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ANNUAL SCIENTIFIC REPORT NO. 3

IONOSPHERIC RESEARCH USING SATELLITES

RADIO OBSERVATORY

NATIONAL COMMITTEE FOR SPACE RESEARCH

HAIFA, ISRAEL

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ABSTRACT

Results of measurements of electron content, of ionospheric slab thickness and of scintillations from three low latitude stations are presented. The three stations are Nairobi (Kenya), Kingston (Jamaica), and Haifa (Israel). Measurements were made at the three stations, of the Faraday polarization of radio signals from the ionospheric beacon satellites S-66 and BE-C, during the period March-June 1965. The results show similar diurnal variations of electron content for the three stations, with a ratio of daytime maximum to predawn minimum or 8-10. Large variation in daytime values of electron content appear between Nairobi and Haifa, indicating large latitudinal gradients. The daytime values at Kingston and Haifa differ by about 25%. There are similar results of slab thickness and of scintillation occurrence at Haifa and Kingston, while at Nairobi the slab thickness values are lower and there is an increase in the percentage of scintillation occurrence, in comparison to the other two stations.

Results of electron content for the declining phase of the solar cycle for midlatitude stations show a marked dependence on the sunspot number. The relationship between electron content and the sunspot number was found to be $N_T \alpha (1 + 0.025 \overline{R} + 0.0001 \overline{R^2})$. Results of electron content at Haifa for the increasing phase of the sunspot cycle show similar relationship between electron content and sunspot number.

TABLE OF CONTENTS

COMPARISON OF ELECTRON CONTENT RESULTS FROM WIDELY-SPACED LOW-LATITUDE STATIONS

The Joint Satellite Studies Group

ABSTRACT

Results of measurements of electron content, of ionospheric slab thickness and of scintillations from three low latitude stations are presented. The three stations are Nairobi (Kenya), Kingston (Jamaica), and Haifa (Israel). Measurements were made at the three stations, of the Faraday polarization rotation of radio signals from the ionospheric beacon satellites S-66 and BE-C, during the period March-June 1965. The results show similar diurnal variations of electron content for the three stations, with a ratio of daytime maximum to predawn minimum of 8-10. Large variation in daytime values of electron content appear between Nairobi and Haifa, indicating large latitudinal gradients. The daytime values at Kingston and Haifa differ by about 25%. There are similar results of slab thickness and of scintillation occurence at Haifa and Kingston, while at Nairobi the slab thickness values are lower and there is an increase in the percentage of scintillation occurence, in comparison to the other two stations.

INTRODUCTION

A great amount of experimental data has been published in the past few years on the variation of electron content over many geographic locations. (e.g. Garriott 1960, Titheridge 1964, Ross 1966). All these studies are based on measurements of propagation effects produced by the ionosphere on radio signals from ionospheric beacon satellites. Few attempts however has been made to combine the results of several stations, (e.g. Bohnsle et al 1965) and it is the purpose of this paper to present results of a joint reduction of data from several widely spaced low latitude stations.

The three stations which participated in this joint venture are listed in Table I.

TABLE I.

Name of Station	Geographic Longitude	Geographic Latitude	Magnetic Latitude	Magnetic Dip
Nairobi	36.82° E	1.32° S	14° S	26° S
Kingston	76.75° W	18° N	30.5° N	50° N
Haifa	35.09° E	32.87° N	29° N	48° N

Of the three stations two, namely Nairobi and Haifa, have the same geographic longitude but differ in their geographic latitudes, while Kingston and Haifa have about the same magnetic latitude (though different geographic latitudes) and different longitudes.

Measurements were made of the polarization rotation of the 20, 40 and 41 MHz signals from the ionospheric beacon satellites S-66 and BE-C. Several hundreds of recordings made during the period March-June 1965 were used for this study. The recordings were analyzed for total electron content as well as for slab thickness and scintillations. The various methods for data reduction employed by the participating stations are described and an estimation of their accuracy is given.

METHODS OF ANALYSIS

The total polarization rotation angle Ω of a plane polarized wave transversing the ionosphere is, to a first order approximation:

$$\Omega = \frac{K}{f^2} \overline{H \cos\theta \sec\chi} \cdot N_t \qquad (1)$$

where: N_t - total electron content of a vertical column in the ionosphere.

f - wave frequency in cycles per second.

K - constant equal to $2.97 \; 10^{-2}$ in M.K.S. units.

H - magnetic-field intensity in ampere-turns per meter.

θ - angle between the magnetic field and the ray path.

χ - the zenith angle of the ray path.

The average bar denotes the weighted mean value of the product at the mean ionospheric height.

In order to obtain N_t the two parameters which have to be determined are the total polarization rotation Ω and the geometrical factor $\bar{M} = \overline{H \cos\theta \sec\chi}$.

a. Determination of Ω.

For low latitude stations the usual polarization rotation ambiguity can be resolved when the ray path from the satellite to the receiving site is transverse to the magnetic field of the earth. The transverse condition can be recorded at receiving stations where the magnetic inclination is less than 55°. At higher magnetic latitudes the transverse point occurs at two low elevation angles. At the transverse point the polarization rotation angle tends to zero and Ω can be determined at any other point of the satellite pass by simply counting fading cycles from the transverse point. This method was first suggested by Garriott (1960).

