CONSIDERATIONS OVER THE PHASE VARIATION OF VLF SIGNALS RECEIVED AT SÃO JOSÉ DOS CAMPOS - SP - BRASIL

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NOTE

The illustrations are not ready for print and they will be presented in slides during the examination of the thesis.

The main illustrations are presented in the parts 3 and 5.

ABSTRACT

The phase variation of the signals in the band of VLF give us some information about the D region of the ionosphere. We prepared a study with the experimental data obtained at São José dos Campos, SP, Brasil (SJC) from two transmitters at different places. The location of the transmitters are Jim Creek, Washington, U.S.A. (NLK) and Trinidad (OMEGA). The diurnal variation of phase presents the same characteristics for both paths, while the seasonal variation of phase presents different behavior for the two paths. A possible reason to explain this difference is given by the difference of behavior of the seasonal ionization and loss in the different geographical latitudes of the D region. The occurence of sudden phase anomalies (SPA) is also different in the two paths. Suggestions are made to explain these features.

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INTRODUCTION

This work is based on experimental work. Its purpose is to show how we can, starting with a simple model, foresee the behavior of certain phenomena that occur in the D region of our ionosphere, by means of the study of the phase variation of radio signals in the band of Very Low Frequency (VLF).

In the first place we will describe the ultimate results of a simple model that tries to describe the propagation of these waves with the minimum number of parameters.

Then, it will be shown how the experimental data are collected. The block diagram of a receiver system and the precision of the data obtained are discussed.

The method of data reduction and the program of the computer, a Burroughs B-3500, is presented for a clearer explanation. The program is for the calculus of the observed month averages. The data are taken during each half an hour for each day. The study is made on basis of the average values.

Plots and results of special values are presented and the plots of every month's average are available also.

Finally the data are analysed and it is shown how with this simple data and model we can arrive at important conclusions on the propagation of VLF waves and the behavior of the D region ionization.

2. THEORETICAL CONSIDERATIONS

This part is divided in two sections, one looking to the behavior known of the D region of ionosphere, the other presenting a single model to study the phase variation of signals received in São José dos Campos, Brasil, from two stations; NLK in Jim Creek, Washington, U.S.A., and OMEGA in Trinidad.

These signals are in the band of Very Low Frequency (VLF),i.e.,from 3 KHz to 30 KHz, in frequency.

The reason of this presentation is to give to the reader an overview of the theory that will be applied latter in the analysis of the experimental results, not the presentation of the theory itself.

2.1 Behavior of the D Region

In the beginning of the century, while doing experiments with radio waves it was discovered that these waves were reflected by some conducting layer. Nowadays the region located between 60 km and 1000 km of height is known as ionosphere. The reflection take place in the ionosphere. The ionosphere results from the interaction of solar energy with the upper atmosphere of the Earth. This interaction produces the ionization of the various types of molecular and atomic constituents of this part of the atmosphere. Afterwords, recombination takes place, forming a closed cycle. Below 60 km height, very little ionization is found and above 1000 km height the term protonosphere is used to describe this ionized region overlying the the ionosphere. The protonosphere is distinguished as consisting of a virtually completely ionized plasma of protons and electrons only.

The division of the ionosphere into regions comes from the old assumption that it was formed by independent conducting layers. Presently we know that the electron density varies continuously but it is still usefull to consider this division for purposes of study.

The ionosphere is divided into three regions: D region from 50 to 90 km height, the E region from 90 to 160 km and F region from 160 to 1000 km. Sometimes there are references to the C region for the part of the lower D region, where C stands for the cosmic ray region.

These limits are not constants and exacts, they have a time variation.

From studies of propagation we know that waves in the band of VLF are reflected by the high electronic density at the level corresponding to the D region (Ratcliffe , 1962).

The geographycal division of the D region is the following:

a) Equatorial D region
b) Middle latitudes D region
c) Polar D region

Equatorial D region - is located in the geographical region near the equator. The main feature of this region is that the ionization is due to cosmic rays, X-rays and ultraviolet radiation (Lyman $-\alpha$).

Middle latitudes D region - is located in middle latitudes and the ionization is caused by particles in very disturbed solar conditions.

Polar latitudes D region - is locate in the geographical polar region. The ionization is caused by the three factors above and frequently by particles.

We will now describe the sources of ionization and the losses processes. The ionization sources are the mentioned above.

Experimental measurements made in the laboratory show that the losses are probably due to the following (Aikin, 1965):

a) Three-body attachment of electrons to molecular oxigen
b) Photo-detachment from O_2
c) Ion-ion recombination
d) dissociative recombination

For a given profile, the large electron density (Ratcliffe, 1962) the lower will be the reflection height, with a shorter phase path as a result.

Based on this fact we will show the results of a model that consider the Earth and the reflection height in the ionosphere like conducting surfaces that guides the waves from transmitter to receiver.

2.2 Model

The idea of presenting a mathematical model for a certain physical phenomenon is to facilitate its study. For instance, a model that depends on five independent parameters allow us to know the behavior of the pheno menon with the individual variation of each parameter, or more than one, or all of them.

When a model is very simple is easy to work with it, but it gives results that does not fit very well the experimental results. When it is very complicated, it gives good agreement with experimental data but is very difficult to work with it, or even impossible.

Today, with the use of electronic computers it is easier to work with more complex models, when necessary.

It is of no practical use for one to work with a certain model that improves the results by one percent since most of the time such improvement implies a great deal of extra work.

In the present work we will try to extract the most from the available data with the simplest possible model.

As we mentioned before in this work we will interest in the VLF band of the radio-spectrum.

There are two ways for studying propagation of waves:

a) The ray theory, that considers the propagation geometrically and

b) The mode theory, that considers one wave like the sum of a certain number of modes.

Let us consider first the meaning of the term mode. The International Dictionary of Physics and Mathematics (Van Nostrand) defines mode of propagation as follows: "A form of propagation of waves that is characterized by a particular field pattern in a plane transverse to the direction of propagation which field patter is independent of position along the axis of the guide".

Now we must choose which theory is more usefull in our case. From (Pekeris, 1950) we have a few conclusions that are described below. The selection is not by inspection and one theory is not better than the other. Each one presents advantages under certain conditions. It has been shown (pekeris, 1950) that for the case of propagation between perfectly reflecting parallel planes, the series expansion based on mode and ray theory are related by a Fourier cosine transform. This suggests that, provided all rays and all modes are taken into account with appropriate corrections for losses, the results from both methods will be the same as has been demonstrated by Wait (1961).

We are interested in working with the minimum number of modes or rays.

Performing the calculations we know that only at short distances a single ray model is satisfactory, but we need a great number of modes to get the same result. At long distances we need more than only one ray to find out the same value.

