1. Classification *INPE-COM.10/PE*
CDU: 550.388.2:681.3.06

2. Period *October 1978*

4. Distribution Criterion

internal [ ]

external [x]

3. Key Words (selected by the author)
IONOSPHERIC PREDICTION;
SIGNAL-TO-NOISE RADIO;
MUF, HF CIRCUITS.

5. Report No.
INPE-1377-PE/175

6. Date *October 1978*

7. Revised by
Ivan Jelinek Kantor

8. Title and Sub-title

A SIMPLIFIED COMPUTER METHOD FOR LONG-TERM CALCULATION OF HF SKY-WAVES CIRCUITS

9. Authorized by
Nelson de Jesus Parada
Director

10. Sector *DCE/GIO* Code *30.371*

11. No. of Copies *17*

12. Authorship *A.A.E. Picquenard*
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13. Signature of first author

14. No. of Pages *16*

15. Price

16. Summary/Notes

Based on already existing prediction methods of HF circuits, a simplified computer prediction program of HF circuits on a long term was worked out, after a discerning study of the envolved parameters.

17. Remarks *This work will be published in the proceedings of the International Solar Terrestrial Predictions.*

A SIMPLIFIED COMPUTER METHOD FOR LONG-TERM CALCULATION OF HF SKY-WAVE CIRCUITS

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When planning a new HF station (Broadcast, AFTN, Costal station, etc.), the frequencies, transmiter power, and antennas, must be selected to supply the required service during 10-20 years.

Consequently, previsions for the signal-to-noise ratio must be calculated for maximum and minimum solar activity, for various months of the year, for various hours of the day, and for the available frequencies, hence being interesting that the computation time be short.

After discussing most of the proposed computational methods, and evaluating the influence of various parameters, a simplified program has been developped, for the case of Brasil, and for short and medium ranges, till some 4.000 Km. In this case, in Brazil, the geomagnetic latitude is low, simplifying the problem.

Computational time, including signal-to-noise calculation, and for a complete solar cycle, is 3 - $3\frac{1}{2}$ minutes for three frequencies, with the B-6700 Burroughs computer.

1. INTRODUCTION

The program described in this paper is intended to supply the necessary informations to the designer of HF radio stations, such as tropical wave or HF broadcast stations, airport stations, costal stations, etc.

An analysis of this type of problem has been made by Haydon and al., 1969, in a qualitative way. Our aim will be to transform those ideas in numerical values, to allow the designer to select frequencies, transmitter power and antenna types.

As the main factor of the service grade is the signal-to-noise ratio, the program must compute the signal received power as well as the mean atmospheric noise power, which in Brazil is very high and is, generally, the dominante type of noise.

The transmitting stations will remain in operation during 10 to 20 years, therefore, calculations must be made for the extreme values of the Wolff number, stated in $R_{12} = 10$ and $R_{12} = 110$ respectively. For both values, the months of March, June, September and December are regarded as typical ones for the grade of ionization and for the atmospheric noise. Each of them is examined, and for each of the referred month calculations are made for each even hour (UT). If we study the circuit in 3 frequencies, we will need 288 calculations, hence the interest in having a fast program.

From another side, sophisticated programs are rather disapointing (CCIR, 1978b), so we can question the advantages of such sophistication, which requires a very extensive use of "loops", due to "cut-and-try" processes. This is peculiarly put in evidence in the 2nd CCIR Method (CCIR, 1978a), and increases the computation time very much.

Based on the above considerations, we attempted to build a program retaining only the strictly indispensable calculations to reach a reasonable accuracy, and without "loops". For this purpose, we have discussed the possible influence of the parameters involved, as will be explained later (item 2).

Another important consideration has been that more than 90% of the HF circuits installed in Brazil are less than 4,000 Km long, and, consequently, remain in low geomagnetic latitude. A circuit of rather short length means less propagation modes to be examined, and a low geomagnetic latitude permits the adoption of a constant "system excess loss" (CCIR, 1970), thus saving some computation. Consequently, we decided to limit our program to a length of 4,000 Km.

2. BASIS FOR OUR PREDICTION TECHNIQUE

The next point has been to discuss the actual importance of the computational processes used in the former methods (CCIR, 1970; Haydon and al. 1976; Laitinen and al., 1962; Lucas and al., 1966), and the grade of influence of the parameters involved, taking into account the limiting values they can have.

2.1. The deviation of the rays by the E-layer

In CCIR, 1970, an account is given of the deviation of the rays when going through the E-layer. (Figure 1).