The method of counting the number of polarization rotations from the transverse point was usually employed at Haifa (Houminer 1966).

Generally the transverse point could be easily identified on the 20 MHz records. In doubtful cases and for some night time records where the transverse point could not be identified, the closely-spaced frequency method for determining N_+, using the 40 and 41 MHz transmissions (Swenson 1962), was employed.

At Nairobi which is near the magnetic equator, and where the transverse point appears nearly overhead, the method of counting fading cycles from the transverse may introduce a big error in the calculation of N_+. The transverse point can be determined on the records with an accuracy of only about half a fading cycle. Such an error on a count of a few cycles may introduce an error well over 10% in N_+. To overcome this difficulty the electron content at Nairobi was determined for the transverse region by a method similar to that used by Golton of the Radio and Space Research Establishment, Slough. An average is taken of the fading rate over about half a minute on either side of the transverse region. This is taken as the fading rate appropriate to the transverse region. By differentiating equation (1) we obtain:

$$\frac{d\Omega}{dt} = \frac{K}{f^2} \left(\overline{M} \frac{dN_+}{dt} + N_+ \frac{d\overline{M}}{dt} \right) \qquad (2)$$

As $\overline{M}$ changes sign in the transverse region, the effect of any constant horizontal gradients in N_+ will be eliminated and the first term in (2) will then be zero. Even when the horizontal gradients are not constant the method should reduce their effect on the fading rate, except for the unlikely cases of a change in the sign of the gradient near the transverse region.

Ω was determined at Kingston in a different way for daytime and night-time records. For daytime records the closely-spaced frequency method for 40 and 41 MHz was used to determine Ω. An analogue circuit was then used to check that Ω against $\overline{M}$ for one of the frequencies gave a smooth curve consistant with a plot of Ω against $\overline{M}$ when an arbitrary zero for Ω was used. For night time records, a plot of Ω against $\overline{M}$ was used to determine the point of zero rotation. The analogue was also used to check the values of Ω against $\overline{M}$ obtained.

No second order corrections were applied to the Nairobi and Haifa data. The Kingston data was corrected for second order effects using the following empirical formula:

$$\Omega_o = \Omega(1 - \frac{X}{2}) (\frac{10.4 - \overline{M}}{10}) \qquad (3)$$

where $X = (\frac{f_oF2}{f})^2$ and $\overline{M}$ is expressed in gauss. The electron content would then be determined by the first order formula (1) with Ω_o inserted instead of Ω. The above empirical formula gave values which were always within 0.5% of the value obtained when Ross' second-order corrections were used (Ross 1965). The inclusion of the second order effects in the analysis resulted in corrections to the first order values of 4% or less, as the electron content was calculated only for passes where the zenith angle was less than 45°.

b. Determination of $\overline{M}$.

The second parameter which has to be determined in order to evaluate N_t, is the geometrical factor $\overline{M}$ (or $\frac{d\overline{M}}{dt}$ for Nairobi). The mean ionospheric height at Haifa for which $\overline{M}$ was calculated was taken as 350 km. This value is believed to be quite close to the height of the average ionosphere above Haifa. At Nairobi and Kingston the mean ionospheric height was taken as 50 km above the height of the F layer maximum. The value of 50 km was chosen after examination of electron density profiles. The real height of the F2 layer was obtained from ionograms. The M values for each station were available in forms of tables provided by AFCRL or NASA.

The estimated absolute accuracy of results for the various stations is between 10-15% for daytime records. This figure is somewhat better for Kingston were second order corrections were applied to the results. For night time records this accuracy is somewhat worse, and for some night records when the polarization rate was extremely low, the absolute error can be as high as 30%.

EXPERIMENTAL RESULTS

a. Diurnal Variations.

The results of the ionospheric electron content up to the satellite height over Nairobi, Kingston and Haifa for the period March-June 1965, are shown in figures 1a, 1b and 1c respectively. The electron content was calculated for each pass where the zenith angle was less than 45°. The total electron content for a pass was then taken as the value for which the sub-ionospheric latitude was closest to that of the receiving stations. In figure 1 the values of electron content at closest approach were plotted against local time, in order to get the diurnal variation of N_t.

There is a scatter of about ±30% in values of N_t for Kingston and Haifa stations, while at Nairobi the scatter is as high as ±50%. The scatter appears mainly during noon and afternoon hours, while at the morning the rise in electron content is rather smooth. This scatter in electron content occurs mainly because of large day to day variation in the ionosphere and is not an indication of an error in the measurements. The day to day variations in electron content appear to be larger at the equatorial station (Nairobi) than in the other two low latitude stations.

For the purpose of comparing the total electron content for the three stations, the mean diurnal curves of figures 1a, 1b and 1c are plotted in figure 2. There appears to be similar diurnal variations in N_t for the three stations with a rather broad daytime peak centered around 13-14 hours local time, a predawn minimum and a fast increase after sunrise. The ratio of daytime maximum value of N_t to that of the predawn minimum is almost the same for the three stations, being about 8 for Haifa, 10 for Kingston and 9 for Nairobi. These figures appear to be lower than those obtained at some other low latitude stations at the same phase of the sunspot cycle (e.g. Skinner 1966, Tyagi et al 1966).

b. Daytime Maximum Values of Electron Content.