On VLF the wavelength and height of reflection are such that only a few modes are important since the higher-order modes are attenuated at a much greater rate than that of the lowest mode. At great distances all propagating modes are comparable in amplitude and must be considered.

In our case, we are considering long distances and the theory that gives the simplest calculation is the mode theory. We cannot speak of modes without speaking of waveguides.

The physical boundaries that guide the waves between transmitter and receiver are the earth's surface and a level in the D region of the ionosphere that reflects the waves. The reflection height is determined by the electron density profile (Ratcliffe, 1962). The electron density profile depends on the ionization, which varies with time and height. The ionization depends on the solar radiation, thus the height of reflection has strong daily variation.

This wave guide is not with sharp boundaries and has a time variation.

What simplifications can we do in order to obtain the simplest model, which still has good agreement with experimental data?

Let us assume that the earth and the upper boundary, where the plasma frequency equals the wave frequency (Ratcliffe, 1962), are perfect electrical reflecting conductor and plane surfaces. Then, let us make the ionosphere a perfect magnetic conductor, with the reflection coefficient R =-1, instead of electrically perfect conductor with reflection coefficient R=+1. If the ionosphere boundary and the earth are not perfect reflector,electric

al and magnetic, but imperfect reflectors, then its R's are complex numbers.

The next step is to consider that the earth and ionosphere are not plane but curved. The last step is take into account the Earth's Magnetic Field.

The chief effect of the Earth's Magnetic Field is to make the ionosphere an anisotropic medium. This effect is of little importance when the paths are near the North-South direction. Both paths we have are almost N-S in direction and we can neglect the effect of the Earth's magnetic field.

Now let us present the ultimate (Wait, 1959) results of a model having this assumptions:

A) Wave guide:

- lower boundary - imperfect electrical conductor; curved.
- upper boundary - imperfect magnetic conductor; curved.

B) Theory:

- Mode theory, with the waves being transverse magnetic (TM).

C) Frequency band:

- VLF

The phase velocity of the n^{th} mode is given the following expression:

$$V_{pn} = \frac{C\left(1 - \frac{h}{a}\right)}{\sqrt{1 - \left(\frac{\left(n - \frac{1}{2}\right)\lambda}{2h}\right)^2}}$$

where:

V_{pn}	=	phase velocity for the n^{th} mode of propagation
C	=	velocity of light in free space
h	=	mean reflection height
λ	=	wavelenght in free space
n	=	mode order
a	=	mean earth radius

Then for v_{p1} or V_p , or for n = 1 we have:

$$v_p = \frac{C(1 - \frac{h}{a})}{\sqrt{1 - \frac{\lambda^2}{16h^2}}}$$

If we have $\frac{\lambda^2}{16h^2} << 1$, then

$$V_p = C(1 - \frac{h}{a} + \frac{1}{2} \times \frac{\lambda^2}{32\ h^2} \ldots)$$

The corresponding phase variation $\Delta\phi$ for a height of reflection variation Δh in a path following a great circle, with lenght D is:

$$\Delta\phi = - \frac{2\pi D}{\lambda} \left(\frac{h}{2a} + \frac{\lambda^2}{16h^2}\right) \frac{\Delta h}{h} \quad \text{(in radians)}$$

The value we have is the time variation, related to the phase variation by

$$\Delta t = \frac{\Delta\phi}{w} = \frac{\Delta\phi}{2\pi f} = \frac{\Delta\phi}{2\pi \frac{c}{\lambda}} \qquad \Delta t = \frac{\Delta\phi\lambda}{2\pi C}$$

or

$$\Delta t = -\frac{D}{C} \left(\frac{h}{2a} + \frac{\lambda^2}{16h^2} \right) \frac{\Delta h}{h} \quad \text{(in seconds)}$$

The minus sign means that there is a time delay.
The reflection height is strongly influenced by the solar illumination of the path, and the total phase lag between transmitter and receiver is given by

$$\Delta\phi = d_o\, \beta_o + d_n \beta_n = d_o\, (\beta_o - \beta_n) + \beta_n\, d$$

where

d_o = part of path in daylight

d_n = part of path at night

d = total path length

β_o = phase variation by unit of length in daylight

β_n = phase variation by unit of length at night

We easily see that the geographical location of the receiver and transmitter are important in the pattern of the recorded daily phase variation.

For a North-South path the transition between day and night is at the same time in almost the whole path and the recorded daily phase variation will present sharp raise and fall by sunset and sunrise. For a East-West path the illumination of the path is gradual and in the records of the daily phase variation the pattern will be a slow rise and fall by sunset and sunrise.

3. DATA ACQUISITION

The data is required by a very simple system. What we want to do is to compare the received phase with the phase of the transmitter or a local high stability oscillator.

For short distances we compare directly the received phase with the phase of the transmitter by means of a telephone line.

For long distances this method is not practical and we compare the received phase with a high stability local oscillator. It is our case and the stability of the local oscillator is 10^{-9}.

A simplified block diagram of the two sistems is shown in Fig. 3.1.

The recording should be of low speed since the phase variations are extremely slow.

We actually have the time delay instead of phase variation, but we know that

$$\Delta t = \frac{\Delta\phi}{w} = \frac{\Delta\phi}{2\pi f}$$

Then we indirectly have the phase variation if we know the time delay Δt. We can read the results of phase variation with a accuracy of $\pm$ 1μs in time delay. The time precision depends on the speed of the paper. Even with very low speed we can easily reach time intervals of ten minutes. The accuracy on the phase variation depends on the frequency of the transmitter station. In our case, we have NLK with 18.6 KHz and OMEGA with 13.6 KHz, thus with

$$\Delta\phi = 2\pi \times f \times \Delta t$$

and

$$\Delta t = 1\mu s \quad \text{or} \quad \Delta t \simeq 10^{-6} s \quad \text{we have}$$

for OMEGA

$$\Delta\phi = 2 \times \pi \times 13.6 \times 10^3 \times 10^{-6} \simeq 8,55 \times 10^{-2} \text{ radians}$$

for NLK

$$\Delta\phi = 2 \times \pi \times 18.6 \times 10^3 \times 10^{-6} \simeq 11,7 \times 10^{-2} \text{ radians}$$

We see that for the greater frequency lower is the accuracy that we can have in the phase variation, i.e., we can detect a phase variation of $11,7 \times 10^{-2}$ radians for NLK and of 8.85×10^{-2} radians for OMEGA.

