RADIO SCIENCE Journal of Research NBS/USNC–URSI
Vol. 68D, No. 1, January 1964

Propagation of VLF Waves Over Distances Between 1000 and 3000 km

B. Burgess

Ministry of Aviation, Royal Aircraft Establishment, Radio Department, S. Farnborough, Hampshire, England

1. Introduction

The study of the propagation of very-low-frequency radio waves over distances lying between 1000 and 3000 km will provide valuable information regarding the propagation characteristics of such waves and the physical properties of the reflecting walls of the earth-ionosphere waveguide. This is because, over the distances discussed in this paper, there is present more than one waveguide mode of propagation which will lead to wave interference pattern. The location of this interference pattern will be sensitive to variations of geographic and ionospheric conditions and time. Hence, a proper understanding of VLF propagation over these distances should lead to (i) better models of the lower ionosphere and its variation with time of day, season and under disturbed conditions, and (ii) a better appreciation of propagation over much larger distances.

Perhaps the most striking features of VLF propagation over these intermediate distances are (a) the departure of the diurnal phase variation from the standard trapezoidal form associated with much longer distances, and, (b) for some distances the received signal strength is greater by day than night, with either marked minima or maxima at times of dawn and dusk.

This paper will deal mainly with the diurnal phase variations of VLF signals received over these distances.

2. Multimode Paths

There has been very little published data on VLF phase measurements over propagation paths in the range 1000 to 3000 km [Decaux and Gabry, 1961; Westfall, 1961; and Silkwood, 1959] and this published data is far from comprehensive. The measurement of signal strength is far easier to make than that of phase and the results of such signal strength measurements are correspondingly more numerous [Hargreaves and Roberts, 1962; Volland, 1961]. Volland [1961] has used his results to study the applicability of both ray and mode theory to propagation over 1000 km path lengths.

From mode theory [Wait, 1957] one would expect the second and third modes to play greater roles

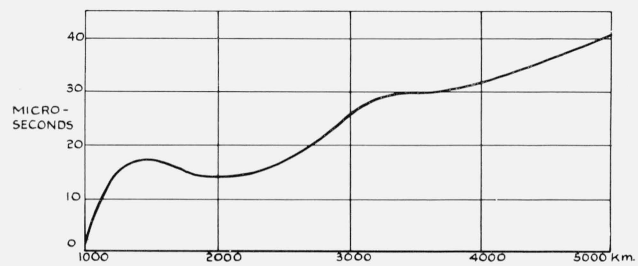

FIGURE 1. *Plot of night-day variation in phase as function of distance.*

in the propagation characteristics as the transmission path lengths decrease from 3000 to 1000 km and that this influence would be different by night and by day.

A convenient way of illustrating this is to compute the expected change in phase from day to night conditions as a function of distance (1000 to 3000 km) for a reasonable model of the propagation waveguide (fig. 1.) At great distances (>3000 km) this variation will be linear. However, as the distance is decreased below 3,000 km the curve departs from linearity in an increasingly oscillatory manner.

3. Experimental Results

Since the summer of 1960, the 16 kc/s transmission from Rugby, England, has been monitored at Rome (Italy) and Malta, and from November 1962 at Idris (Tripoli, Libya) instead of at Malta. Figure 2 shows representative monthly mean diurnal variations of the phase of GBR as recorded at these stations during winter conditions.

3.1. Rome-GBR Path (1500 km)

It is evident from figure 2a that the phase during the day does not exhibit a variation which could be explained by a single mode of propagation and a *D*-region which behaves as the tail of a Chapman layer. In fact, instead of the usual "concave-down" phase pattern, a "concave-up" pattern is noticed symmetrically around noon. This, together with the complex phase variations for the hour or two after sunrise, indicates the presence of more than one mode of propagation during the

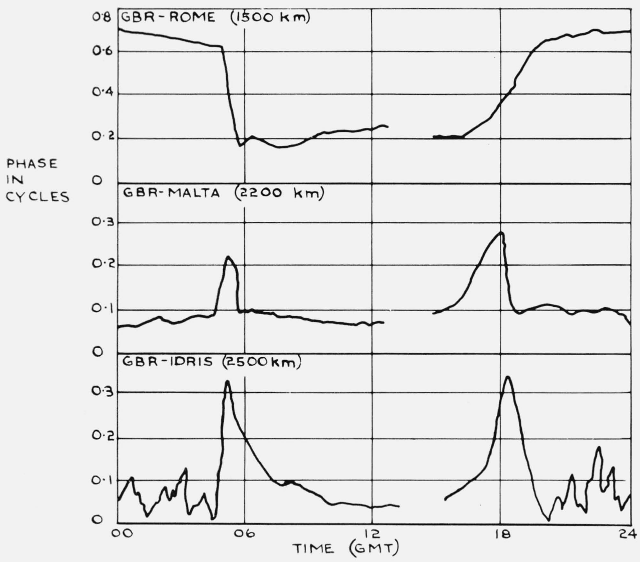

FIGURE 2. *Representative plots of diurnal phase variations of GBR (16 kc/s) at (a) Rome, (b) Malta, and (c) Idris N. Africa.*

day. The nighttime phase shows a regular behavior in that the phase steadily advances from about 2200 hr UT to its presunrise value. The diurnal variation of phase itself varies by a factor of two from winter to summer, being larger in winter.

3.2. Malta-GBR Path (2200 km)

The daytime variation of phase of the GBR-Malta transmission indicates a marked solar control as evident from figure 2b. On mode theory, assuming one mode present at Malta between dawn and dusk, the reflecting layer is some 15 to 20 km lower by day than night, the amount varying with time of year. Solar flare evidence will be presented in a further paper which strongly suggests only one mode of propagation present during the daytime.

At dawn and dusk the signal strength of GBR throughout the year shows fairly deep minima, the nighttime level of signal being greater than the daytime level. This, together with the rapid variations occurring in the phase of signal at these times, indicates the reception of a second mode during the hours of darkness. The phase variation from night to day conditions is very small, although the phase variations at dawn and dusk can be appreciable.

3.3. Idris-GBR Path (2500 km)

At Idris the daytime behavior of the phase of GBR is very similar to that recorded at Malta, as also are the variations at dawn and dusk. One radical difference, however, is the behavior of the phase under night conditions. At certain times of the year, while the nighttime phase of GBR at Malta is relatively stable (random phase deviation of order few degrees), the phase recorded at Idris over say an hour or two will have varied within limits of say approximately ± 90 deg. With the attainment of daylight conditions the phase stability of the signal is restored. In conjunction with these periods of phase instabilities, the nighttime signal strength is much smaller than the daytime level by some 5 to 10 db. This indicates that even out to these distances from a transmitter (2500 km), the second mode, alone or possible together with higher modes, is sufficiently strong to be of comparable magnitude to the first mode under night conditions.

4. Some Concluding Remarks

In this summary paper it is not possible to enter into a discussion of a theoretical interpretation of the above data, but, in essence, the mode theory as developed by Wait can give a picture which agrees with the outlined experimental results. The behavior of signal strength and phase over the paths discussed when inspected in detail, puts the mode theory to a stringent test and the simple model of an upper ionospheric boundary in the form of a step seems no longer to suffice. The explanation of the explanation of the experimental results should lead to a more realistic model of the *D*-region for use in VLF propagation work.

5. References

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(Paper 68D1–309)