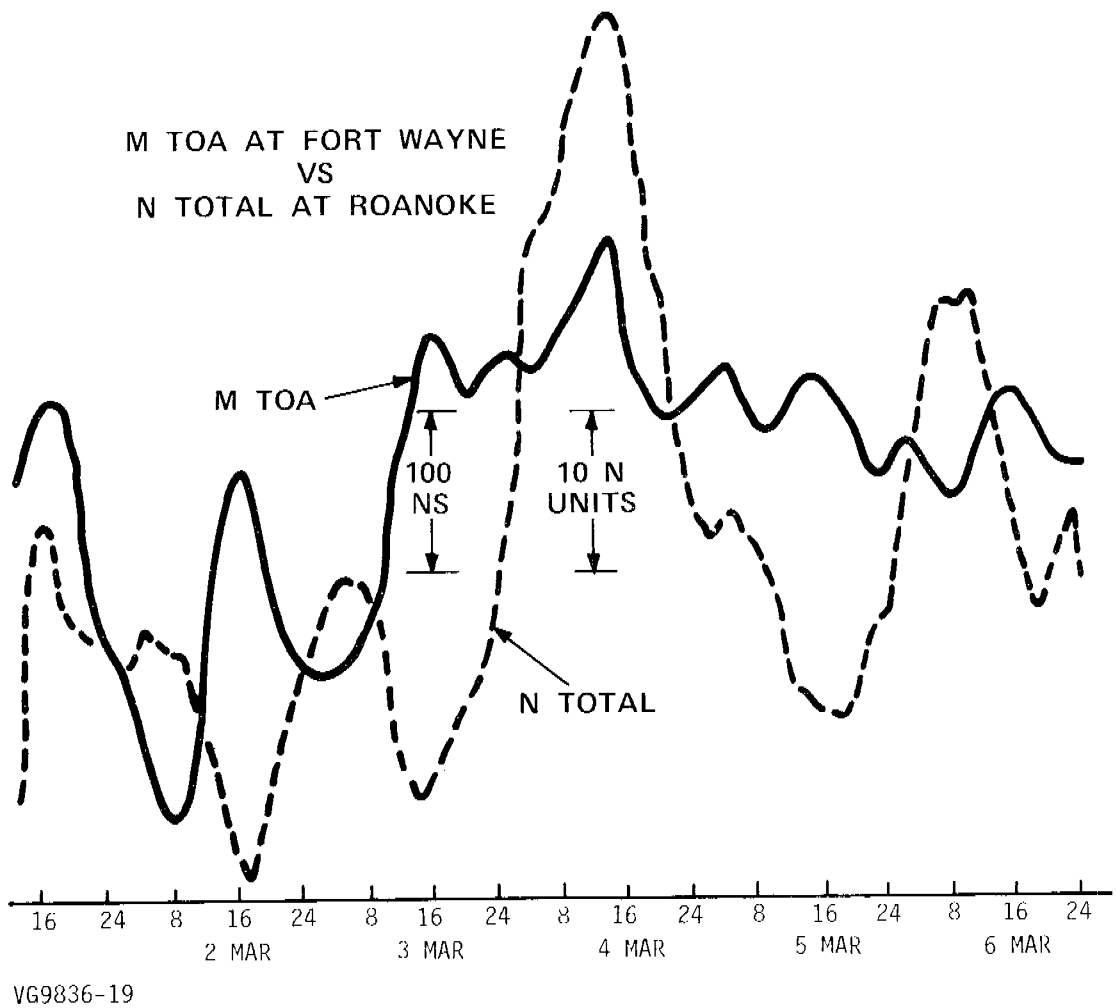

Fig. 13 - MTOA at Fort Wayne and N-Total at Roanoke

To further test the hypothesis that the changes in propagation time are correlated with N-dry, the curve of Figure 8 was combined with the approximation for lapse rate to give the following relationship for propagation time correlation.