Let us see the magnitude of this difference

$$p = \frac{11.7 - 8.55}{11.7} = 0.269 \qquad p = 26.9\%$$

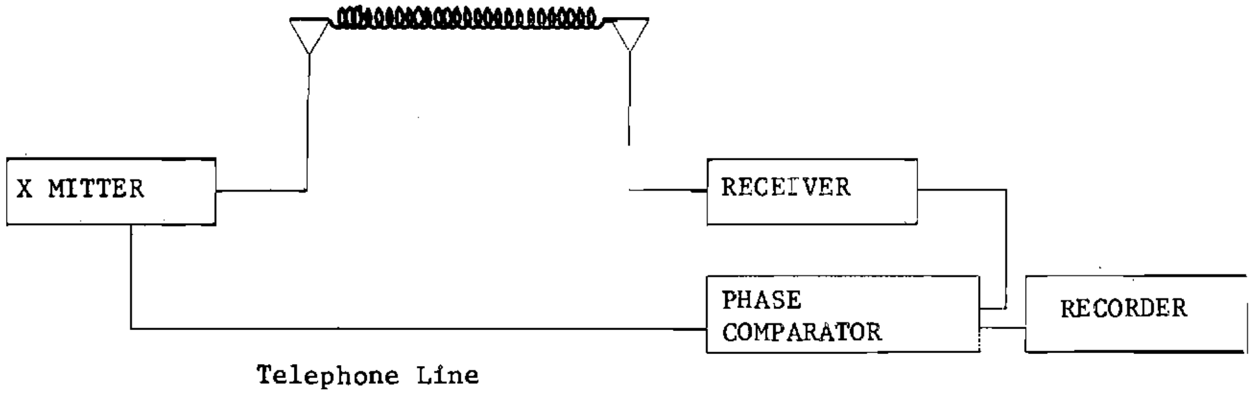
The data about the transmitter are chosen in Watt (1967) and, Reder and Viccione (1967).

We will give a table with some useful parameters

TABLE 2.1

Station	Geographical Coordinates	Geomagnetic Coordinates	Distance to SJC (km)	Transmitter Power (KW)
NLK	$48^{\circ}12'$N $121^{\circ}55'$W	53°N 295°	10900	250
OMEGA	$10^{\circ}42'$N $061^{\circ}38'$W	22°N 009°	4000	3
SJC (Receiver)	$23^{\circ}18'$S $045^{\circ}51'$W	$12{,}6^{\circ}$S $21{,}7^{\circ}$	-	-

Short Distances



Long Distances

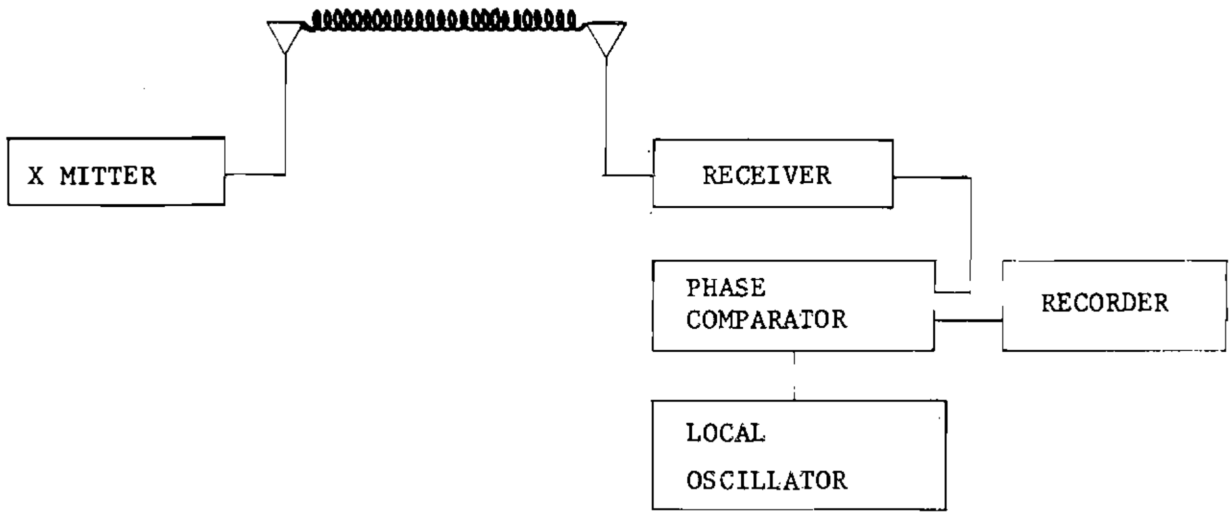


Fig. 3.1

4. DATA REDUCTION

There are several ways of performing the data reduction. We will describe here the one used at CNAE.

The phase variations are recorded with respect to a high stability local oscillator in a paper tape with the time in the longitudinal direction.

The time is in Universal Time (UT) and the phase variation is measured in micro-seconds. Values are observed each half an hour. These data are put in punched cards and results are obtained for every half an hour for the month average. The program used is transcribed in Appendix A. The computer used is a Burroughs B-3500 of CNAE. The resulting plots can be seen in figures in part 6.

Since stabilities of the local oscillator and transmitter are different, then over the signal appears an oscillation that is eliminated by a linearization of the oscillations.

The procedure for avoiding the oscillations is as follows:first and last values are taken for each day, subtracted for each value the value of the straight line that passes by these two points. For each day we first correct the value by this method and then take the average. The plots for every corrected day and the months averages are thus obtained. The computer gives directly the plots of the corrected day and month averages.

The coefficient of inclination of the straight line passing by the initial and final points is here called B. The plots of B for every day is presented in figures of the part 6 and it can be seen that it shows a slow variation. This permits one to use a value of B for an entire day. Figures of part 6 display this simple procedure.

In our data a day begins at 1700 UT and finishes it at 1700 UT of the next day. The computer input is comprised of the following data:
For each day:

a) Day of the year (1 to 365 or 366)

b) Month

c) Year

d) Day of the month

e) The first value of the day (that is called A)

f) All the values for each half hour

For each month:

a) The station

b) The frequency

The program is very versatile and with proper modifications can be used for other stations.

Figures in part 6 show available month averages, typical days and plots of the more significant features. In part 6 we have a complete index of every figure.

5. ANALYSIS OF THE RESULTS

Based on the simple procedure outlined above, we shall now present the data analysis and some conclusions.

Some characteristics are well known, while others are just now being studied. In order to situate the problem we will discuss the main characteristics, namely:

These main characteristics we will talk of, are:

a) Diurnal variation

b) Seasonal variation

c) Study of Sudden Phase Anomalies (SPA)

c-1) Determination of the effective recombination coefficient at the height of reflections

c-2) Suggestion related to the fact that SPA do not occur at equatorial latitudes as frequently as at middle latitudes.

