REPORT 716-3

THE PHASE OF THE GROUND WAVE

(Question 1/5)

(1978-1982-1986-1990)

1. Introduction

1.1 The phase of the ground wave is important for two major reasons. The stability of this phase makes possible precision radionavigation systems such as Decca and Loran-C. Conversely, the precision with which the phase of the ground wave is measured by these navigation systems makes possible precise experimental verification of ground-wave propagation theories.

1.2 It is convenient to define the phase of the ground wave, Φ, as the sum of a primary phase and a secondary phase, Φ_s. At a distance, d, from a transmitter, the phase of the ground wave may be written:

$$\Phi = nkd + \Phi_s$$

where n is the surface value of the refractive index of the atmosphere and $k = 2\pi/\lambda$, where λ is the free-space wavelength of the ground-wave signal. In this equation, the secondary phase Φ_s is in units of radians. However, in most applications it is expressed as a phase delay time in microseconds according to the relationship:

$$t_s = \frac{\Phi_s \cdot \lambda}{2\pi \cdot 300} = \frac{\Phi_s \cdot 10^6}{2\pi f}$$

where:

- t_s: secondary phase delay time (μs);
- Φ_s: secondary phase (rad);
- λ: wavelength (m); and
- f: frequency (Hz).

The remainder of this Report is concerned with the various factors which influence the secondary phase and with methods of calculating this secondary phase.

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* This Report is brought to the attention of Study Group 2.

2. Smooth homogeneous earth

The basic starting point for the calculation of the secondary phase is the theory of ground-wave propagation over a smooth homogeneous earth [Johler *et al.*, 1956]. Current methods are identical to that used to compute the ground-wave amplitude curves found in Recommendation 368. This basic method can also be applied to pulsed radionavigation systems [Johler *et al.*, 1979].

In order to extend this basic method to more general cases, it is useful to formulate the calculations in terms of a general surface impedance [Hill and Wait, 1980]. Many of the methods used to calculate the phase of the ground wave employ an effective surface impedance concept which incorporates an effective conductivity and permittivity.

3. Secondary phase perturbations

At frequencies below about 3 MHz, the smooth homogeneous earth theory can be used to calculate the phase of the ground wave, to the degree of accuracy required for navigation systems, over sea paths including those with large waves. On land paths, however, the secondary phase is modified by changes in the electrical characteristics along the path, terrain irregularities, and sub-surface layers. Various methods have been developed for predicting the perturbation in the secondary phase due to these factors [Samaddar, 1979].

3.1 *Sub-surface layers*

The effect of sub-surface layers on ground-wave propagation is described in Report 229. The same effective impedance method [Wait, 1970] used to calculate the ground-wave amplitude can be used to calculate the phase of the ground wave if an appropriate model of the sub-surface electrical characteristics [Johler and Horowitz, 1974] exists for calculating the effective ground impedance. This same method can be used over sea paths to predict the effect of sea ice on the phase [Bourne *et al.*, 1970].

3.2 *Non-homogeneous paths*

When the electrical characteristics or surface impedance along a path change (e.g. at a land-sea boundary), there is a corresponding sudden change in both the amplitude and phase of the ground wave. The phase in this case can be calculated by the Millington-Pressey method [Pressey *et al.*, 1953]. This method is completely analogous to the Millington method for computing the ground-wave amplitude over non-homogeneous paths. The phase of a ground-wave signal over a two section path can be calculated from the Millington method formulae, found in Annex II of Recommendation 368, if the amplitudes in the formulae are replaced with the corresponding homogeneous earth phases.

Measurements on Loran-C signals (100 kHz) over a 600 km path in North Norway have shown good agreement between the measured values and the values calculated by the Millington-Pressey method. It is also possible to achieve good results by using the simplified (graphical) Millington method [Saether and Vestmo, 1987].

When the electrical characteristics of the Earth are different in different directions, the wavefront is bent towards the area with the lowest conductivity. This may cause problems for direction finding systems. Measurements in Denmark have shown that signals from a radio beacon (374 kHz) had deviations up to 10^0 from the correct azimuthal direction [Stokke, 1988].

3.3 *Terrain irregularities*

Report 1145 contains a description of an effective impedance theory for calculating ground-wave propagation factors over irregular terrain. The accuracy desired for navigational applications, however, requires very complex calculations. In this case, it is more efficient to use the integral equation method to compute the phase of the ground wave.

3.4 *Integral equation method*

The integral equation method is described in Report 1145. This method can be used to calculate the phase of the ground wave over terrain which is both irregular and non-homogeneous. Figure 1 shows a comparison of computational methods and experimental measurement [Samaddar, 1979]. The path shown crosses both Death Valley, California with an elevation of 100 m below sea level and the Sierra Nevada mountain range. The Millington-Pressey method calculation used a two-layer smooth earth effective impedance model.