The daytime maximum values of total electron content vary from one station to another. The $N_{t\ max}$ values are $2.9 \cdot 10^{17}$ elec/m^2, $2.0 \cdot 10^{17}$ elec/m^2 and $1.5 \cdot 10^{17}$ elec/m^2 for Nairobi, Kingston and Haifa respectively. Of the three stations Haifa and Nairobi have the same geographic longitude though different latitudes, the geographic latitudes being 33° N and 1.5° S for Haifa and Nairobi respectively. It is interesting to note that the daytime maximum value of electron content over Nairobi is almost twice as high than $N_{t\ max}$ over Haifa. The average latitudinal gradient between the two stations is about $0.4 \cdot 10^{17}$ elec/m^2 per degree of subsatellite latitude. It is most unlikely that the increase in N_t is linear over this range of latitudes or that it is due to the variations in the sun's zenith angle. It was however noted before at Haifa (Houminer 1966) as well as at Delhi which is situated at about the same magnetic latitude as Haifa (Tyagi et al 1966), that there is a marked increase in the daytime electron content as one goes towards the magnetic equator.

As for Kingston and Haifa which are situated on a similar magnetic latitude, the difference in the daytime maximum of electron content is about 25%. As the two stations are too widely spaced (Kingston longitude is 75° W while Haifa's is 35° E) this variation in $N_{t\ max}$ can only indicate that longitudinal gradients exist.

c. Slab Thickness Variations.

The equivalent slab thickness of the ionosphere τ is defined as:

$$\tau = \frac{N_t}{N_{max}}$$

where N_{max} is the maximum electron density of the F2 layer peak. For a α-Chapman electron density profile the following relation holds:

$$N_t = 4.13\ H\ N_{max}$$

$$\text{or} \qquad \tau = 4.13\ H$$

where H is the scale height.

Thus by determining τ, one can obtain the scale height (or temperature) of the ionized layer, if the electron density profile does not differ much from a Chapman model.

The mean diurnal variations of τ over Haifa, Kingston and Nairobi for the period March-June 1965 are shown in figure 3. For each pass the slab thickness was calculated using N_T at closest approach and N_{max} obtained from ionosonde observations. The calculated values were then grouped in one hour intervals and the hourly means are shown in figure 3.

The mean diurnal variations of the equivalent slab thickness for Kingston and Haifa are rather similar with noontime values of about 250 km and predawn values of about 150 km. There is though a big difference in results between 4-7 hours local time. This may be explained by the large gradients in the ionosphere at these hours and the fact that the ionospheric sounding is not taking place at the corresponding subionospheric point of the pass.

The Nairobi mean values of equivalent slab thickness are systematically lower than τ in Haifa or Kingston for most of the observed time. The midday value is only 210 km in comparison to 250 km at Haifa and Kingston. This would imply that the mean scale height (or the mean electron temperature) is lower over Nairobi. This conclusion seems to be consistent with the electron temperatures observed with the Aeriel satellite which showed that the electron temperature decreased with decreasing latitudes (Bohnsle et al 1965). Similar latitudinal trend in the mean electron temperatures at mid-latitudes was noticed in the analysis of data from the ionospheric topside sounder Alouette (Bauer and Blumle, 1964).

d. Scintillations.

The Faraday fading records for the period March-June 1965 were also analysed for scintillations. The analysis was a qualitative one and scintillations indices have been assigned according to weather the scintillations were mild, moderate or severe. The percentage of occurence of scintillations versus the local time in Nairobi, Kingston and Haifa are shown in figures 4, 5 and 6 respectively.

Figures 4a, 5a and 6a give the percentage of occurence of all scintillations, while figures 4b, 5b and 6b show the percentage of occurence of severe scintillations. It is obvious from the above figures that generally the scintillations observed at the three stations were mild to moderate, with severe scintillation occuring mainly during the night time. The diurnal variation of all scintillations occurence (figures 4a, 5a and 6a) is rather similar for the three stations with an increase in the frequency of occurence of scintillations during night time and a maximum at about 02-03 hours local time. Another maximum appears in the morning hours, between 09-12 local time. The same morning maximum in a similar season was observed at a midlatitude station (Allen and Mullen 1966). Their analysis of scintillations of the 54 Mc/s beacon on Transit 4A for the period July 1961 - December 1963 show that the morning maximum appears only at the spring equinox and thus it is clearly a seasonal effect. Being observed at widely spaced stations and at different phases of the solar cycle, it is evident that this unexpected phenomenon is independent of geographic location and of solar activity.

The percentage of occurence of scintillations at Nairobi is higher than in Kingston or Haifa. This is to be expected as it has been shown that the occurence of irregularities increase in the equatorial region (Calvert and Schmid, 1964), on the other hand the frequency of scintillation occurence at Kingston and Haifa is very similar.