5.1 Diurnal Variation

Following the last conclusions of the simple model described early we know that the phase variation follows the law:

$$\Delta\phi = -\frac{2\pi D}{\lambda}\left(\frac{h}{2a} + \frac{\lambda^2}{16h^2}\right)\frac{\Delta h}{h}$$

where

D = great circle path between transmitter and receiver

λ = wavelenght in free space

h = mean reflection height

Δh = mean reflection height variation

a = earth's radius

The measured quantity is the time delay (instead of the phase variation), i.e.,

$$\Delta t = \frac{\Delta\phi}{2\pi f} = \frac{D}{C}\left(\frac{h}{2a} + \frac{\lambda^2}{16h^2}\right)\frac{\Delta h}{h}$$

Among six parameters that we take in account, D, c, a, λ, h, Δh, the last two are the variable ones. By other means we know the range of variation of these two parameters, which are approximately:

for h 73 to 70 km by day

for Δh 13 to 19 km above the daylight value

We have data from two transmitters:

Transmitter	Location	Frequency (KHz)
OMEGA	Lat.:$10^{\circ}42'$N Long.:$061^{\circ}38'$W	13.6
NKL	Lat.:$48^{\circ}12'$N Long.:$121^{\circ}55'$W	18.6

Knowing the locations of the transmitter and the receiver, at São José dos Campos (SJC) Lat.: $23^{\circ}18'$S Long.: $45^{\circ}51'$W, we can compute D, the great circle distance between transmitter and receiver.

This computation is made by means of simple spherical trigonometry.

D = distance between transmitter and receiver in degrees.

$$\text{hav } D = \cos LA \cos LB \text{ hav } LOAB + \text{hav } (LA + LB)$$

where

LA = latitude of transmitter

LB = latitude of receiver

LOAB = difference of longitude between receiver and transmitter

For NLK - SJC

$$\text{hav } D = \cos 48.2 \cos 23.3 \text{ hav } 76.1 + \text{hav } 71.5 = 0.573$$

$$D = 98.4^{\circ} \qquad 1 \text{ minute} = 1852 \text{ m}$$

$$D\ (\text{km}) = 98.4 \times 60 \times 1.852 \text{ km}$$

$$D = 10959 \text{ km}$$

For OMEGA - SJC

$$\text{hav } D = \cos 10.7 \cos 23.3 \text{ hav } 33.9 + \text{hav } 17.2 = 0.0987$$

$$D = 36.7^{\circ} \qquad 1 \text{ minute} = 1852 \text{ m}$$

$$D = 36.7 \times 60 \times 1.852 = 4000 \text{ km}$$

Now let's compute, theoretically, the values for Δt for several limits of reflection heights and for several Δh, for each path - NLK-SJC and OMEGA -SJC.

In first place we will indicate how the computations are made and then we will present a table of the results for each station.

OMEGA For h = 75 km Δh = 13 km

$$c = 3.0 \times 10^{8} \text{ m/s}$$

$$a = 6370.0 \times 10^{3} \text{m}$$

$$\lambda = \frac{c}{f} = \frac{3.0 \times 10^8}{13.6 \times 10^3} = 22.0 \times 10^3 m$$

$$D = 4.0 \times 10^6 m$$

$$\Delta t = \frac{4.0 \times 10^6}{3.0 \times 10^8} \left(\frac{75 \times 10^3}{12740 \times 10^3} + \frac{(22.0)^2}{16 \times (75.0)^2} \right) \frac{13.0 \times 10^3}{75.0 \times 10^3} = 25.8 \ \mu s$$

TABLE 5.1

f = 13.6 KHz

For OMEGA

h (km)	h(km)	Δt(μs)
69	13 15 17 19	30.0 34.5 39.0 43.5
70	13 15 17 19	29.0 33.4 38.0 42.4
71	13 15 17 19	28.0 32.4 36.7 41.0
72	13 15 17 19	27.4 31.6 25.9 40.1
73	13 15 17 19	27.0 31.2 35.4 39.6
74	13 15 17 19	26.3 30.4 34.4 38.4
75	13 15 17 19	25.8 29.8 33.8 37.8

TABLE 5.2

f = 18.6 KHz

For NLK

h (km)	Δh (km)	Δt (μs)
69	13	60.0
	15	69.5
	17	78.9
	19	88.0
70	13	59.0
	15	68.0
	17	77.4
	19	86.5
71	13	58.0
	15	66.5
	17	75.6
	19	84.5
72	13	57.5
	15	66.2
	17	75.1
	19	84.0
73	13	56.5
	15	65.0
	17	74.0
	19	82.5
74	13	56.0
	15	64.5
	17	73.1
	19	81.8
75	13	55.1
	15	63.6
	17	72.0
	19	80.6

From the average phase variation of each month, we have calculated the mean total variation of the whole period, for each station. Let's compare these values with those of the tables 5.1 and 5.2.

Naturally, this simplified model does not take in account the Earth's Magnetic Field, but we can easily see from (Wait, 1960) that this effect does not effect very much a almost North-South path, and we can neglect it.

Tables 5.3 and 5.4 present the experimental data.

TABLE 5.3

Station	Month	Average daily phase variation (μs)
NLK	Jan 1965	80
	Feb	80
	Mar	78
NKL	Jan 1966	81
	Feb	75
	Mar	81
	Apr	74
	May	74
	Jun	79
	Jul	80
	Aug	72
	Sep	80
	Oct	69
	Nov	79
	Dec	77
NKL	Jan 1967	79
	Feb	78
	Mar	81
	Apr	78
	May	72

TABLE 5.3 (Cont.)

Station	Month	Average daily phase variation (μs)
OMEGA	Apr 1967	23
	May	25
	Jun	26
	Jul	27
	Aug	28
	Sep	28
	Oct	29
	Nov	31
	Dec	32
OMEGA	Jan 1968	31
	Feb	30
	Mar	28
	Apr	25

TABLE 5.4

Station	Mean total variation
NKL	77.5 μs (in 20 months)
OMEGA	27.9 μs (in 13 months)

Following our model (Wait, 1959) we see that in average, if we consider h = 72 km Δh = 13 km, for OMEGA, and h = 70 km and Δh = 17 km, the experimental data fits our model.

Because of the difference of path it is expected that the reflection heights vary along the path; furthermore the ionizing agents are different (Aikin , 1965) in the equatorial and in the middle latitudes D region.

The path OMEGA-SJC is all located under the equatorial D region and the NLK-SJC is located part under this region and part under the D region of middle latitudes. By subtraction we can infer features of the D region of middle latitudes. It's surprising that this simple model fits so well the experimental data. One interesting fact has occurred which can illustrate the validity of the model used. When we began to receive the signals from OMEGA in 13.6 KHz, by mistake we were informed that the transmitter was HAIKU, HAWAII. From the records we observed the sharp rise and fall of the trace by sunset and sunrise, which is a characteristic of the North - South path of propagation, instead of the slow rise and fall that is normally observed in approximately East-West paths, like Hawaii-SJC.