With the geomatry of Figure 1, using $R_0 = 6{,}371$ Km, $h_m E = 110$ Km, and making $\alpha = \alpha_E$, as suggested by Rawer, 1960, we find

$$\sin\alpha = 0.983 \cos\Delta \qquad (1)$$

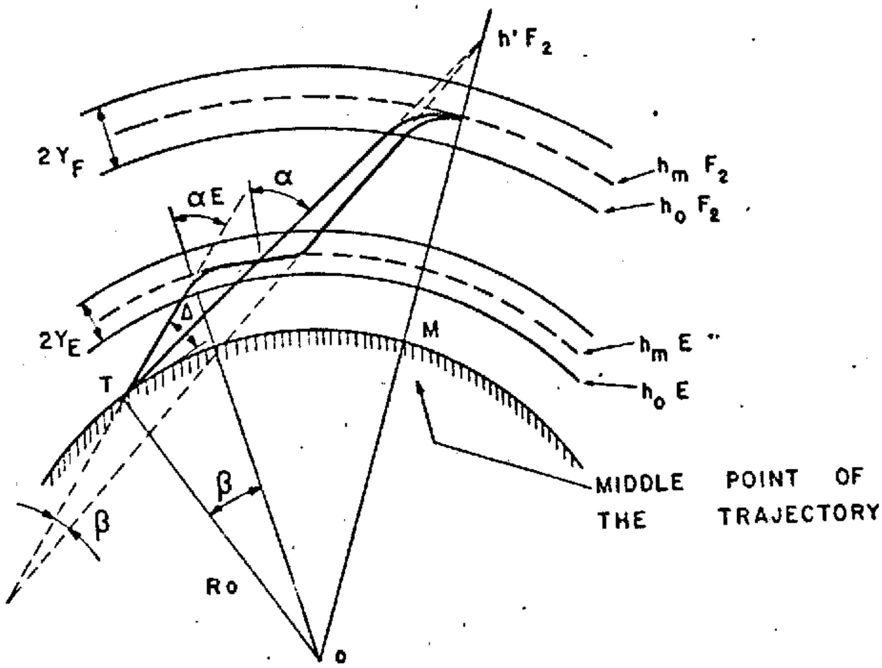


Fig. 1 - GEOMETRY FOR THE DEVIATION BY THE E-LAYER

Putting Z for the percent difference between the used frequency f and the maximum frequency that the E layer can reflect, we can write:

$$U = \frac{f_0E \sec \alpha}{f} = \frac{1}{1 + 0.001Z} \qquad (2)$$

We can now calculate β versus Δ and Z. The result of this calculation is given in Figure 2.

As it is very difficult to use departure angles $\Delta < 5^0$, and as for $Z < 1$ we are very near of the reflexion by the E-layer, we conclude that β will be always very small, and that we can neglect it in subsequent calculations.

It seems that the CCIR has reached the same conclusion, as CCIR, 1978a, does not more mention deviation by E layer, any more.

2.2. Influence of $h'F,F_2$ on the calculation of signal received power

The virtual height of reflexion by the F,F_2 layer depends on the frequency and on the geographic position of the reflexion point. If we take into account the variation with frequency, the resultant computation is