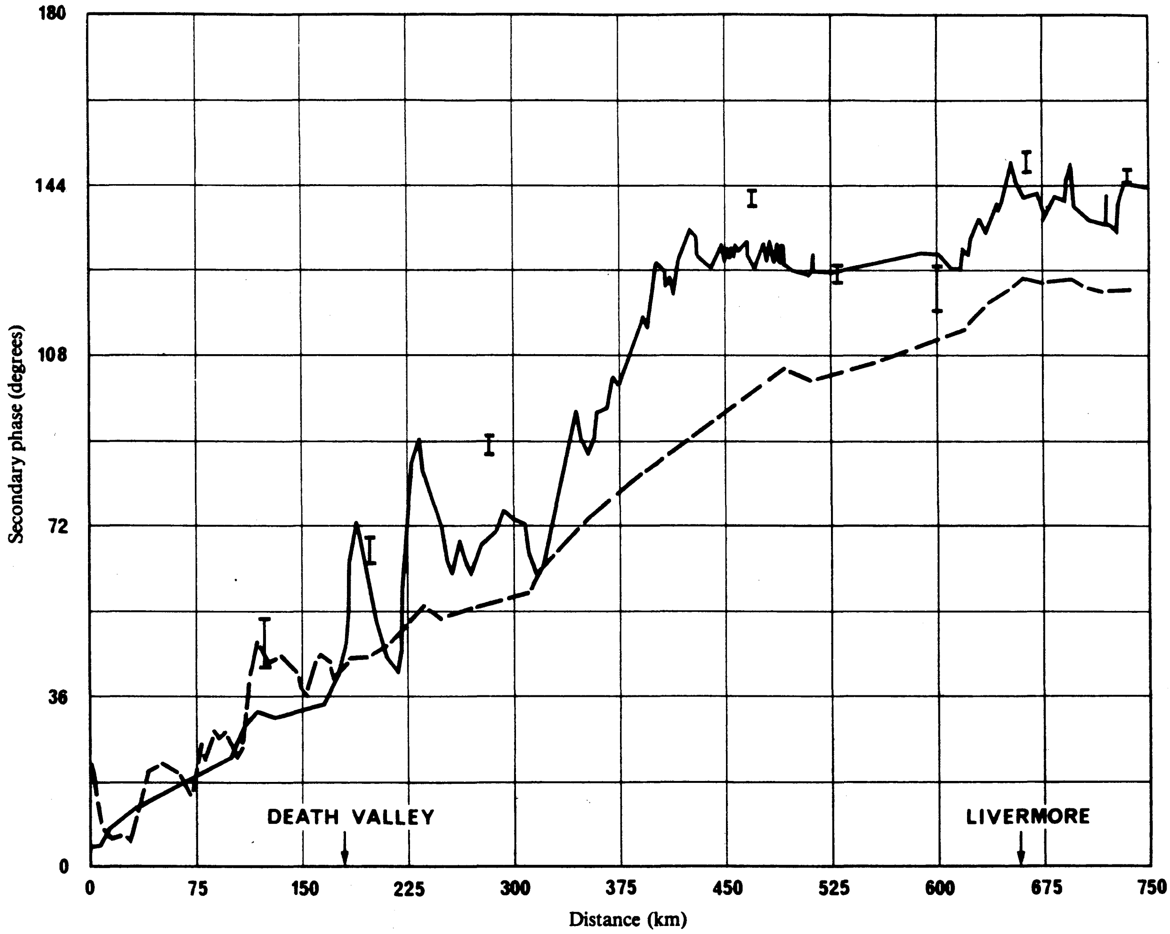

FIGURE 1 – *A comparison of the measured and calculated phase for the USA West Coast Loran-C system.*

(The measured points are shown by the symbol (I). The solid line was calculated by means of the integral equation method. The dotted line was calculated by means of the Millington-Pressey method with effective surface impedances for a two-layer model. At 100 kHz, a secondary phase of 36° corresponds to 1 µs (see § 1.2 above)).

4. Meteorological effects

Several investigations of the stability of Loran-C signals have revealed phase variations corresponding to time-of-arrival variations of as much as ± 0.5 µs [Doherty and Johler, 1975; Samaddar, 1980]. These variations have both a diurnal and long-term characteristic and are correlated with changes in the gradient of the dry term of the refractive index. The longer term variations are associated with the passage of a weather front along the measurement path.

Changes in the phase of the ground wave are found to precede the passage of a warm front. Similar changes associated with the passage of a cold front occur after its passage. It appears that the correction of navigational data in an average sense for meteorological effects may be possible in the future with the use of weather station and system monitoring station data.

Measurements at 100 kHz over a 600 km path, mostly over poorly conducting land in North Norway, have shown seasonal climatic variations in the phase delay time of the order of 200 - 400 ns [Saether and Vestmo, 1987].

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