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VLF PROPAGATION OVER DISTANCES BETWEEN 200 AND 1500 KM

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Introduction

The measurements discussed in this paper were undertaken as part of an evaluation of the NBS-WWVL (20 kHz) time and frequency station near Fort Collins, Colorado. The main items to be discussed are the: (1) variation in the VLF ground phase pattern as a function of distance from the transmitter; (2) magnitude of the diurnal phase variation as a function of distance from the transmitter; and (3) correlation of the phase fluctuations at 19.9 and 20.0 kHz at a distance of about 1300 km from the transmitter.

Phase-Distance Variations

At VLF the phase velocity is, in general, not constant with distance from the transmitter [1, 2]. This is to be expected since ionospheric wave guide theory shows that the signal at any point along the ground depends upon the interaction of several ionospheric wave guide modes [1]. Near the transmitter several modes are important; however, the higher order modes are attenuated rapidly with distance so that at great distances the phase pattern is primarily due to just one mode. The measurements discussed in this paper are near the transmitter so that the resultant phase versus distance pattern will depend upon the interaction of several modes.

Although one is generally interested in the phase velocity for navigational or time dissemination problems, it will be convenient in this section to discuss the results in terms of the quantity $\Delta\phi$ (= $\phi_m - \phi_c$), where ϕ_m is the measured accumulated phase over some path at a distance R from the transmitter (phase path distance), and ϕ_c is the phase path distance if the signal had propagated with the speed of light in a vacuum over the same path.

For the sake of completeness, ϕ_m is related to the phase velocity by the following expressions. By definition, the phase velocity $V_p(R)$ at a point R, is given by

$$V_p(R) = \frac{2\pi f}{d\phi/dR}, \qquad (1)$$

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where f is the radio frequency and ϕ is the phase. Therefore, the total phase accumulated over R is

$$\phi_m = 2\pi f \int_0^R \frac{dR}{V_p(R)} .$$

If V_p is constant, then

$$V_p = \frac{2\pi f R}{\phi_m} ;$$

otherwise, equation (1) gives some average effective velocity.

Figure 1 shows the results of some 20.0 kHz measurements made in a southerly direction from Fort Collins over distances ranging from 250 to 550 km. In this figure $\Delta\phi$ is given in microseconds where $\Delta\phi$, microseconds = $\Delta\phi$, radians/$2\pi f$. The figure shows, for example, that at a distance near 300 km the measured phase path exceeds the free space phase path by about 5 microseconds whereas near 550 km just the opposite is the case.

It is possible to deduce a theoretical $\Delta\phi$ versus distance pattern by assuming a particular structure for the propagation medium. The solid line shown in Figure 1 is one such theoretical result obtained using the daytime model ionospheric profile shown in Figure 2. In this calculation it is assumed that the earth's magnetic field strength is 0.5 Gauss, the direction of propagation is toward magnetic south, the dielectric constant relative to a vacuum = 15, and that the ground conductivity is 0.005 (ohms^{-1} meter^{-1}). The calculation was made on a high speed computer using a method developed by Johler [3], and the ionospheric profiles have been used previously by Johler with reference to other studies [4].

It is evident from the figure that the amplitude and period of the measured and theoretical $\Delta\phi$ versus distance variations are similar; however, there appears to be a phase shift between the two patterns. It is not clear at the present time what modifications in the model profile will be required to remove the discrepancy. However, there would appear to be a good possibility of using the experimental data to find a more realistic model profile.

Diurnal Variation of a Function of Distance From the Transmitter

Blackband [5] has studied the magnitude of the diurnal phase shift as a function of distance from the transmitter. In general, these observations refer only to the ionospherically reflected portion of the signal whereas in timing and navigation applications both the ground and sky waves are received.

Figure 3 shows the result of some 20 kHz measurements of the total vertical field made at several distances in a southerly direction from Fort Collins. Note that ϕ_{ND}, along the ordinate scale, is the phase averaged around local midnight minus the phase averaged around local noon. The solid line is a theoretical result obtained using the day and nighttime profiles shown in Figure 2. The figure shows that there is a fairly good correspondence between the experimental and theoretical results in that both show a rapid change with distance beyond 300 km. However, the measured diurnal magnitude drops more steeply with distance and has a greater total variation than does the theoretical.