With the data we had, we had calculated D, having $\Delta t = 23\ \mu s$ (Apr 1967)

and $C = 3.0 \times 10^8$ m/s

$a = 6370 \times 10^3$ m

$$f = \frac{c}{\lambda} = 13.6 \text{ KHz} \qquad \lambda = 22.0 \times 10^3 \text{m}$$

As the frequency were lower than that of NLK, we used a lower Δh, keeping the same height of reflection.

Then $h = 70$ km (as for NLK - SJC)

and $\Delta h = 13$ km, an acceptable value for the frequency used.

$$D = t \times c \times \frac{h}{\Delta h} \times \frac{1}{\frac{b}{2a} + \frac{\lambda^2}{16h^2}} = 3200 \times 10^3 \text{m}$$

If we were in Oct 1967 instead of Apr 1967, the result would have been exactly the 4000 km for D.

We concluded that the actual station should be along the general

North-South direction, at 3200 km of our receiving station which in fact was the case for the OMEGA station at Trinidad.

5.2 Seasonal Variation

In the transmission from OMEGA we found a clear seasonal variation, which is displayed in Fig. 5.1. Observe that Fig. 5.2 for NLK does not display similar seasonal variations.

This variation for one station and not for the other, is an interesting feature, which can be explained by the diferences of frequencies and paths, as will be shown in the following paragraphs.

In first place we will coment the data and then give a possible reason for this abnormal behavior.

The available data from OMEGA are for the period April 1967 to April 1968.

The minimum occurred in April 1967 with t = 23 μs.

The transmitter OMEGA is located at $10^{0}42'$N and the receiver $23^{0}18'$S. The path is in the equatorial geographical region and the reflections occur in the equatorial D region. Furthermore the path is assymetric with approximately two thirds in the Southern Hemisphere.

The percentual phase variations for OMEGA, in the whole period are:

For maximum $\Delta t = 32\ \mu s$, then $\Delta\phi = 2\pi \times 13.6 \times 32 \times 10^{3} \times 10^{-6} =$ 2.740 radians

For minimum $\Delta t = 23\ \mu s$, then $\Delta\phi = 2\pi \times 13.6 \times 23 \times 10^{3} \times 10^{-6} =$ 1.965 radians

$$P = \frac{2740 - 1965}{2740} = \frac{775}{2740} = 0.283 \quad \text{or } p = 28.3\%$$

The percentual phase variations for NLK, in the whole period are

For maximum $\Delta t = 81\ \mu s$, then $\Delta\phi = 2\pi \times 18.6 \times 10^{3} \times 81 \times 10^{-6} =$ 9.490 radians

For minimum $\Delta t = 69\ \mu s$, then $\Delta\phi = 2\pi \times 18.6 \times 10^3 \times 69 \times 10^{-6} =$ 8.070 radians

$$P = \frac{9490 - 8070}{9490} = \frac{1420}{9490}\ 0.15 \quad \text{or} \quad p = 15\%$$

We see that for OMEGA **there** is a greater percentual variation than for NLK, and also a more regular variation.

This means that for greater distances the earth-ionosphere behaves like a more perfect "wave guide" than for short distances OMEGA-SJC and the seasonal dependence is greater for the OMEGA-SJC path.

The path OMEGA-SJC is entirely under the equatorial D region and we can infer that the equatorial D region had a greater seasonal variation than the middle latitudes D region. This could explain the smaller seasonal variation of the phase of signals from NLK, which has a path with half of it under the middle latitude D region. The variations in phase are associated with electron density profiles variation.

In the other hand the phase variations of OMEGA has a <u>regular</u> and <u>large</u> variation while NLK has a <u>slight</u> and <u>irregular</u> variation.

There are three ways that can be used to explain this difference of behavior, namely:

a) The path lenght,
b) The differences of frequency, and
c) The electron density profile time variation in the height of middle latitudes and equatorial D regions.

The difference of path lenght is responsible for a smaller percentual variation for the longer path, because statistically for long distances (NLK-SJC) the different electron density profiles along the path produces a smaller variation in average for the longer path.

The passage through different regions with different behavior suggests different seasonal behavior for the equatorial and middle latitudes D region.

The percentual difference in frequency for OMEGA and NLK are

f(OMEGA) = 13.6 KHz

f(NLK) = 18.6 KHz

$$P = \frac{18.6 - 13.6}{18.6} = \frac{5.0}{18.6} = 0.269 \qquad \text{or}$$

P = 26.9%

This difference is not very great, the transmitters used in one and other case are of the same type, with different but similar antennae (Watt, 1967). The receiver system is the same. Both signals are in the VLF band of the radio spectrum. The pattern of one and other recorded phase variation signals are equal, except by the amplitude of the phase variation. The conclusion is that the frequencies are not responsible for the different seasonal behavior.

The transmitter NLK is located at $48^{o}12'$N, then a great part of the path NLK-SJC is under the middle latitude D region. The other part is located under the equatorial D region, like the OMEGA-SJC path. This seems to be the characteristic difference between the two paths.

We conclude that seasonal variation observed in the OMEGA-SJC path is due to the seasonal variation of the equatorial D region electron density profile.

For NLK-SJC path, this regular variation of the equatorial D region is masked by the irregular seasonal electron density profile variation of the middle latitudes D region.

The explanation of this part can be done, if we suppose that when the electron density in the daytime F region increases all the profiles of other regions will increase also.

In the equatorial F region exist a December anomaly that is a increase in the daytime electron density profile in December (Narasinga Rao, 1966) (Yonezawa and Arima, 1959).

If in December the nightime profile is the same that for other months and the daytime profile is greater, then the diurnal variation will

be greater and this could explain the seasonal variation in the OMEGA-SJC path.

In August the path OMEGA-SJC is under the winter in its main part (Southern Hemisphere), thus this can explain the secondary peak in August in the figure 5.1.

In addition to the December anomaly, in December there is a winter anomaly in the Northern part of the path, but this part is only thirty per cent of the whole path.

By the data we have we can infer that, near the equator the December anomaly is of greater importance than the winter anomaly, in the D region.

For the NLK-SJC path, this effect is not seen then we can infer that the seasonal behavior of the middle latitudes D region is not so regular like the seasonal behavior of equatorial D region.

5.3 Study of Sudden Phase Anomalies

The Sudden Phase Anomalies (SPA) are a sudden phase advance, with a slow returning. They are produced by a sudden extra ionization and then a return to the normal equilibrium value. This extra ionization is produced by solar X-rays which are known to increase during observation of optical solar flares. The return to the equilibrium status is made slowly following the expression below (De Mendonça and Scarabucci, 1966) and we can calculate the effective recombination factor at the height of reflections:

$$\alpha eff = \frac{1 - (\frac{\phi 2}{\phi 1})^2}{N\ (t_2 - t_1)}$$

where:

ϕ_1 - value of the phase just after the maximum of the SPA
ϕ_2 - phase at a chosen time during the decay
t_1 - time of the phase ϕ_1
t_2 - time of the phase ϕ_2
N - electron density at the height of reflection

This expression is an approximation. In its deduction was assumed that the increment in electron density during a SPA is much greater than the normal electron density. Also is assumed that αeff remains constant.

