V. L. F. Signal Fadings during Sunrise and Sunset Observed on Transequatorial Propagation Paths

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Recebido em 20 de Fevereiro de 1971

VLF signal periodic changes during sunrise and sunset transitions are studied at several frequencies on different transequatorial paths. A well known interpretation for the amplitude fadings is coníirmed, but inconclusive results are obtained for nighttime difference in attenuation rates for the first and second order modes of propagation.

São estudadas variações periódicas de sinais VLF durante transições de amanhecer e anoitecer, em diversas frequências e vários trajetos de propagação transequatoriais. Confirma-se uma bem conhecida interpretação para o efeito, relativa aos "fadings" em amplitude, mas os resultados não são conclusivos para a variação de atenuação para os modos de primeira e segunda ordem na propagação noturna.

VLF (verp low frequency) signal fadings during sunrise and sunset transitions are observed on long propagation paths due to destructive interference at the receiver between the first-order mode originally excited by the transmitter and the converted second-order mode at the terminator as it moves along the path. An explanation of such more or less cyclic changes was given by Crombie[1,2] by relating the distance D moved by the terminator along the path during two successive signal minima, to the phase velocities v, and v, of the first and second order modes, respectively, in the nighttime portion of the propagation path, i.e.,

$$D = (1/f_0)\, v_1\, v_2/(v_2 - v_1), \tag{1}$$

where f_0 is the considered signal frequencp. More recently, Steele and Crombie[3] has shown that the difference in attenuation rate between the second and the first order modes can be determined from two successive pronounced phase variations $\Delta\phi$ and $\Delta\phi'$ observed during the signal amplitude fadings. The difference in attenuation rates will be

$$\alpha_2 - \alpha_1 = 20\{log(E_2/E_1) - log(E'_2/E'_1)\}/S \qquad (dB/Mm) \tag{2}$$

where S(*in* Mm) is the distance moved by the terminator during the time interval between two successive phase deviations (corresponding to signal maxima), $E_2/E_1 = tan\,\Delta\phi$ and $E'_2/E'_1 = tan\,\Delta\phi'$ (when $E, < E,$ and

$E'_1 < E'_2$). Indices 1 and 2 are for the first and second order modes of propagation, and E_1, E_2 are the relative field strengths before the effect for the first-order mode and converted second-order mode, respectively, and E'_1, E'_2 the same parameters after the onset effect.

The data used in this note consisted of a number of averaged VLF transequatorial transmissions across the South Atlantic Geomagnetic Anomaly, received by two tracking stations, controlled by an atomic frequency standard oscillator, situated at Campos do Jordão, São Paulo, Brasil (Latitude = –22°46′, Longitude = –45°35.5′) (see Figure 1). Observing periods and considered transmissions are presented in the Table. The work is concerned only with the averaged features observed. For each period of observation, the mean velocity of the terminator was computed for the corresponding propagation path. This approximation is acceptable when one considers that the paths are almost entirely situated at temperate latitudes. The number of fadings for a certain transmission depends on

Table

Transmitter	*Frequencv kHz*	*Distance Mm*	*Prriod of Obseroation*
GBR - Rugby	16.0	9.5	**DEC** 3 - **DEC** 18, 1966
	16.0	9.5	**MAY** 9 - **MAY** 24, 1967
NPG - Jim Creak	18.7	10.9	**MAR** 1 - **MAR** 15, 1967
GBZ - Criggion	19.6	9.5	**MAY** 9 - **MAY** 16, 1966
	19.6	9.5	**JUL** 10 - **JUL** 25, 1966
	19.6	9.5	**SEP** 9 - **SEP** 24, 1966
WWVL-Ft. Collins	20.0	9.3	**OCT** 15 - **OCT** 30, 1966
	20.0	9.3	**DEC** 3 - **DEC** 18, 1966
	20.0	9.3	**JAN** 4 - **JAN** 15, 1967
NSS - Annapolis	21.4	7.6	**AUG** 25 - **SEP** 9, 1966
	21.4	7.6	**SEP** 25 - **OCT** 10, 1966
	21.4	7.6	**OCT** 15 - **OCT** 30, 1966
	21.4	7.6	**DEC** 18 - **JAN** 2, 1966-67
NBA, Balboa	24.0	5.1	**MAR** 23 - **APR** 7, 1966
	24.0	5.1	**APR** 8 - **APR** 23, 1966
	24.0	5.1	**MAY** 9 - **MAY** 16, 1966
	24.0	5.1	**AUG** 14 - **AUG** 24, 1966
	24.0	5.1	**SEP** 9 - **SEP** 24, 1966
	24.0	5.1	**NOV** 11 - **NOV** 19, 1966
	24.0	5.1	**NOV** 20 - **DEC** 1, 1966
	24.0	5.1	**DEC** 18 - **JAN** 2, 1966-67
NPM - Hawaii	26.1	12.9	**AUG 25 - SEP 9, 1966**
	26.1	12.9	**SEP** 25 - **OCT** 10, 1966
	26.1	12.9	**NOV** 10 - **NOV** 19, 1966
	26.1	12.9	**NOV** 19 - **DEC** 1, 1966

the path and on its position in relation to the sunrise or sunset shadow line and on wavelength. During selected periods of observation, at least two fadings were noticeable at sunrise and/or sunset and the daily mean time interval between fadings were considered for the calculations. A typical example of data is shown in Figure 2.