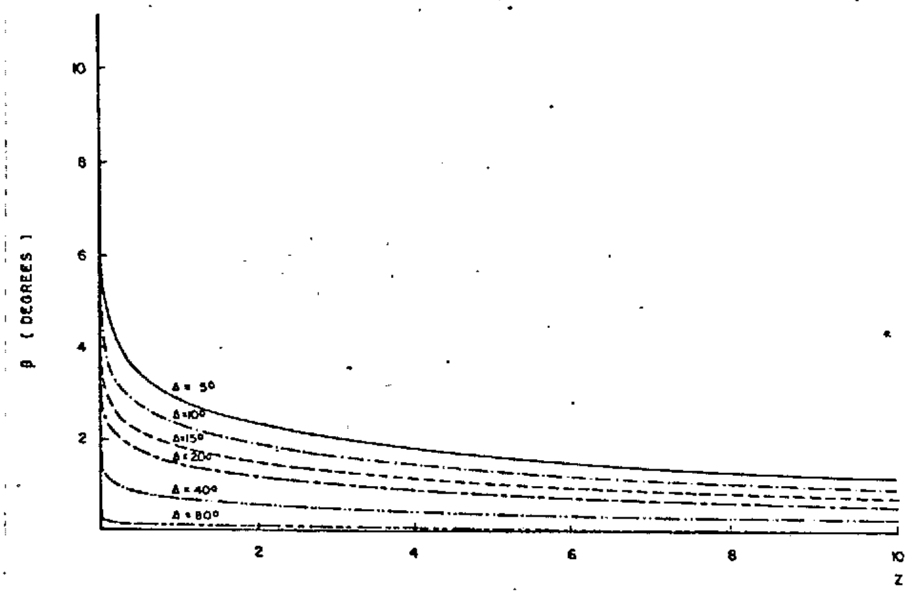


Fig. 2 - DEVIATION β VERSUS Δ AND Z

rather complex (CCIR, 1970; CCIR, 1978b). On the other hand, as we limit our circuit to a length of 4,000 Km, the reflexion points in the case of the 2 x F mode, cannot be more distant than 2,000 Km, which limits the variation of $h'F,F_2$, betweer these points.

The variation of $h'F,F_2$ has two consequences: a variation of Δ, and hence of the gain of the antenna and, correlatively, a variation of the incidence angle on the D-layer, modifying the absorption. We shall examine the possible values of both effects.

2.2.1. Influence of $h'F,F_2$ on Δ

With the geometry of Figure 3, we obtain, for the case of 1 hop on the F,F_2 layer,

$$\frac{d\Delta}{dh'F_2} = \frac{1}{R_0} \frac{\sin\theta}{\left(1+\frac{h'F_2}{R_0}\right)^2 - 2\left(1+\frac{h'F_2}{R_0}\right)\cos\theta + 1} \qquad (3)$$

If we take $R_0 = 6371$ Km and $h'F_2 = 350$ Km, we have

$$\frac{d\Delta}{dh'F_2} = \frac{1}{6371}\left(\frac{\sin\theta}{2.1129 - 2.1099\cos\theta}\right) \qquad (4)$$

Diferentiating for θ, we find that the maximum of $d\Delta/dh'F_2$ is reached for $\theta = 3{,}05^0$ (680 Km, value in agreement with the already published graphs) and

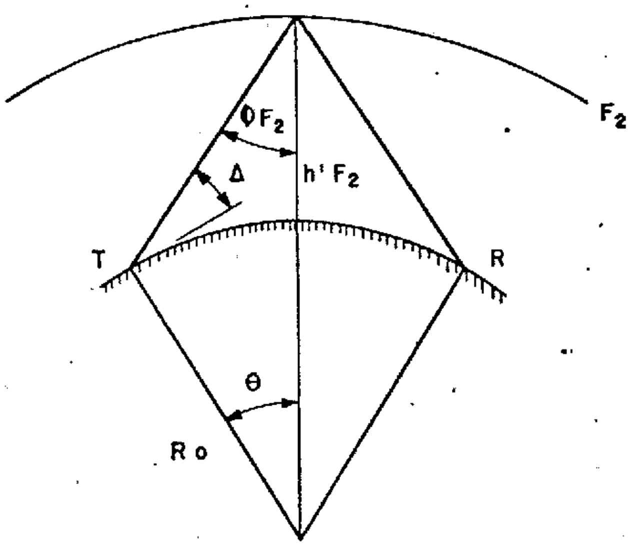


Fig. 3 - GEOMETRY FOR 1 HOP ON THE F-LAYER

that:

$$\left(\frac{d\Delta}{dh'F_2}\right)_{Max} = 0.0799^0 \text{ per Km}$$

This gives us ± 8^0 for a variation of ± 50 Km of $h'F_2$.

In the case of 2 hops on the F,F_2 layer, we shall have the geometry of Figure 4.

Let us put $h_0 = (h_1 + h_2)/2$ and $h' = (h_2 - h_1)/2$, and assume that $h' << h_0$, using the subscript 0 for the values of the variables when $h' = 0$, and making $\Delta' = \Delta_0 - \Delta$.

Ater some approximations on the trigonometric functions, we find the following equations:

$$\begin{aligned} - R_0 \Delta' \sin \Delta_0 &= (R_0 + h_0 - h')(\phi_1 - \phi_0) \cos \phi_0 - h' \sin \phi_0 \\ &= (R_0 + h_0 + h')(\phi_2 - \phi_0) \cos \phi_0 + h' \sin \phi_0 \end{aligned} \quad (5)$$

By means of these equations, and using again the geometry of Figure 4, we can calculate the difference Δ' between the true angle Δ and the angle Δ_0 calculated using $h_1 = h_2 = h_0$. For R_0 = 6371 Km, h_0 = 350 Km, h' = 25 Km and for a total distance of 4,000 Km, we find $\Delta' = 0.0049^0$.