CONCLUSIONS

Comparison of electron content results from three widely spaced low latitude stations has been made. The three stations are paired so that two of them namely Nairobi and Haifa, have the same geographic longitude, while Kingston and Haifa have the same magnetic latitudes. Results from the three stations show similar diurnal variation of electron content with a ratio of daytime maximum to predawn minimum of 8-10. The daytime maximum values of electron content varied from one station to another. Big differences in electron content values appear between Nairobi and Haifa, indicating large latitudinal gradients. On the other hand results of electron content from Kingston and Haifa differ by about 25%, only. Kingston and Haifa show similar results of slab thickness and have almost the same frequency of scintillation occurence. This is to be expected as the two stations are equally situated in respect to the magnetic equator. Nairobi which is an equatorial station, have lower values of slab thickness and shows an increase in the percentage of occurence of scintillations in comparison to the other two stations. This is in agreement with observations of the Aeriel satellite and the ionospheric topside sounder Alouette.

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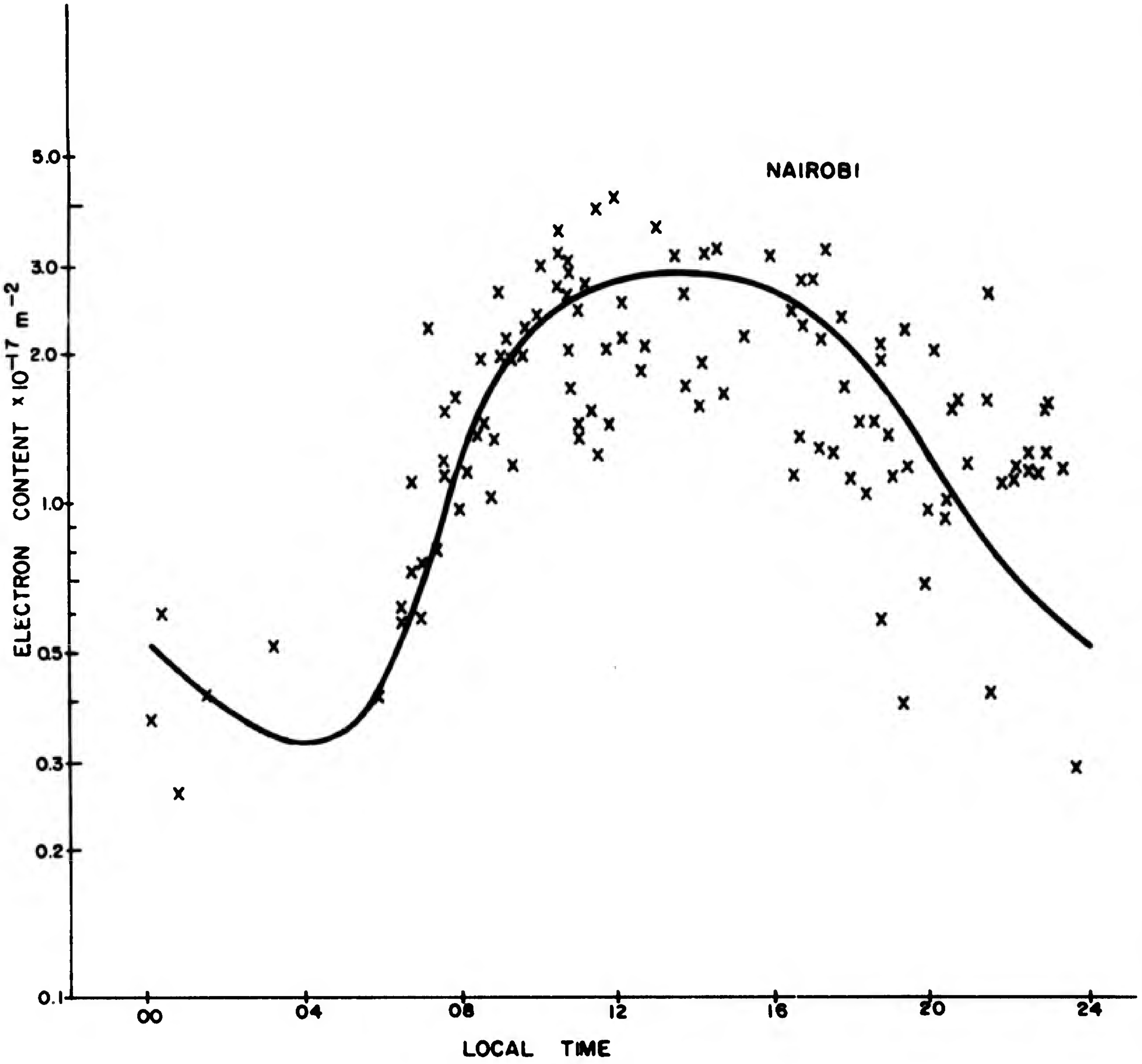

FIG. Ia: ELECTRON CONTENT OVER NAIROBI PLOTTED AGAINST LOCAL TIME FOR THE PERIOD MARCH – JUNE 1965.

