THE IONOSPHERE AS A MEASURE OF SOLAR ACTIVITY

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Abstract—Critical frequencies of all regular ionospheric layers vary diurnally, seasonally, with geographic latitude and longitude, and with solar activity so that, for any location and any season

\[ f_0 = G(t) + H(t)S \]

where \( f_0 \) is the critical frequency, \( G \) and \( H \) are functions of \( t \), the time of day, and \( S \) is the sunspot-number. For locations where such ionospheric trends are well established, observations of critical frequency may be used to determine an ionospheric "sunspot-number". If values of \( F2 \)-layer critical frequency for hours near local noon are used, since these generally have the most pronounced variation with solar activity, the ionospheric "sunspot-number" obtained is considerably closer to its running-average value than are ordinary sunspot-numbers to their running averages. In addition, this measure is practically independent of varying atmospheric conditions and personal variation among observers, and therefore probably presents a more precise index of solar activity.

(1) Introduction: Parallelism of ionospheric and solar phenomena

Correlation between the long-term variations of critical frequencies for the various layers of the ionosphere and those of many other solar and terrestrial phenomena which vary causally with solar activity has been known for some time [see 1, 2 of "References" at end of paper], their co-variation with sunspot-number being of considerable practical importance in the prediction of usable radio frequencies [3, 4].

Comparison of the data in Figures 1, 2, and 3, where noon critical frequencies for the \( F2 \), \( F1 \), and \( E \)-layers of the ionosphere, as well as midnight values of the \( F2 \)-layer, are presented together with their 12-month running averages, for Washington (D.C.), Huancayo (Peru), and Watheroo (Western Australia) with the sunspot-data presented in Figure 4 shows that:

(a) There exists long-term parallelism between the 12-month running averages of the critical frequencies and the sunspot-number, although there is no obvious short-term parallelism.

Lack of accurate short-period parallelism may result for several reasons. Since variations in sunspot-number and the critical frequencies are co-causal, short-term variations in either may be to some extent the result of independent statistical variation, or of variable factors other than solar activity. [Besides, the 12-month running averages, which serve to remove the seasonal variations of critical frequencies as well as smooth the time-trends may obscure any short-term fluctuations.]

(b) The relative change of ionospheric critical frequency with sunspot-number varies with layer, geographical location, and time of day.
In general, the amount of this variation increases with the magnitude of the quantity under consideration.

(c) Magnitude of the seasonal variation generally varies with the quantity under consideration.
(d) The 12-month running-average curves of critical frequency are smoother than those for sunspot-number.

This suggests that measurements of ionospheric critical frequencies, being fairly continuous, may furnish a preferable index of solar activity.
Fig. 4. VARIATION OF ZURICH SUNSPOT NUMBER.
Individual measurements of critical frequency are rather precise, given to the nearest 0.1 Mc, entail far less personal judgment among observers, and are not impaired by variable atmospheric observing conditions as are measurements of sunspot-number. Moreover, day-to-day variability is such that a fair current estimate may be obtained from only a few days' observations.

The examples of critical-frequency data presented here are those for which the longest time-series are available. The general characteristics noted above in their variations apply to all layers, at all hours of the day, and for all of about 60 ionosphere stations at widely different geographical locations.

(II) Relation between critical frequencies and sunspot-number

The relation between ionospheric critical frequency and sunspot-number is approximately linear, for all layers, all times of day, and all geographical locations. That the relation is generally as close as that exhibited in Figure 5, which is a typical case, is remarkable when one considers the very arbitrary nature of the relative sunspot-number (the sum of the total sunspot-count plus ten times the number of spot-groups, all multiplied by a constant characteristic of observatory apparatus and...
seeing conditions) chosen by R. Wolf nearly a century ago as an index of solar activity. It is of interest that the linearity of this relationship parallels the linear relationship found by E. Pettit [5] between solar emission of ultra-violet light and the number of sunspot-groups.

The slopes and zero-intercepts of such curves are different for different times and places. All indicate that the zero-value of solar activity as measured by sunspot-numbers lies far above that derived from ionospheric critical frequencies.

The monthly index (or ratio of monthly-average critical frequency to the 12-month running average centered at that month) is nearly constant, although for some times and places it exhibits a slight variation with sunspot-number. Thus plots of critical frequencies, for any given month, against sunspot-number, are likewise approximately linear.

For any ionospheric layer, at any time or place, the variation of critical frequency may therefore be represented by the expression

\[ f^0 = G(t) + H(t)S \]

where \( f^0 \) is the critical frequency, \( S \) is the smoothed sunspot-number, and \( G \) and \( H \) are functions of the time of day, \( t \), which are appropriate to the season and location.