$$\Delta t = (.015d - 2)\ (N_{dry} - 250) \text{ nanoseconds} \qquad (4)$$

where d is the path length in kilometers

$$N_{dry} = \frac{77.6\ P}{T} \quad \text{(from Equation 2)}$$

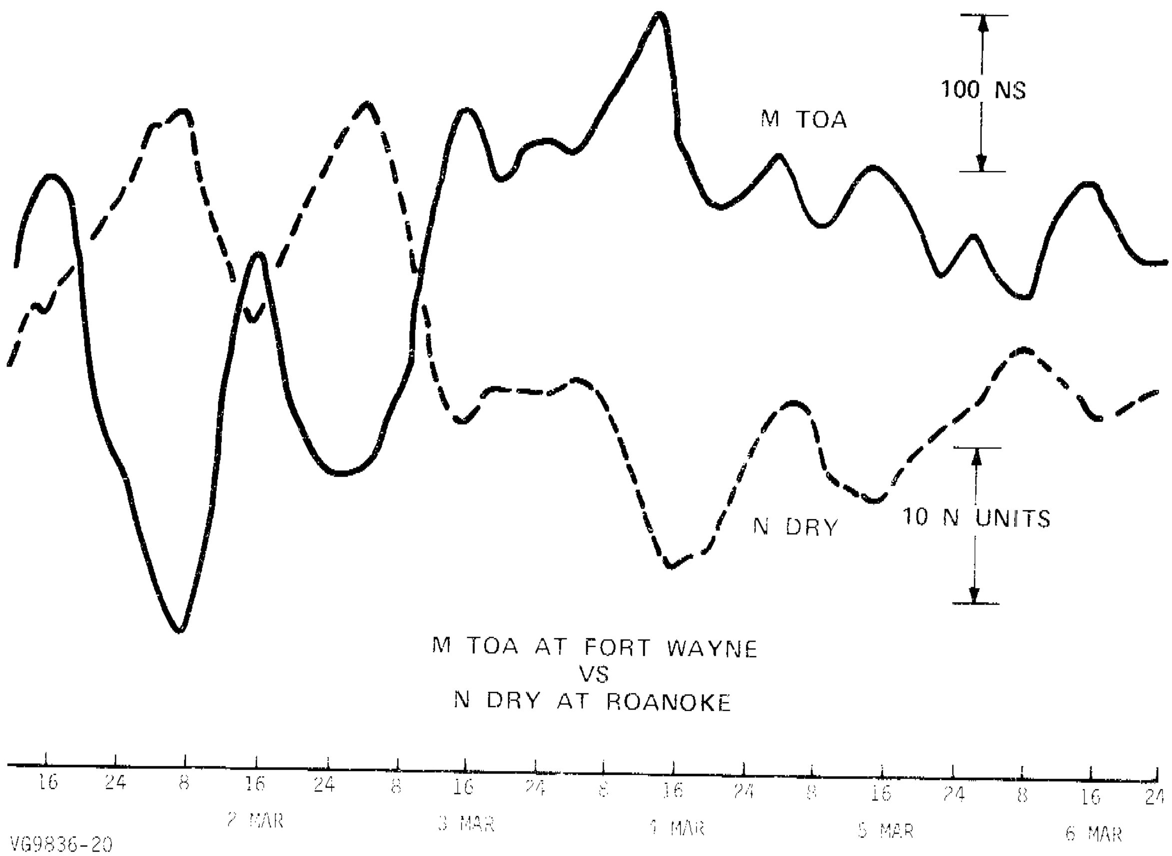

Fig. 14 - MTOA at Fort Wayne and N-Dry at Roanoke

Figure 15 shows the MTOA data of 1 - 6 March corrected by the above formula, using pressure and temperature data from Roanoke. The RMS fluctuation is decreased by a factor of 2.

Huntington, W. Va. is located closer to the center of the Carolina Beach - Fort Wayne path than Roanoke. Using data from that station produces results shown in Figure 16. The RMS fluctuations after correction are reduced to 30% of the original.

CONCLUSIONS

It has been shown that observed variations in time of arrival of Loran-C signals which tend to have a diurnal character are caused by changes in effective propagation velocity and not by hardware or by skywave interference. Further, the correlation with the "dry" term of the refractivity along the path has been established. A relationship of the dry term at the surface to the lapse rate, and therefore to changes in second phase factor, has been shown. A numerical expression capable of reducing fluctuations over a 1000 km path by a factor of 2.5, using surface weather data along the path, has been demonstrated. The rationale for use of the "dry" term of the refractivity is purely empirical. A physical explanation is left to the physicists.