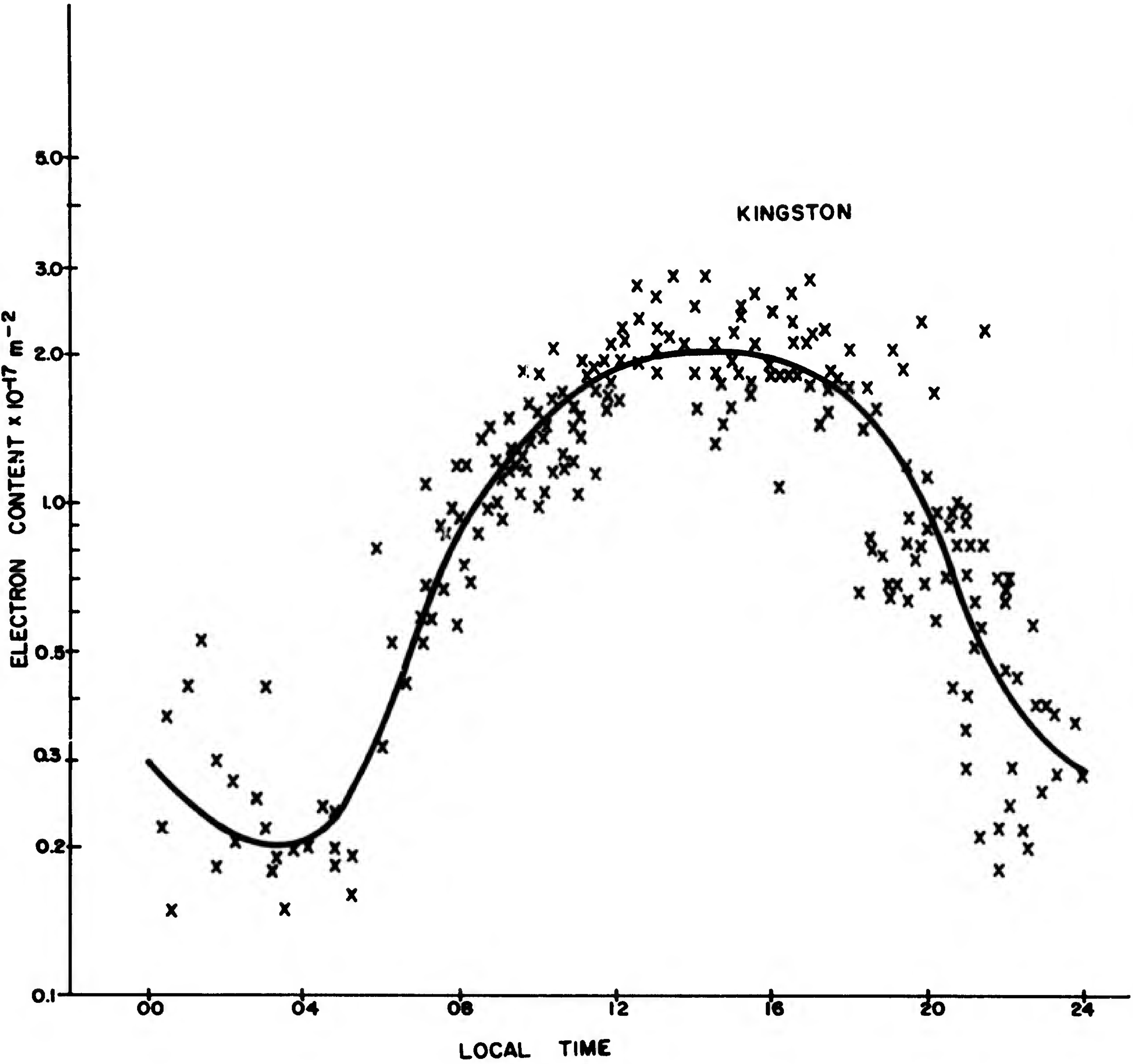

FIG. Ib. : ELECTRON CONTENT OVER KINGSTON PLOTTED AGAINST LOCAL TIME FOR THE PERIOD MARCH – JUNE 1965.