In the same way, we can calculate the displacement $2R_0\ (\theta_2 - \theta_0)$ of the

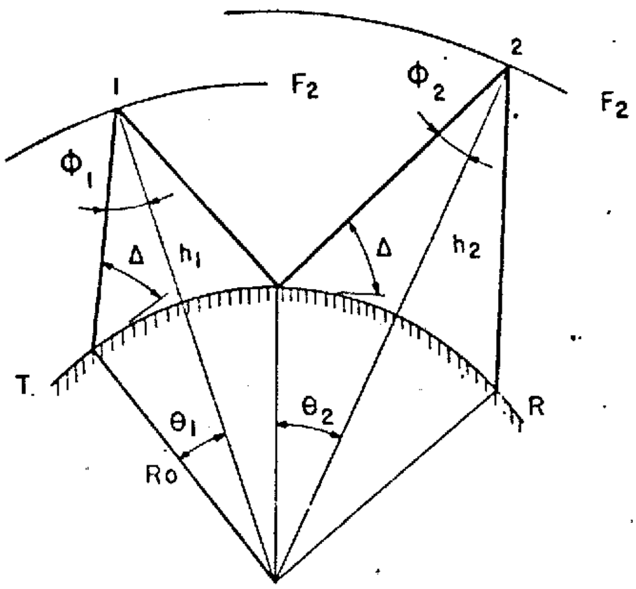


Fig. 4 - GEOMETRY FOR 2 HOPS ON THE F-LAYER

reflexion point on the ground. With the same values of the data, we find 55 Km.

In view of these results, our conclusion is that we can use the mean value, h_0, of the virtual heigths on both ionospheric reflexion points, instead of the true values h_1 and h_2.

2.2.2. Influence of h' F, F_2 on the absorption

The angle of incidence on the D layer is a function of the angle of departure, which in turn varies with $h'F, F_2$, as seen in the preceding items. The figure 5 gives the geometry involved.

We have immediately:

$$\sin \phi_D = \frac{R_0}{R_0 + h_D} \cos \Delta$$

$$\tan \Delta = \frac{(h'F_2 + R_0) \cos \theta_{F_2} - R_0}{(h'F_2 + R_0) \sin \theta_{F_2}} \qquad (6)$$

$$D = 2 R_0 \theta_{F_2}$$

$$A \propto \sec \phi_D$$

These equations have been solved for $h_D = 60$ Km, and $250 \leq h'F_2 \leq 500$Km.

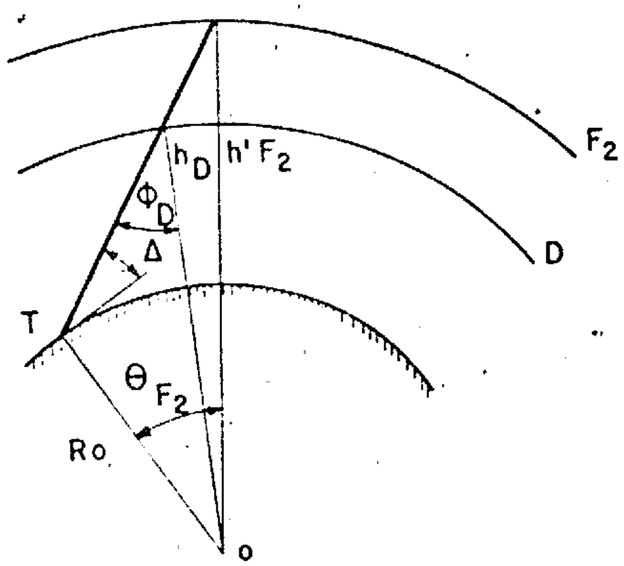


Fig. 5 - GEOMETRY FOR THE ANGLE OF INCIDENCE ON THE D-LAYER

The results are drawn, on the graph of the Figure 6, where sec Φ_D is given as a function of D and $h'F_2$.