From the experimental data in 1965, was found that the product Nαeff was approximately a constant and equal to $5.0 \times 10^{-4} s^{-1}$ (De Mendonça and Scarabucci, 1966).

In making calculations for s SPA occurred in Aug 29, 1966, in the path NLK-SJC, we have

$$\phi_1 = 19 \times 10^{-6} s$$

$$\phi_2 = 11 \times 10^{-6} s$$

$$t_1 = 1520 \text{ UT}$$

$$t_2 = 1540 \text{ UT} \qquad \Delta t = 20 \times 60 = 1200 \text{ s}$$

and assuming that $N = 300 \text{ cm}^{-3}$

We obtain

$$N\,\alpha\text{eff} = \frac{1 - \left(\frac{11}{19}\right)^2}{(1200)}$$

$N\,\alpha\text{eff} = 5.54 \times 10^{-4} s^{-1}$, in agreement with the results obtained by De Mendonça and Scarabucci (1960). Assuming $N = 300 \text{ cm}^{-3}$ we have $\alpha\text{eff} = 1.85 \times 10^{-6} \text{ cm}^3 s^{-1}$.

The change in reflection height is also calculated by (Westfall, 1961):

$$\Delta h = \frac{c \times \Delta t}{D \left[\frac{\lambda^2}{16h^3} + \frac{1}{2a}\right]}$$

where:

c = velocity of light in free space = 3.0×10^8 m/s

λ = wavelenght in free space = 16.1×10^3m (NLK)

a = Earth's radius = $6370 \times 10^3 m$

D = Great circle distance NLK - SJC = $10900 \times 10^3 m$

h = normal reflection height = $70.0 \times 10^3 m$

$\Delta t = t_2 - t_1 = 1200$ s

Calculating for the SPA occurred in August 29, 1966, in the NLK-SJC path,

$$\Delta h = \frac{3.0 \times 1200 \times 10^5}{10900 \times \left[\frac{(16.1 \times 10^3)^2}{16 \times (7.0 \times 10^4)^3} + \frac{1}{2 \times 6370 \times 10^3} \right]}$$

then:

$$\Delta h = 2.64 \times 10^3 m$$

Stored records of all 1965, 1966, 1967 SPA of NLK-SJC path are available.

In 1965 we have registered six SPA, in the NLK-SJC path. They are:

TABLE 5.5

SPA	TIME UT
Apr 11	14:54
May 15	18:30
May 16	19:00
Jun 05	18:00
Oct 01	20:00
Oct 02	15:48

Looking to this data we observed the following feattures:

a) When occurring a SPA, in the same time also occurred a SEA (Sudden Enhancement of Atmospherics).

TABLE 5.6

SPA	OCCURRENCE OF SEA
Apr 11	Yes 15:04 UT
May 15	Yes 18:20 UT
May 16	Yes 19:03 UT
Jun 05	Yes 18:10 UT
Oct 01	Yes 20:28 UT
Oct 02	No - -

b) When occurring a SPA, several hours before occurred a class 2 or 3 solar flare:

TABLE 5.7

SPA	OCCURRENCE OF CLASS 2 OR 3 SOLAR FLARE
Apr 11	Apr Class 2: 08:29 UT
May 15	—
May 16	May 16 Class 2: 06:00 UT, Class 2: 13:14 UT
Jun 05	—
Oct 01	Sep 30 Class 2: 13:13 UT, Class 2:15:13 UT, Class 2:19:21UT
Oct 02	Oct 01 Class 2: 20:25 UT

c) Sometimes in the same time of the SPA exists an flare:

TABLE 5.8

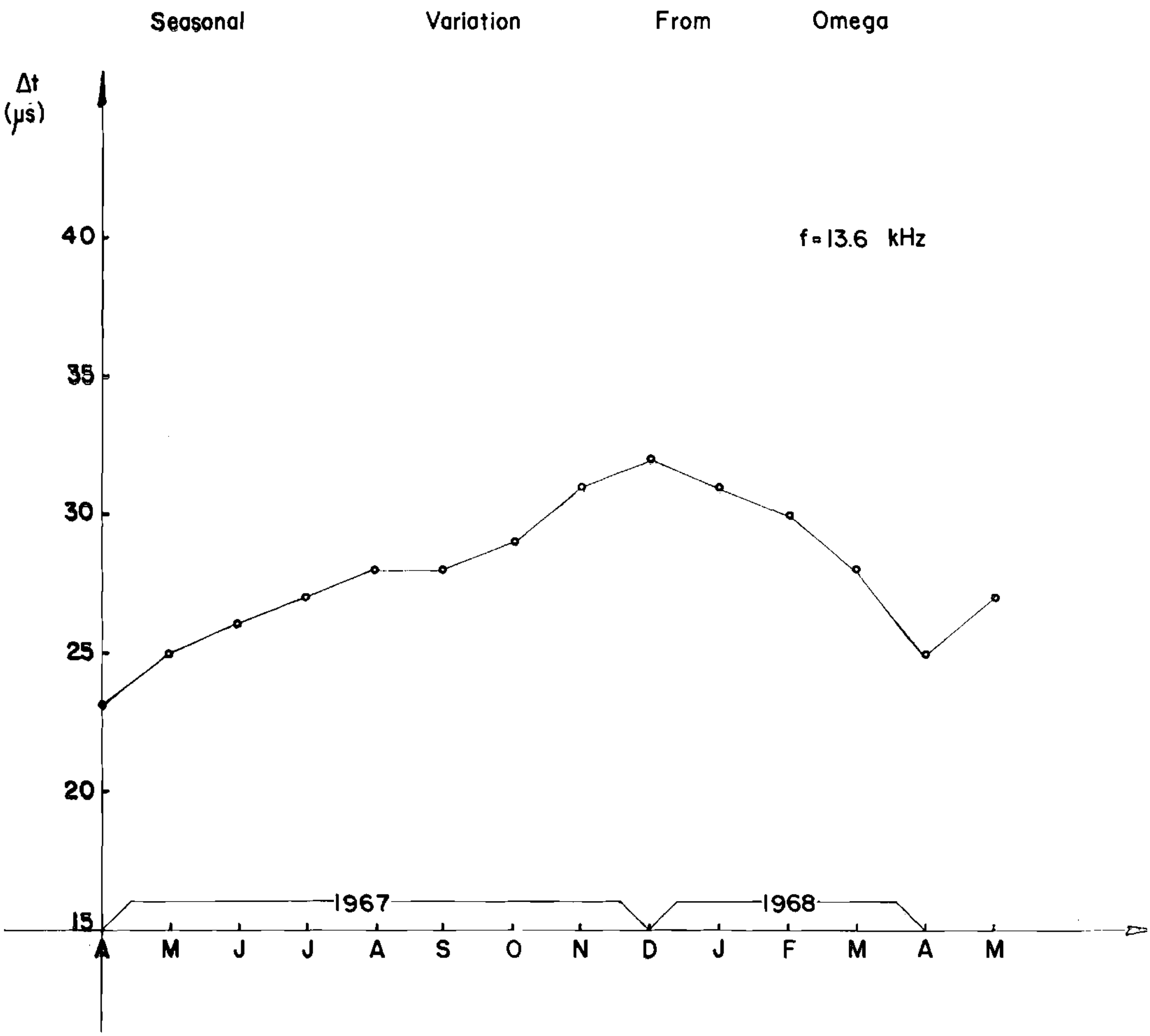
SPA	OPTICAL FLARE
Apr 11	—
May 15	—
May 16	—
Jun 05	Class 1: 18:07 UT
Oct 01	Class 2: 20:25 UT
Oct 02	Class 2: 16:12 UT