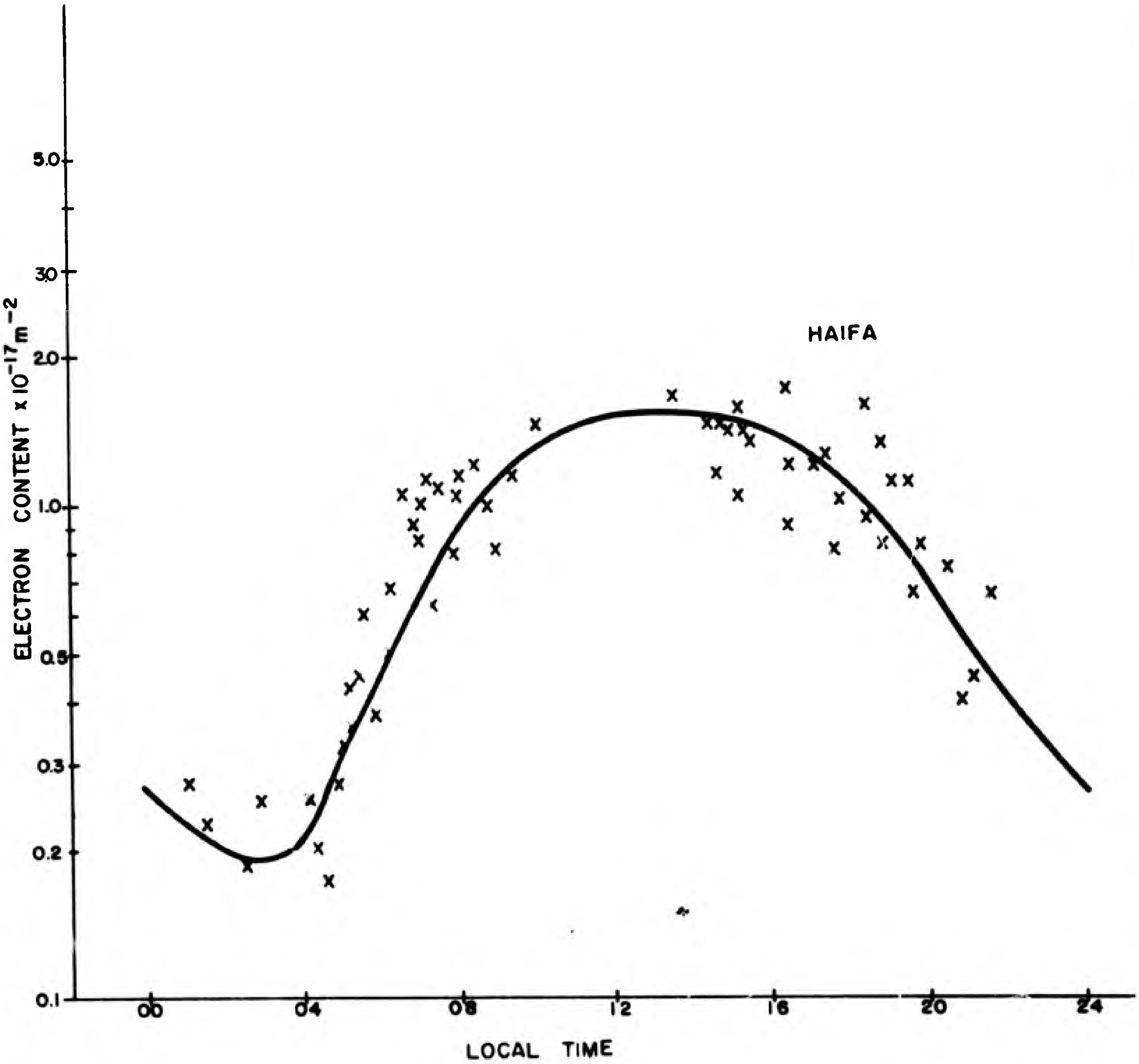

FIG. Ic. : ELECTRON CONTENT OVER HAIFA PLOTTED AGAINST LOCAL TIME FOR THE PERIOD MARCH – JUNE 1965.