Correlation in the Phase Fluctuations

An important parameter in timing and navigational systems is the amount of correlation in the phase fluctuations of signals transmitted simultaneously at slightly different frequencies [6, 7]. During a short period of time in November 1966, observations were made simultaneously of the 19.9 and 20.0 kHz signals. These observations were made at a location about 1300 km south of WWVL, Fort Collins. Each day's data was divided into a nighttime and daytime portion with a duration of 6 to 8 hours. The dividing was done so as to exclude the rapid phase variations near sunrise and sunset. The correlation in the phase fluctuations at the two frequencies is given in the table below along with the corresponding variance of the phase fluctuations at 20.0 kHz.

	Daytime		Nighttime	
	Correl. Coef.	Variance $(\mu s)^2$	Correl. Coef.	Variance $(\mu s)^2$
	0.97	0.35	0.97	5.1
	0.94	0.21	0.96	0.37
	0.97	1.0	0.97	1.40
	0.84	1.6	0.94	0.5
Ave.	0.93	0.79	0.96	1.84

The table shows that, in general, the correlation is quite high. Also, there does not appear to be any significant difference in the correlation between day and night even though the average variance of the phase fluctuations is larger at night.

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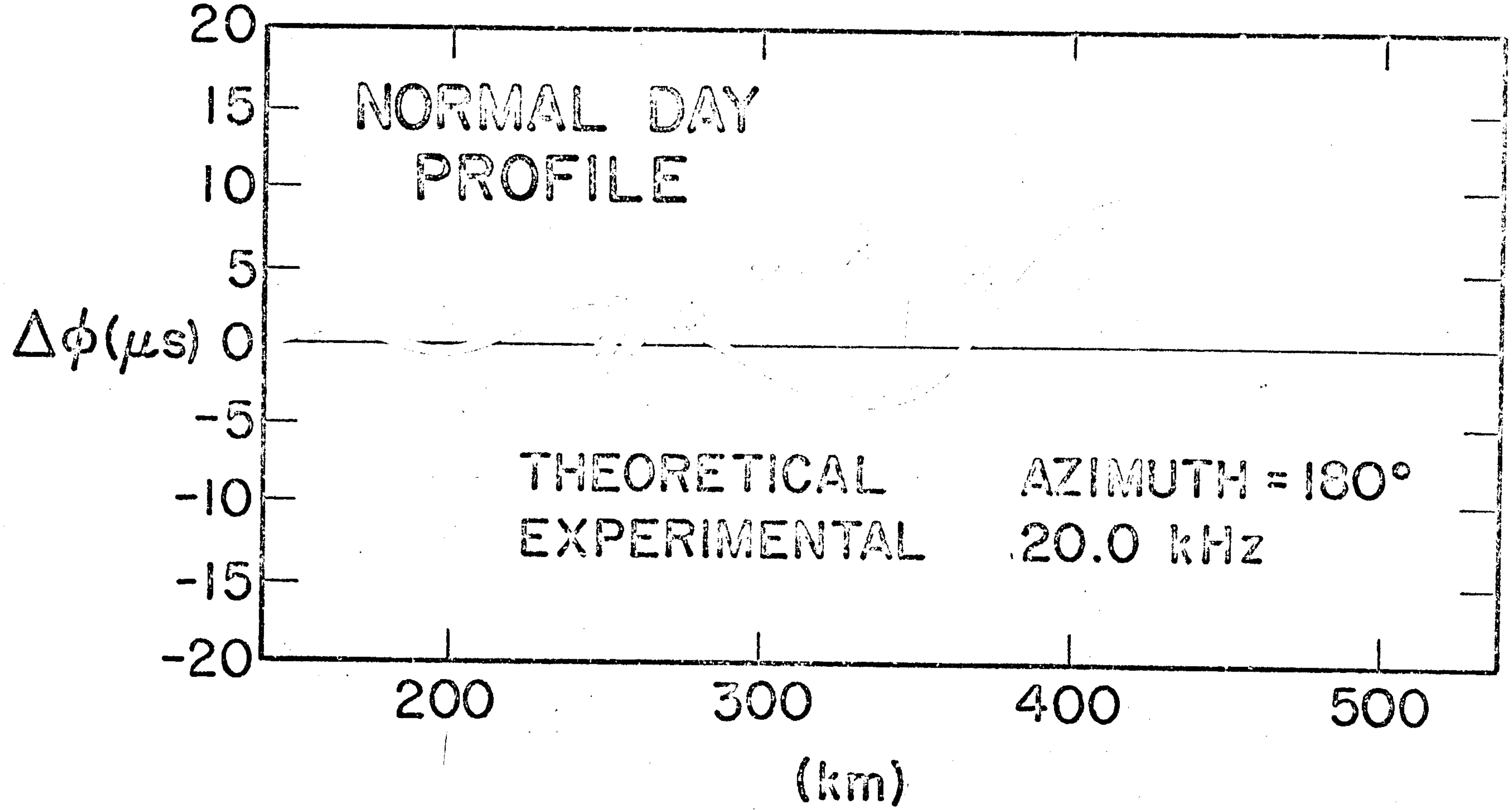
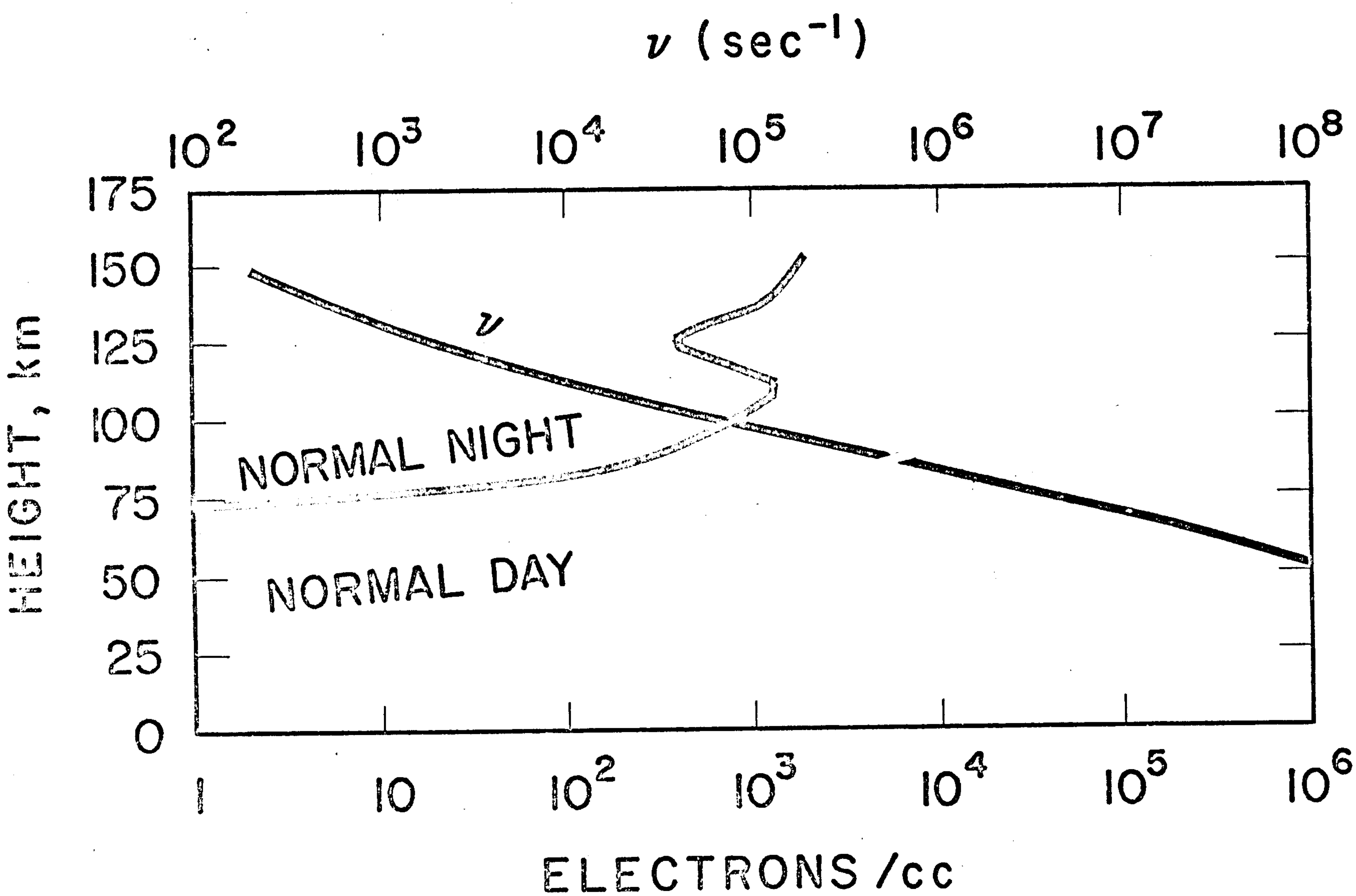
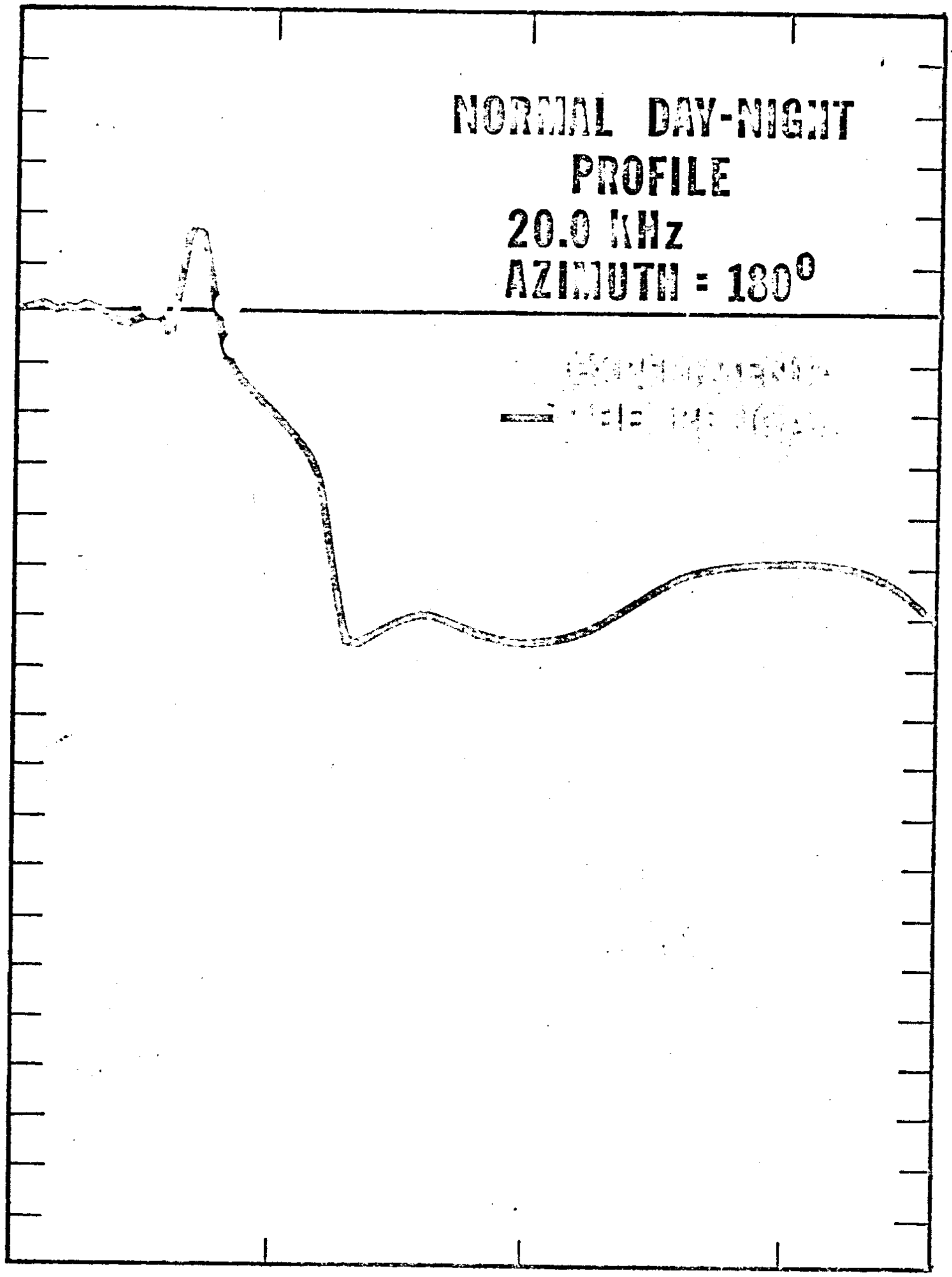

20
15
10
5
Δφ(μs) 0
-5
-10
-15
-20
NORMAL DAY
PROFILE
THEORETICAL
EXPERIMENTAL
AZIMUTH = 180°
20.0 kHz
200
300
400
500
(km)


ν (sec⁻¹)
10^2
10^3
10^4
10^5
10^6
10^7
10^8
HEIGHT, km
175
150
125
100
75
50
25
0
ν
NORMAL NIGHT
NORMAL DAY
1
10
10^2
10^3
10^4
10^5
10^6
ELECTRONS /cc


NORMAL DAY-NIGHT
PROFILE
20.0 kHz
AZIMUTH = 180°