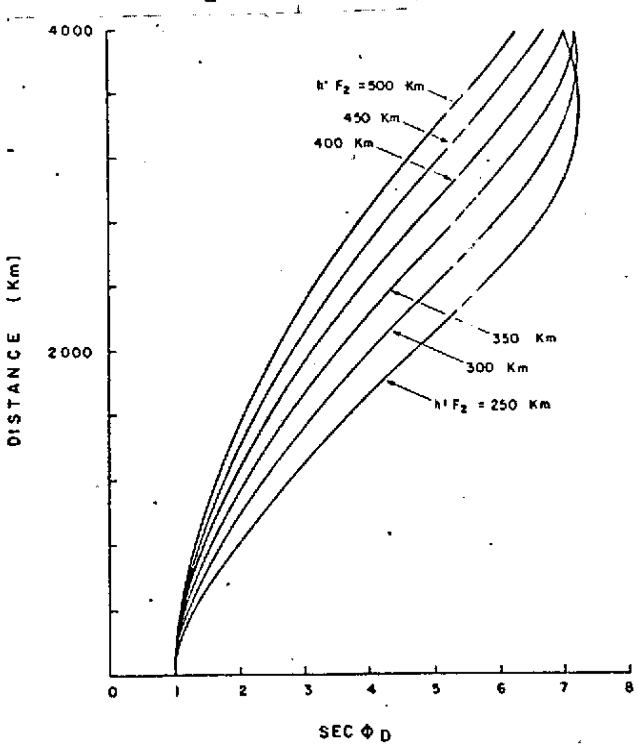


Fig. 6 - ABSORPTION AS A FUNCTION OF $H'F_2$ AND D

From this figure, we can conclude that, for a variation of $h'F_2$ of ± 50 Km, the variation of the absorption will be of the order of ± 15 %. As the calculation of the absorption is the weak point of all the methods, this inaccuracy is certainly tolerable.

2.3. Conclusions for our program

From the preceding discussion, we can draw the following conclusions:

a) The deviation of the ray by the E layer can be disregarded.

b) Due to the broad radiation diagram of the HF antennas, the values found for the error on Δ cannot substantially modify the gain of these antennas, for a variation of 50 Km of $h'F_2$.

c) In the case of 2 hops F,F_2, we can use the median of both values of $h'F,F_2$ without appreciable error.

d) The error on the value of the absorption for a variation of 50 Km of $h'F_2$ can be tolerated.

e) As the variation of $h'F_2$ with the frequency will be, in the worst case, of the order of 50 Km, we can use, without unacceptable errors, a fixed value of $h'F_2$, irrespective of the frequency.

3. OUTLINE OF OUR METHOD

As already mentionned, our method is intendet to calculate MUF, signal received power, and mean atmospheric noise power for the following conditions:

- R_{12} = 10 and R_{12} = 110
- Months of March, June, September and December
- Even hours in UT

3.1. Propagation modes

We consider only the following modes:

- for $0 < D < 2000$ Km : 1E, $1F_2$, $2F_2$
- for $2000 < D < 4000$ Km : 2E, $1F_2$, $2F_2$

The possibility of existance of each mode is determined by the conventional method, examining the position of the used frequency in relation with the MUFs of the layers of interest, occultation of the F_2 layer by the E layer is also examined.

We dont consider the probability of existence of the various modes, however we calculate FOT and HPF. The signal received power is calculated for the strongest mode.

3.2. MUF

3.2.1. E-MUF

First, we calculate the MUF(2000)E by the formulas proposed in Lucas and Haydon, 1966.

$$\text{MUF(2000)E} = 3,41 + 38.43I - 68.07I^2 + 89.97I^3 - 70.97I^4 + 29.51I^5 - 4.99I^6 \text{ MHz} \quad (7)$$

with:

$$I = J(1 + 0.0037\ R_{12})(\cos 0.881\ \chi)^{1,3} \quad (8)$$

Where χ is the solar zenithal angle.

For $\chi > 102^0$, we take $I = 0$. We take $J = 1$.

The MUF(2000)E is transformed in MUF(D)E by means of the well-known nomogram (CCIR, 1967). No allowance is made for variations of the E-MUF with time.

3.2.2. F_2-MUF

The calculation of the monthly median value of F_2-MUF is made exactly as explained in the CCIR Report 340 (CCIR, 1967), except that the nomogram of page 396 of the referred document has been transformed into algebraic formulas.

Later, allowance is made for the statistical distribution of the MUF, by calculating the values of the deciles: FOT, with a probability of 90%, and HPF, with a probability of 10%. This is made by multiplying the monthly median values of the MUF, as calculated above, by the coefficients given in the Table 5.1 of CCIR, 1970.

3.3. Angles of departure

The virtual heigths of reflexion used are:

- for the E layer : 105 Km
- for the F_2 layer : those given by (Laitinen and Haydon, 1962), translated from a geographic map to a numerical matrix, for $+ 5^0 \leq \Phi \leq - 35^0$ and for the even hours in local time.