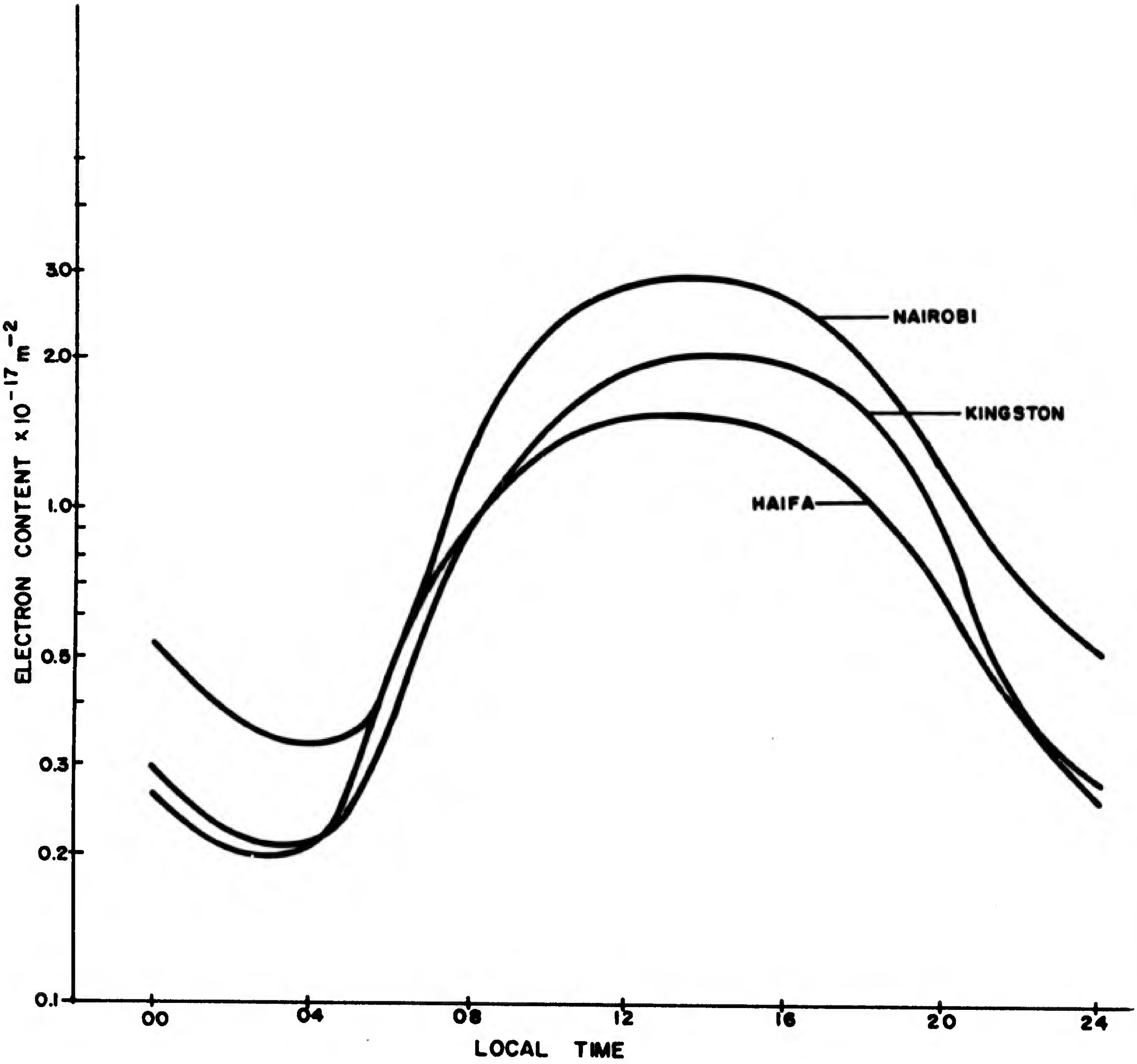

FIG. 2. : MEAN DIURNAL VARIATION OF ELECTRON CONTENT OVER NAIROBI, KINGSTON AND HAIFA.