Sometime the velocity of the paper tape changes because of fluctua tions of the input voltage. Due to this fact a little difference in time is not very important and it does not show in the month average. At our station the exact time calibration is made once a day by 1700 UT.

We can conclude from this data that the phenomenon that produces a SPA, could be the same that produces SEA. The optical importance of a solar flare does not correlate well with X-rays fluxes. The occurrence of Class 2 optical solar flare several hours before the occurrence of a SPA indicates that possibly the ionization could be caused by solar particles in addition to the X-rays.

The path NLK-SJC presents a considerable number of SPA but the OMEGA-SJC only present one SPA occurred in Feb.1, 1968.

One thing that can suggests the correlations we made is that solar particles are also an important source of ionization and this particles are led to middle and high latitudes by the earth's magnetic field. Near the equator little influence had them on the ionization of the D region.



Seasonal Variation From Omega
Δt
(μs)
40
35
30
25
20
15
f = 13.6 kHz
1967
1968
A
M
J
J
A
S
O
N
D
J
F
M
A
M

Fig. 5.1

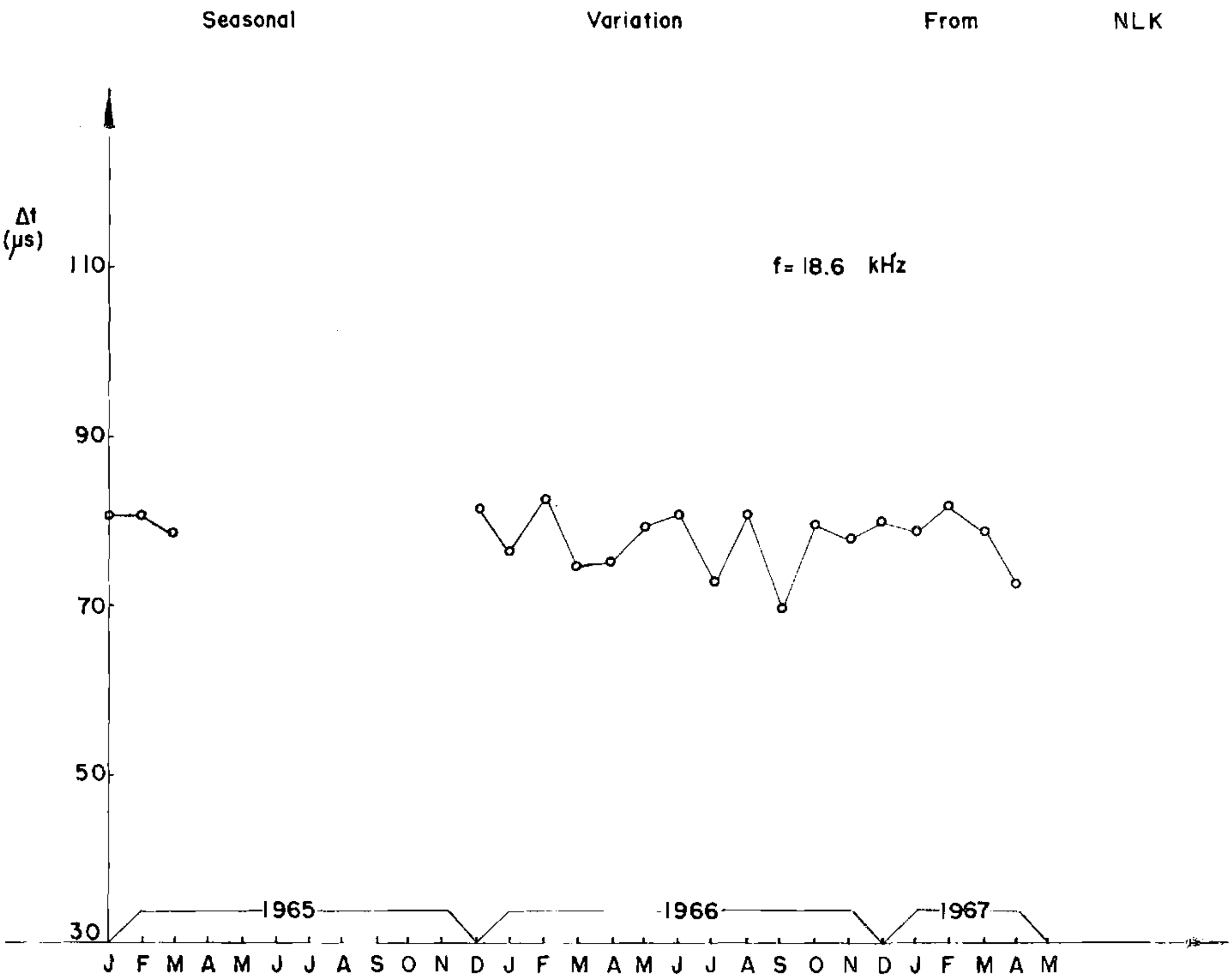

Seasonal Variation From NLK
Δt (μs)
110
90
70
50
30
f= 18.6 kHz
1965
1966
1967
J F M A M J J A S O N D J F M A M J J A S O N D J F M A M

Fig. 5.2

6. EXPERIMENTAL RESULTS

Now we will present the months averages obtained from the data. We have plots of the B variation, plots of seasonal variation for each station, the recordings for a typical day and a registered SPA (Sudden Phase Anomaly).