Using these data, simple geometrical reasonings give the angle of departure Δ for the various modes.

The angle Δ, for the modes F_2, allows us to calculate the skip-distance for the E layer and for this angle. The frequency of occultation by E is now deduced in the same way as in item 3.2.1.

3.4. Attenuation

The attenuation suffered by the waves is the sum of the free-space attenuation along the geometrical paths, the ionospheric attenuation, and the reflexion loss on the ground.

3.4.1. Free-space attenuation

We use a method suggested by Laitinen and Haydon, 1962. First, the attenuation A_1, in free space and for the distance on the great-circle, is calculated. After this, the following formula, deduced from Figure 56 of the above reference gives the complement of atenuation due to the actual path

$$A_2 = 0.823733\ 10^{-1} + 0.808697\ 10^{-2}\Delta + 0.243386\ 10^{-2}\Delta^2 - 0.470163\ 10^{-4}\Delta^3 + 0.566952\ 10^{-6}\Delta^4 \quad (9)$$

3.4.2. Ionospheric attenuation

This attenuation is calculated for each hop by the following formula (CCIR, 1970; Lucas and Haydon, 1966).

$$A_i = \frac{677{,}2 \sec \phi}{(f+f_H)^{1.98} + 10.2} (1 + 0.0037 R_{12}) \left|\cos(0.881\chi)\right|^{1.3} \qquad (10)$$

Where ϕ is the angle of incidence at a heigth of 100 Km. For $\chi > 102^0$, the product of the two last factors is taken as 0.1.

3.4.3. Reflexion loss on the ground

This loss is calculated as indicated in CCIR, 1970. A matrix covering the ranges $+15^0 \leq \Phi \leq -55^0$ and $-90^0 \leq \lambda \leq -34^0$ discriminantes between "sea" and "ground".

3.4.4. Excess loss

As indicated by CCIR, 1970, an excess loss is added. For low geomagnetic latitude, this loss is given in 9 dB by the referred document.

3.5. Noise

The atmospheric noise factor, Fam, is calculated according to Zacharisen and Jones, 1970, and corrected for the actual passband of the receiver, b, by the formula:

$$P_N = Fam + 10 \log_{10} b - 204 \quad dBW \qquad (11)$$

3.6. Signal-to-noise ratio

As a rule, the discrimination gain of the receiving antenna can be disregarded, so the received power will be given by

$$P_R = 10 \log P_T - \Sigma A \quad dBW \qquad (12)$$

Where P_T is the EIRP of the transmitter, in Watts, and ΣA is the sum of the attenuations. This gives

$$S/R = P_R - P_N \quad dB \qquad (13)$$

Provision is made for calculating the gain of the transmitting antennas by the formulas given in Lucas and Haydon, 1966, thus deducing the power of the transmitter, P_T.

4. CONCLUSIONS

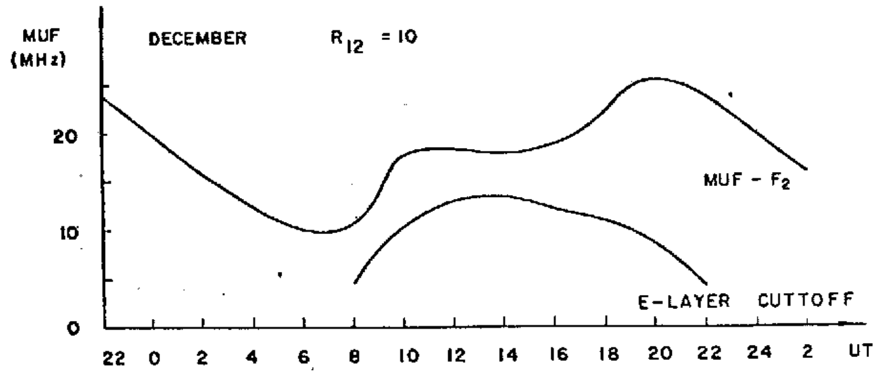
Limiting the range to 4,000 Km the area of utilization to the Brazilian region and discussing the type of calculation strictly needed to remain within a reasonable precision, we have developped a straigthfoward and fast program for the calculation of the performance of the HF circuits throughout a full solar cycle.

Comparing our results with those found by Barghausen, 1969 and by Lucas and Haydon, 1966 we have not found any significant difference.