This relationship allows great condensation of the information afforded by ionospheric data, since it may be given nomographic representation. The above equation may be given the determinant form

\[
\begin{vmatrix}
0 & (L - l_1f^0) & 1 \\
δ & l_2S & 1 \\
M & N & 1
\end{vmatrix} = 0
\]

where

\[ M = l_1δ/[l_1 + l_2/H(t)] \]

and

\[ N = [L - l_2l_1G(t)]/H(t)[l_1 + l_2/H(t)] - LL_1/[l_1 + l_2/H(t)] \]

The left and middle terms in any row of the determinant indicate corresponding \( x \)- and \( y \)-coordinates for the nomographic scales, if the origin of coordinates is taken at the lower left-hand corner of the nomogram, and if \( δ \) is the width of the nomogram, \( L \) the total length of the \( f^0 \)-scale, and \( l_1 \) and \( l_2 \) are scale-factors, respectively, for the \( f^0 \)- and \( S \)-scales.

Figures 6, 7, and 8 present nomograms of this type correlating the yearly-average \( f^0F2 \) for Washington (D. C.), Huancayo (Peru), and
Watheroo (Western Australia) with sunspot-number. A straight line passed through the appropriate value of time of day, on the central (time) scale, intercepts corresponding values of $f^2F2$ and $S$ on the two vertical
scales. Nomograms of this type have also been constructed for each month, as well as those for the yearly-average values, shown here, and for various ionosphere stations [6].

The condensation of the time-scale into a nearly collapsed loop indicates in this case (as well as in other cases not shown here) that the relationship between values of $f_0^*$ and $S$ roughly approximates a simple multiplicative time-function, if a "zero"-value on the $S$-scale is selected at a sufficiently low value. Similar nomograms constructed for correlation of $E$- and $F_1$-layer critical frequencies with sunspot-number have timescales which are straight lines, indicating such a relationship, where

$$f_0^* = F(t)[S + A]$$

Values of $A$, the negative value of "sunspot-number" corresponding to zero-values of critical frequency are approximately, for the $E$-layer, 1000, 570, 460, and 400, respectively, for the locations Fairbanks (Alaska),
Washington (D. C.), Huancayo (Peru), and Watheroo (Western Australia). Values of A for the F1-layer are, respectively, 470 (rather poorly determined), 770, 360, and 350.

(III) Application of ionospheric data to measurement of solar activity

Both the generally good correlation between sunspot-number and critical frequency, and the greater smoothness of critical-frequency variation, suggest that ionospheric frequencies may serve as a more reliable measure of solar activity than sunspot-number.

Maximum reliability in ionospheric measure of solar activity should be attained by the use of data only from stations where a long series of such measurements are available so that solar activity trends are well established, and by the selection of critical frequencies for such use that exhibit maximum solar-activity variation with respect to random day-to-day variation, or sensitivity to abnormal effects, such as those of ionospheric storminess.

It may be readily seen by inspection of the data of Figures 1, 2, and 3 that F2-layer critical frequencies vary more with solar activity than do those of other ionospheric layers. Inspection of the homograms of Figures 6, 7, and 8 shows that F2-layer critical frequencies near midday generally vary more with solar activity than do those for other times of day.

The three ionospheric stations at Washington (D. C.), Huancayo (Peru), and Watheroo (Western Australia) possess the longest time-series of such data available for all hours of the day, the first possessing a series of data beginning in 1933.

Values of ionospheric "sunspot-number" were obtained for each of these stations, from the monthly-average foF2 at each of the five hours centered on noon, and these values averaged for each month.

These data, obtained by the use of nomograms constructed from monthly trends of foF2, are presented in Figure 9, together with their 12-month running-average values. Similar values, not shown here, were obtained by means of nomograms constructed from trends of yearly-average foF2, for which a constant monthly index (or ratio of monthly-average to yearly-average foF2) was assumed. These latter values closely approximated those derived from monthly trends.

Comparison of the data of Figure 9 with the sunspot-data of Figure 4 shows that the ionospheric "sunspot-numbers" deviate considerably less from their running-average values. The standard deviations of the monthly values from their 12-month running-average value, centered on the month are, respectively, for the relative sunspot-numbers, the ionospheric "sunspot-numbers" derived from yearly-average trends with constant monthly indexes, and the ionospheric "sunspot-numbers" derived from monthly
Fig. 9. Variations of ionospheric sunspot number as determined by trend of monthly average $I_{\text{Fz}}$.
trends, 14.9, 10.4, and 9.5. In all cases, the distribution is slightly skewed toward the higher values.

(IV) Conclusion

Because of the precision in measurement of ionospheric critical frequencies, their close correlation with solar activity, their ability to measure far lower values of solar activity than those given by sunspot-number, and their consistence, as demonstrated above, their use seems to afford what at present may well be our most precise measure of general solar activity.

References

[3] Interservice Radio Propagation Laboratory, Methods used by IRPL for the prediction of ionosphere characteristics and maximum usable frequencies, IRPL-R4, December 31, 1943.
[4] Interservice Radio Propagation Laboratory, Predicted F2-layer frequencies throughout the solar cycle, for summer, winter, and equinox season, IRPL-R16, July 18, 1945.

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