APPENDIX A

```
C      PHASE MEASUREMENTS ON VLF.
C      CALCULO DO VALOR CORRIGIDO E MEDIA MENSAL
C      DIMENSIONAMENTO DAS VARIAVEIS UTILIZADOS
C      O DENOTES EQUALS
       DIMENSION EME(49),MEDIA(49),D(49)
       DOUBLE PRECISION ANOMES,TRAM2
       REAL MEDIA
C      IMPRESSAO DO TITULO INICIAL(VLF)
       WRITE(6,600)
  600  FORMAT(1H2)
       WRITE(6,100) (F,IO1,12),(ELE,JO1,8)
  100  FORMAT(15X,2HVV,35X,2HVV,10X,2HLL,30X,4A5,/,16X,2HVV,33X,2HVV,11X,
      12HLL,30X,4A5,/,17X,2HVV,31X,2HVV,12X,2HLL,30X,2HFF,/,18X,2HVV,29X,
      22HVV,13X,2HLL,30X,2HFF,/,19X,2HVV,27X,2HVV,14X,2HLL,30X,2HFF,/,20X
      3,2HVV,25X,2HVV,15X,2HLL,30X,2HFF,/,21X,2HVV,23X,2HVV,16X,2HLL,30X,
      42HFF,/,22X,2HVV,21X,2HVV,17X,2HLL,30X,2HFF,/,23X,2HVV,19X,2HVV,18X
      5,2HLL,30X,2HFF,/,24X,2HVV,17X,2HVV,19X,2HLL,30X,2A5,/,25X,2HVV,15X
      6,2HVV,20X,2HLL,30X,2A5,/,26X,2HVV,13X,2HVV,21X,2HLL,30X,2HFF,/,27X
      7,2HVV,11X,2HVV,22X,2HLL,30X,2HFF,/,28X,2HVV,9X,2HVV,23X,2HLL,30X,2
      8HFF,/,29X,2HVV,7X,2HVV,24X,2HLL,30X,2HFF,/,30X,2HVV,5X,2HVV,25X,2H
      9LL,30X,2HFF,/,31X,2HVV,3X,2HVV,26X,2HLL,30X,2HFF,/,32X,2HVV
      C1X,2HVV
      A,27X,2HLL,30X,2HFF,/,33X,3HVVV,28X,4A5,12X,2HFF,/,34X,1HV,29X,4A5,
      B12X,2HFF)
C      LEITURA DO NOME DA ESTACAO TRANSMISSORA E DA FREQUENCIA
  700  READ(5,150) TRAM1,TRAM2,FREQ
  150  FORMAT(A5,A10,F5.2)
C      LEITURA DO ANO E DO MES
  160  READ(5,200) ANOMES
  200  FORMAT(A10)
C      INICIALIZACAO DAS VARIAVEIS MEDIA E D
       DO 10 KO1,49
       MEDIA(K)O0.
   10  D(K)O0.
C      LEITURA DA DATA,A,B,VALORES(PARA UM DIA)
   80  READ(5,250,ENDO60) KDATA1,KDATA2,KDATA3,KDATA4,A,B,(EME(K),KO1,49)
  250  FORMAT(1X,I3,3I2,F5.0,F6.3,F4.0,11F5.0/16F5.0/16F5.0/5F5.0)
C      CORRECAO DOS VALORES PARA UM DIA
       TO0.
       BO(EME(49)-A)/24.
       DO 20 KO1,49
       YOA+B*T
       IF(EME(K).EQ.2.0E4) GO TO 20
       EME(K)OEME(K)-Y
   20  TOT+.5
```

```
C     IMPRESSÃO DO NOME DO TRANSMISSOR,DA DATA,DE A E DE B
      WRITE(6,300)
  300 FORMAT(1H1)
      WRITE(6,350) TRAM1,TRAM2,FREQ,KDATA1,KDATA2,KDATA4,KDATA3,A,B
  350 FORMAT(12X,11HTRANSMISSOR,1X,A5,1X,A10,10X,10HFREQUENCIA,F6.2,1X,3
     1HKHZ,//,12X,3HDIA,1X,2HDO,1X,3HANO,I4,10X,3HMES,I3,10X,3HDIA,1X,2H
     2DO,1X,3HMES,I3,10X,3HANO,1X,2H19,I2,10X,1HA,1HO,F6.0,10X,1HB,1HO,F
     36.3,/)
C     IMPRESSAO DOS VALORES CORRIGIDOS E DO GRAFICO CORRESPONDENTE
      LT1O17
      LT2O00
      DO 30 KO1,49
      IF(EME(K).EQ.2.0E4.OR.EME(K).LT.-20..OR.EME(K).GT.50.) GO TO40
      LO(EME(K)+20.)*9.9/7.
      IF(L.EQ.0) GO TO 950
      WRITE(6,1100) LT1,LT2,EME(K),(BLANK,IO1,L),ASTER
 1100 FORMAT(2I2,F10.2,9X,100A1)
      GO TO 750
  950 WRITE(6,1100) LT1,LT2,EME(K),ASTER
      GO TO 750
   40 WRITE(6,400) LT1,LT2,EME(K)
  400 FORMAT(2I2,F10.2)
  750 LT2OLT2+30
      IF(LT2.EQ.30) GO TO 30
      IF(LT1.EQ.24) LT1O00
      LT1OLT1+1
      LT2O00
   30 CONTINUE
C     CALCULO DA MEDIA MENSAL
   50 DO 70 KO2,49
      IF(EME(K).EQ.2.0E4.OR.EME(K).LT.-20..OR.EME(K).GT.50.) GO TO 70
      MEDIA(K)OMEDIA(K)+EME(K)
      D(K)OD(K)+1.
   70 CONTINUE
      GO TO 80
   60 DO 110 KO2,49
      IF(D(K).EQ.0.) GO TO 120
      MEDIA(K)OMEDIA(K)/D(K)
      GO TO 110
  120 MEDIA(K)O20000.
  110 CONTINUE
      WRITE(6,500)
  500 FORMAT(1H1)
      WRITE(6,650) ANOMES
```

```
 650 FORMAT(1X,7HCALCULO,1X,2HDA,1X,5HMEDIA,1X,4HPA-A,1X,A10,/)
     LT1=17
     LT2=00
     DO 130 K=1,49
     IF(MEDIA(K).EQ.2.0E4.OR.MEDIA(K).LT.-20..OR.MEDIA(K).GT.50.) GO TO
    114
     L=(MEDIA(K)+20.)*9.9/7.
     IF(L.EQ.0) GO TO 1050
     WRITE(6,1100) LT1,LT2,MEDIA(K),(BLANK,I=1,L),ASTER
     GO TO 850
1050 WRITE(6,1100) LT1,LT2,MEDIA(K),ASTER
     GO TO 850
  14 WRITE(6,400) LT1,LT2,MEDIA(K)
 850 LT2=LT2+30
     IF(LT2.EQ.30) GO TO 130
     LT2=00
     LT1=LT1+1
     IF(LT1.EQ.24) LT1=00
 130 CONTINUE
     DATA F,ELE,ASTER,BLANK/5HFFFFF,5HLLLLL,1H*,1H /
  90 STOP
     END
```

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