5. SAMPLE CALCULATIONS

Figure 7 shows the MUFs for the path Rio de Janeiro (23.00°S, 43.50°W) to Belém (1.50°S, 48.50°W) for R_{12} = 10 e R_{12} = 110 on December.

Figure 8 shows the signal-to-noise ratio for the same path, R_{12} = 10 and R_{12} = 110, same month, for transmitting antenna gain of 1.8 dB, transmitting power of 1 Kw, receiver noise bandwidth of 100 Hz and operating frequencies of 13, 15 and 17 MHz. Those curves are interruped for operating frequencies greater than the HPF and also for negative values of the signal-to-noise ratio. In this figure the symbols "+" represent points where the curves would be interruped for operating frequencies greater than the MUF and "0" points of interruption for operating frequencies greater than the FOT. The continuous line corresponds to $1F_2$ mode and the dashed line the 2E mode.



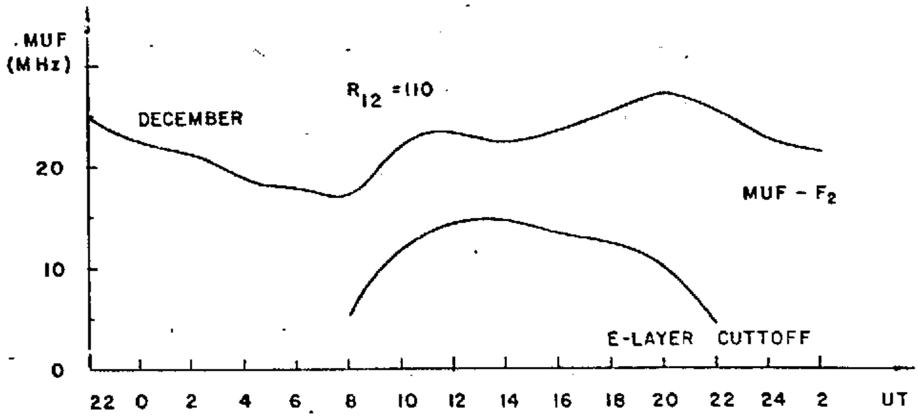
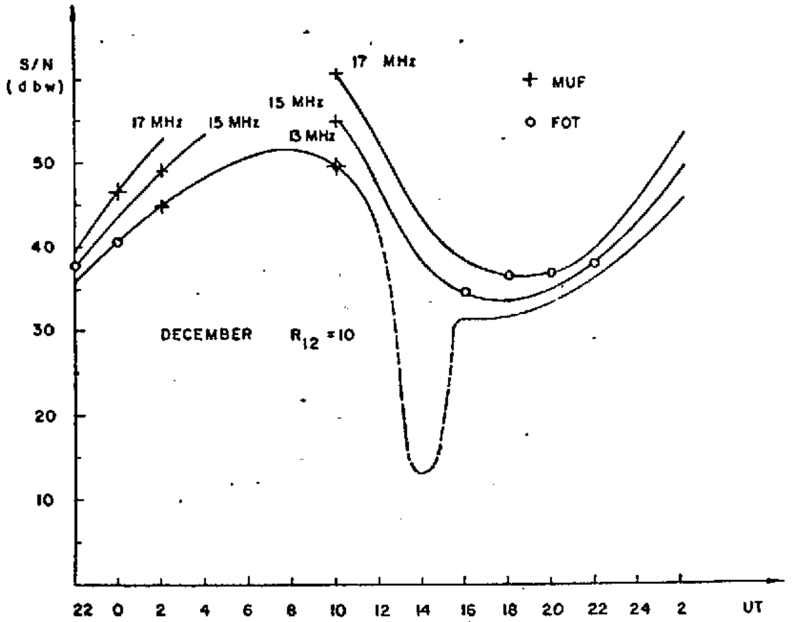