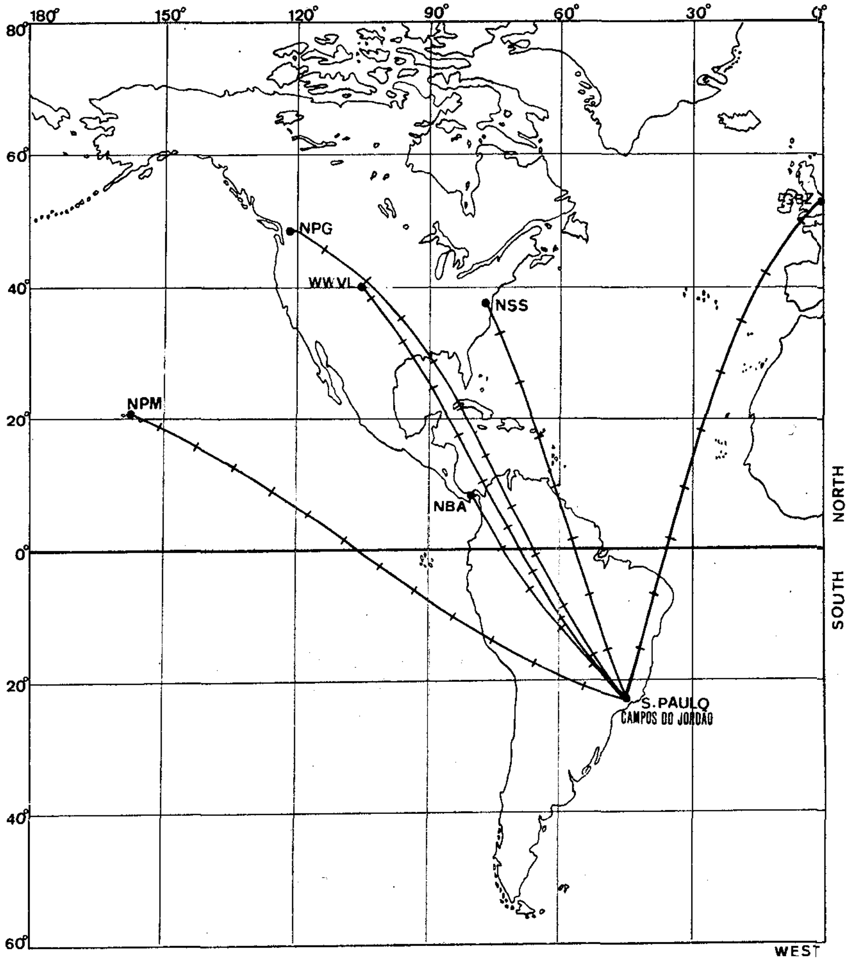

Figure 1. Map showing the geographical situation of the various VLF transmissions considered in this paper. The dots over the paths indicate distances in Mm. In order to locate approximately the Geomagnetic Anomaly, the dashed line corresponds to a contour of 0.3 gauss constant field at 100 km altitude (after Roederer, Hess and Stassinopoulos, NASA Rept. **X-642-65-182, 1965).**