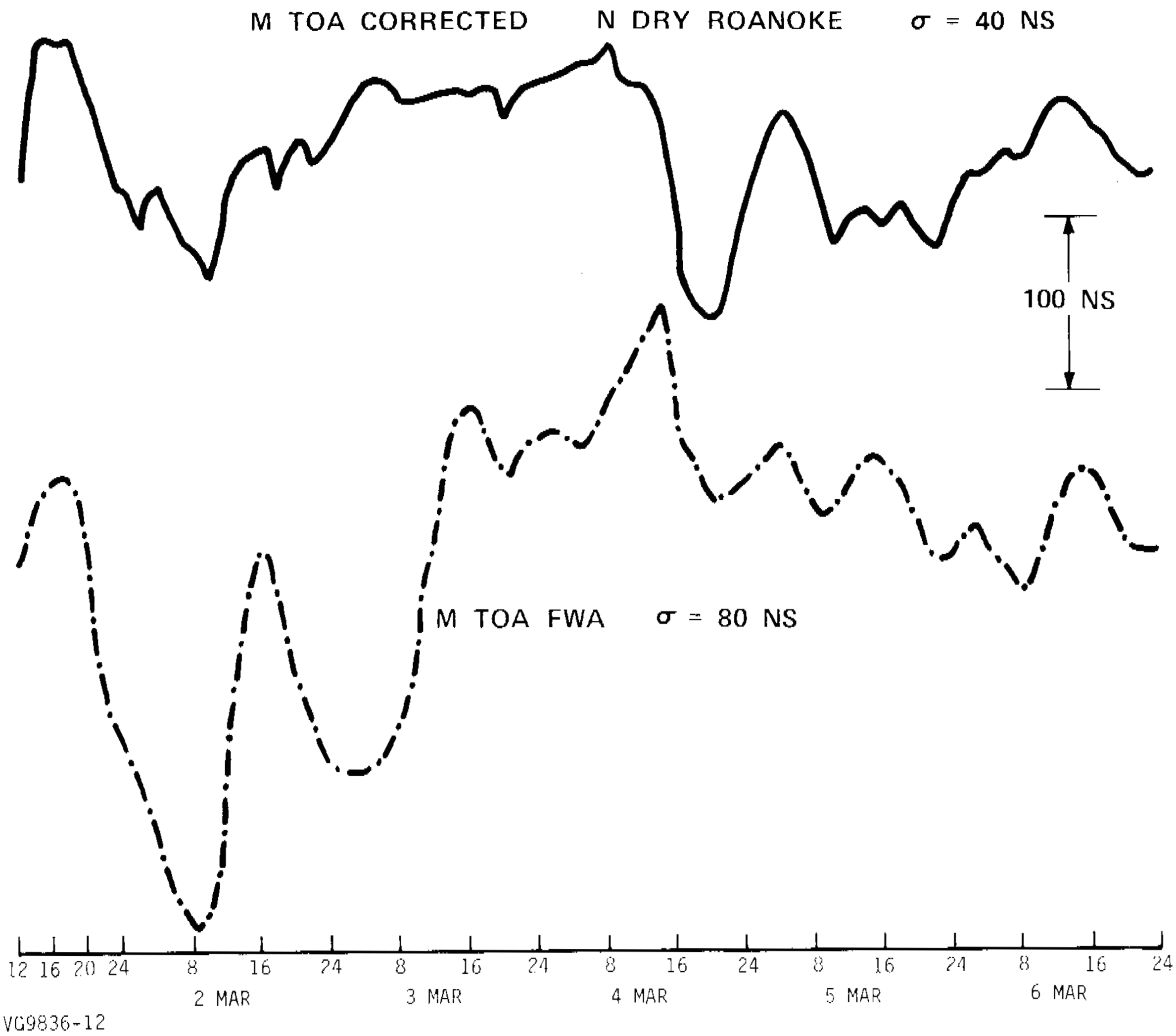

Fig. 15 - Correcting MTOA using Roanoke Weather

ACKNOWLEDGEMENT

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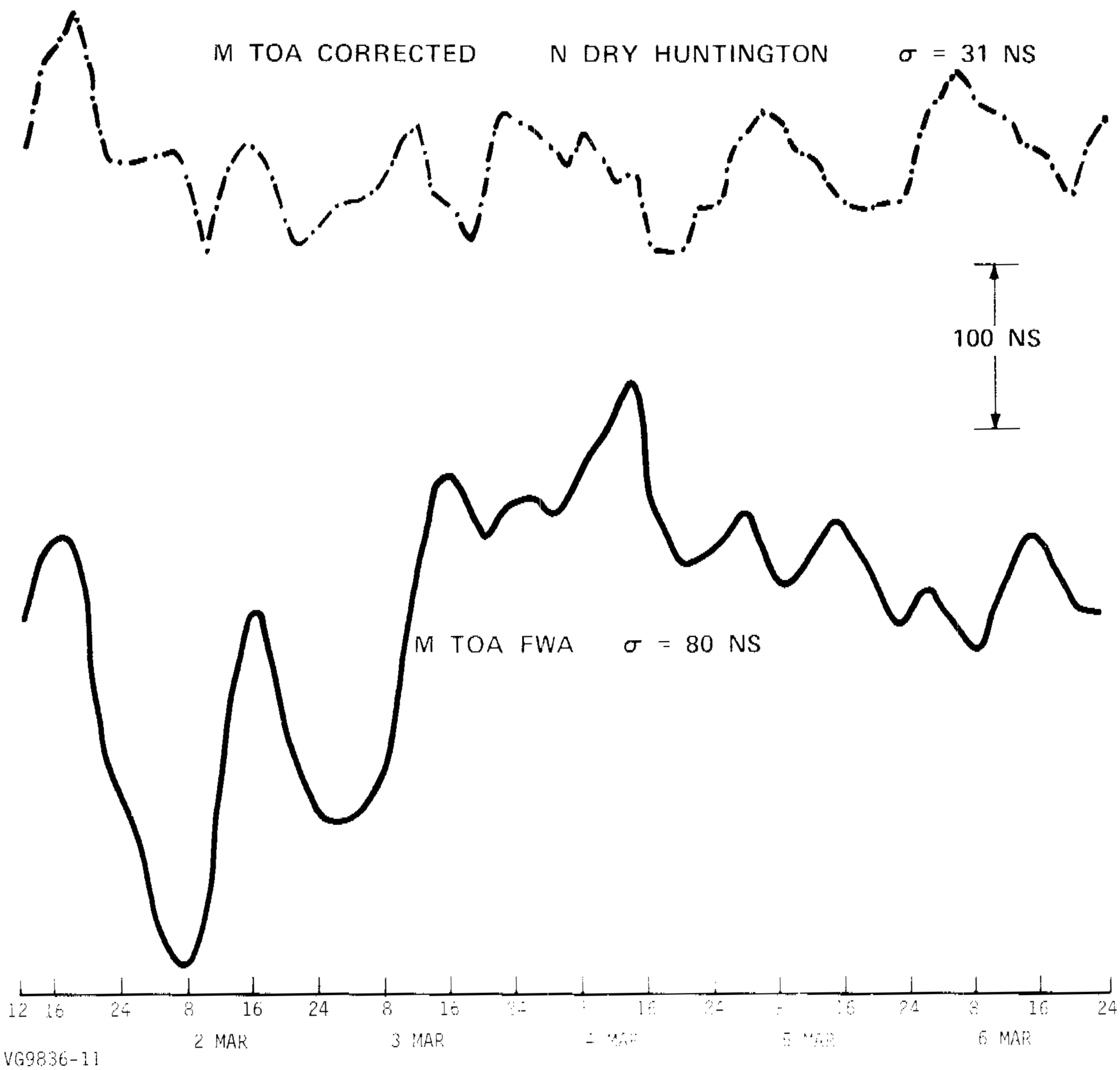

Fig. 16 - Correcting MTOA using Huntington Weather

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QUESTIONS AND ANSWERS

MR. WAYNE H. CANNON, York University:

Please clarify one point. You just used the metrological data at the same site as your LORAN receiver is located? Is that correct?

MR. DEAN:

No, that is wrong. The data I used consisted of data at a couple of different points along the path between the two. And actually that last curve used the data at Huntington, West Virginia, which is approximately the midpoint between Carolina Beach and Fort Wayne.

MR. CANNON:

So, you are attempting some kind of metrological average along the path?

MR. DEAN:

That is correct, and we did some work on taking the average temperature along the path. That seemed to be a little better correlated than any individual point. The only problem was that all of this was being done by hand, and the labor became so great that we didn't do very many.

MR. CANNON:

I saw the ground conductivity classifications there on the map. Did you do anything with that data at all?

MR. DEAN:

No, because the data that I got out of NBS-573 was just for a σ5. I just made the simplifying assumption that the average conductivity was about 5 and let it go at that. I am sure that we could go back into Johler's formulas. He may have written up some new ones since then and that could be worked out. But I just haven't done it.