Fig. 7 - MUFs FOR THE RIO DE JANEIRO TO BELÉM PATH FOR DECEMBER



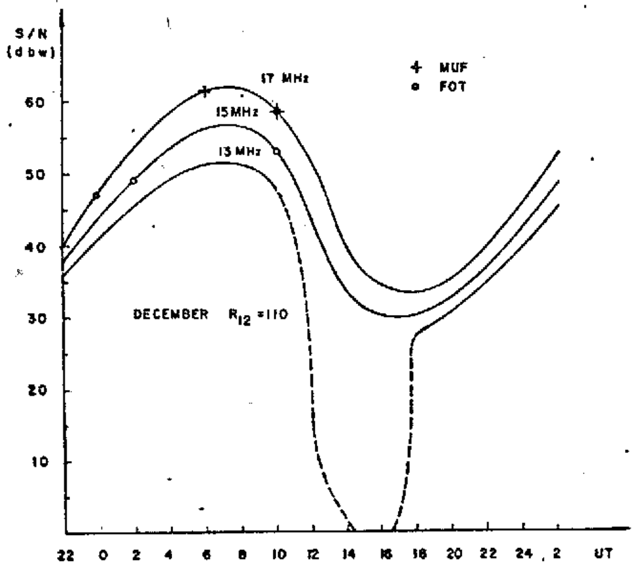


Fig. 8 - SIGNAL-TO-NOISE RATIO FOR THE RIO DE JANEIRO TO BELÉM PATH FOR DECEMBER, R_{12} = 10 and R_{12} = 110

6. REFERENCES AND BIBLIOGRAPHY

Barghausen, A.F., J.W. Finney, L.L. Proctor, and L.D. Schultz (1969): Predicting Long-term Operational Parameters of High-frequency Sky-wave Telecommunications Systems, ESSA Tech. Rept. ERL 110-ITS 78, Boulder, Col.

CCIR, 1964: World Distribution and Characteristics of Atmospheric Radio Noise, CCIR Rept. 322, ITU, Geneva.

CCIR, 1967: CCIR Atlas of Ionospheric Characteristics, CCIR Rept. 340, ITU, Geneva.

CCIR, 1970: CCIR Interim Method for Estimating Sky-wave Field Strength and Transmission Loss at Frequencies between the Approximate Limits of 2 and 30 MHz, CCIR Report 252-2, ITU, Geneva.

CCIR, 1978a: Draft Supplement to Report 252-2. Second CCIR Computer-based Method for Estimating Sky-wave Field Strength and Transmission loss at frequencies between 2 and 30 MHz, CCIR XIV th Plenary Assembly, Doc. 6/1070-E.

CCIR, 1978b: USA. Comparison of Methods used to Compute HF Sky-wave Field Strength, CCIR Special Preparatory Meeting (WARC-79), Doc. P/109-E.

Haydon, G.W., D.L. Lucas, and R.A. Hanson (1969): Technical Considerations in the Selection of Optimum Frequencies for High-Frequency Sky-wave Communication Services, ESSA Tech. Rept. ERL 113-ITS 81, Institute for Telecommunication Sciences, Boulder, Col.

Haydon, G.W., M.Leftin, and R. Rosich (1976): Predicting the Performance of High Frequency Sky-wave Telecommunication Systems (The use of the HFMUFES 4 Program) OT Report 76-102, Boulder, Col.

Jones, W.B., and R.M. Gallet (1962): Methods for Applying Numerical Maps of Ionospheric Characteristics, Journal of Research of the NBS, Vol.66 D, Nr. 6, pp. 649-662.

Jones, W.B. R.M. Gallet, and M. Leftin (1966): Advances in Ionospheric Mapping by Numerical Methods, NBS Technical Note 337, Boulder, Col.

Laitinen, P.O., and Haydon, G.W. (1962): Analysis and Prediction of Sky-wave Field Intensities in the High Frequency Band, Tech. Rept. 9, U.S. Army Signal Radio Propagation Agency, Fort Moumouth, N.J.

Leftin, M., S.M: Ostrow and C. Preston (1967): Numerical Maps of Monthly Median h'F,F_2 for Solar Cycle Minimum and Maximum, ESSA Tech. Memo. IERTM - ITS A69, Boulder, Col.

Lucas, D.L., and G.W. Haydon (1966): Predicting Statistical Performance Indexes for High Frequency Ionospheric Telecommunication Systems, ESSA Tech. Rept. IER. 1 -ITS A 1, Boulder, Col.

Lucas, D.L., and Harper, J.D.Jr. (1965) A Numerical Representation of CCIR Report 322 High Frequency (3-30 MC/S) Atmospheric Radio Noise Data, National Bureau of Standards Technical Note 318, Washington, D.C.

Picquenard, A.A.E. (1974): Radio Wave Propagation, McMillan, London.

Rawer, K. (1960): Radio Propagation between a Space Vehicle and the Earth in the Presence of the Ionosphere, Space Research, Proceedings of the First International Space Science Symposium, NICE, pp. 245-271.

Zacharisen, D.H., and Jones, W.B. (1970): World Maps of Atmospheric Radio Noise in Universal Time by Numerical Mapping, (draft) Boulder, Col.