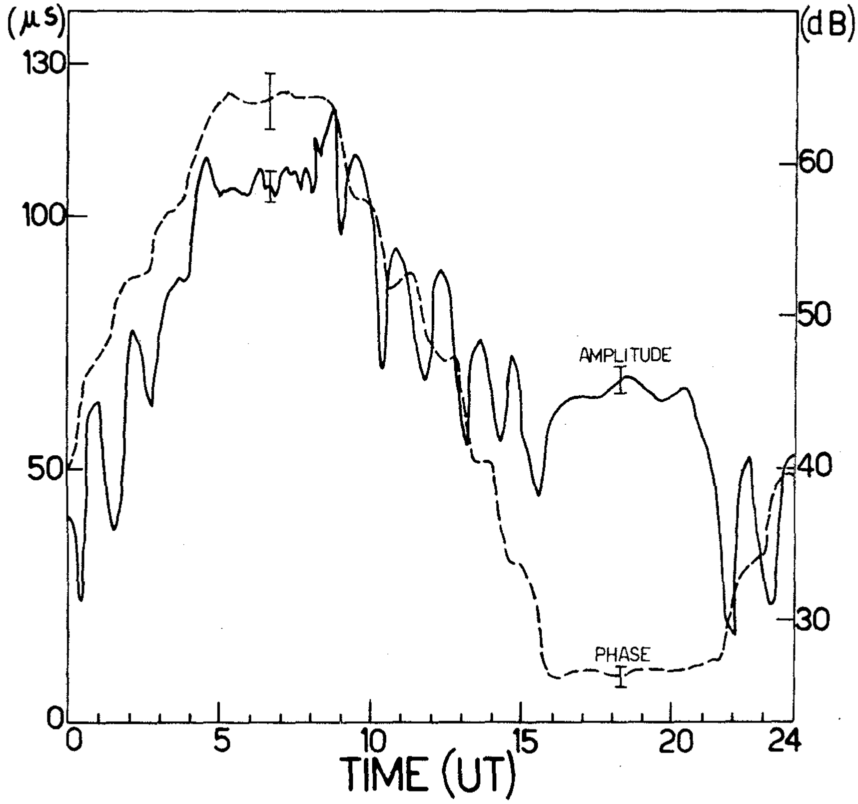

Figure 2. A typical diurnal phase and amplitude variation, averaged for NPM São Paulo transmission at 26.1 k Hz, from September 25 to October 10, 1966. The amplitude fadings are clearer than the phase steps at sunrise and sunset transitions.

Figure 3 shows the frequency dependence of D. The dashed line corresponds to points calculated using Equation (1), with phase velocities published by Wait and Spies[4], for an isotropic model of ionosphere presenting nighttime conductivity gradient of 0.5 km^{-1} and considering the ground as a nearly perfect conductor. The experimental results are plotted in this Figure with the estimated inaccuracies. The agreement with theory is remarkable in spite of the diversity of propagation paths and periods selected. The results still favour a nighttime reference height of 90 km for the upper boundary of the earth-ionosphere waveguide.

On the other hand, the mean values for the time intervals between fadings suggest that the two quantities **D** and *S* can be considered to be equal.

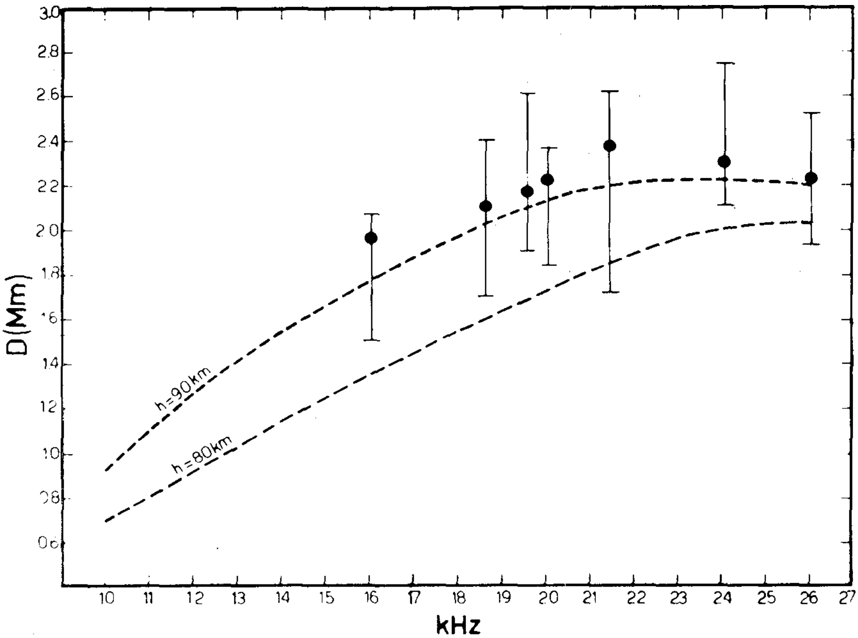

Figure 3. Frequency dependence of D. The experimental points are mean values for all periods of observation at a single frequency, and bars indicate the extreme inaccuracy ranges estimated.

Some values for $u, -\alpha_2$ were derived for onset transitions where the converted second order mode was less than the unconverted first mode (E, < E,). The results from these calculations are quite inconclusive. The condition *E, < E,* was only characterized in few cases, i.e., on GBR (16.0 kHz) transmissions and in some periods of NSS (21.4 kHz), NBA (24.0kHz) and NPM (26.1 kHz) transmissions without any apparent dependente on the season. The values for $u, -\alpha_1$ calculated for these cases are not in good agreement with theoretical computations made with attenuation rates published by Wait and Spies[4], ranging from – 1.8 dB/Mm (for NPM) to 3 dB/Mm (for NBA). The step-like behaviour of the phase is more pronounced at sunrise than at sunset as noticed by some authors (Refs. 1, 5 and 6). At the same time, many serious uncertainties affect the phase analysis at that transition periods, specially at transequatorial paths, as was also extensively shown by Reder and Westerlund[6] and Lynn[7], making such determinations difficult and inaccurate.

The authors are grateful to R. M. de Souza and O. T. Matsuura, in conducting computer work and to B. Chu and O. Fanto for reduction work. They also acknowledge computer time made available by EPUSP - *Centro de Cálculo Numérico,* and by the Institute for Exploratory Research, N.J., U.S.A.. This work is sponsored by the US Army Element, Defense Research Officie, Latin America (grant No. DA-ARO-49-092-G77), *Fundação de Amparo a Pesquisa do Estado de São Paulo* (FAPESP) and *Conselho Nacional de Pesquisas* (*CNPq*).

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