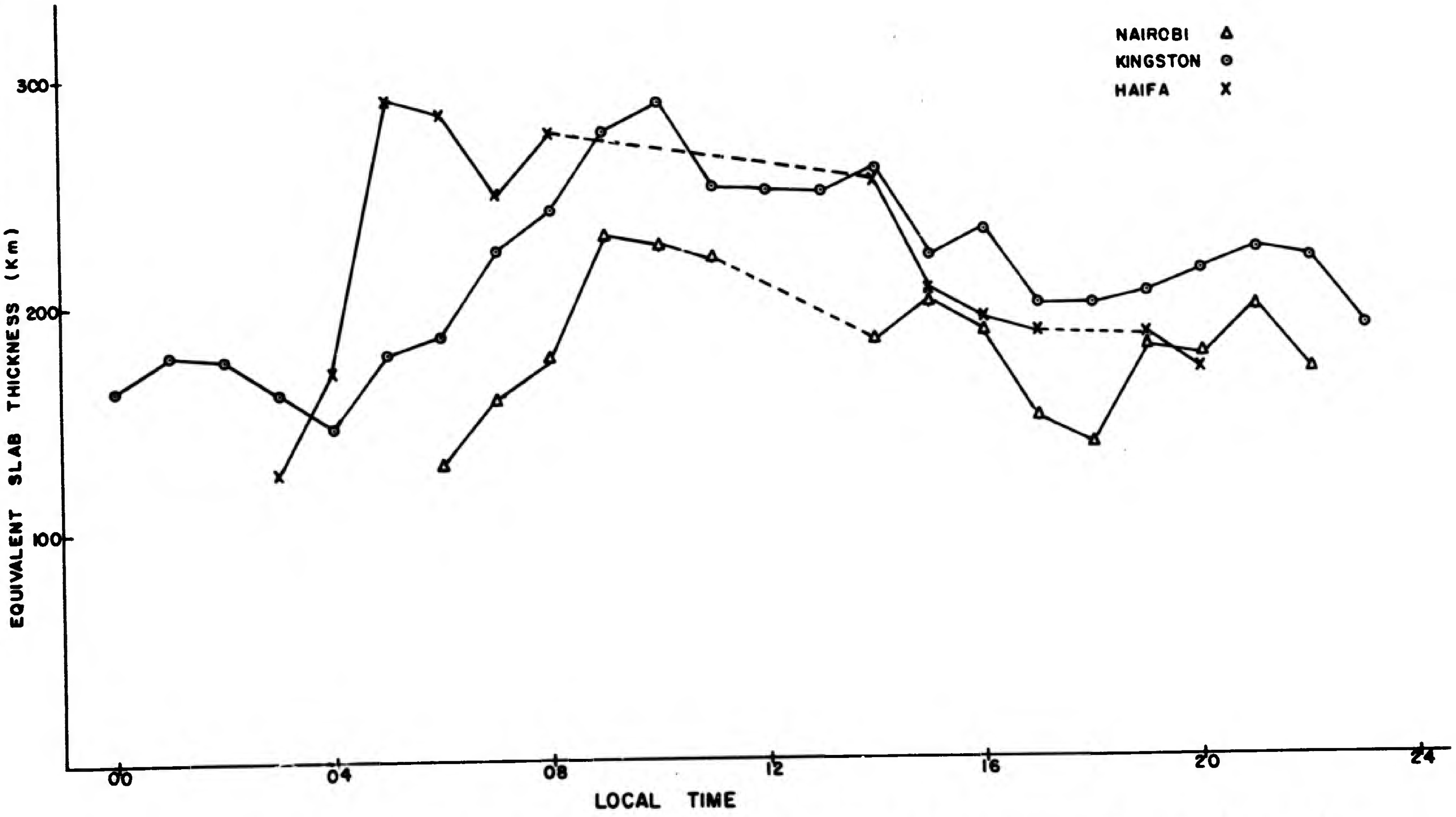

FIG. 3: MEAN DIURNAL VARIATION OF THE EQUIVALENT SLAB THICKNESS OVER NAIROBI, KINGSTON AND HAIFA FOR THE PERIOD MARCH - JUNE 1965.

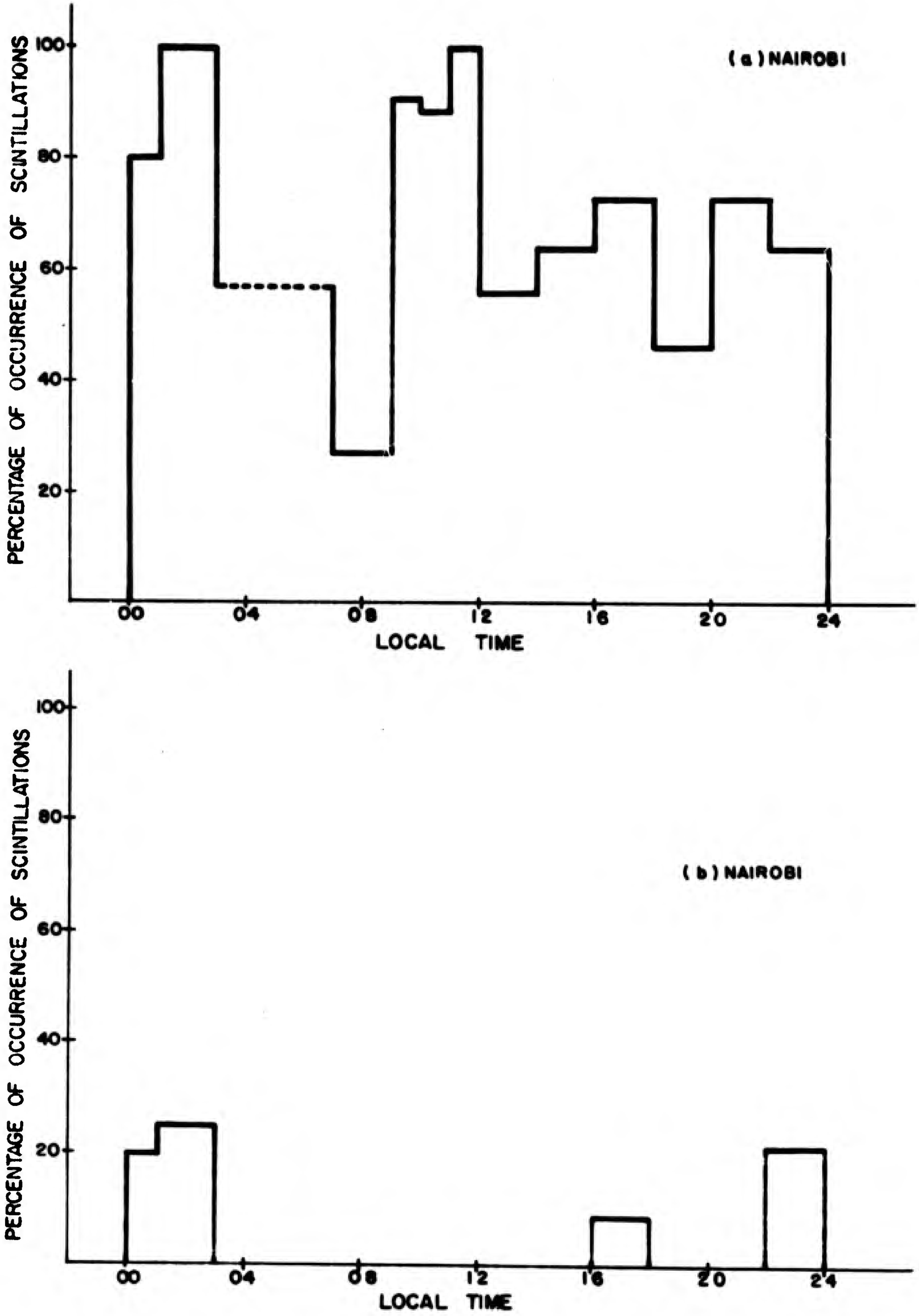

FIG. 4: PERCENTAGE OF OCCURRENCE OF (a) ALL SCINTILLATIONS AND (b) SEVERE SCINTILLATIONS AT NAIROBI, FOR THE PERIOD MARCH-JUNE 1965.

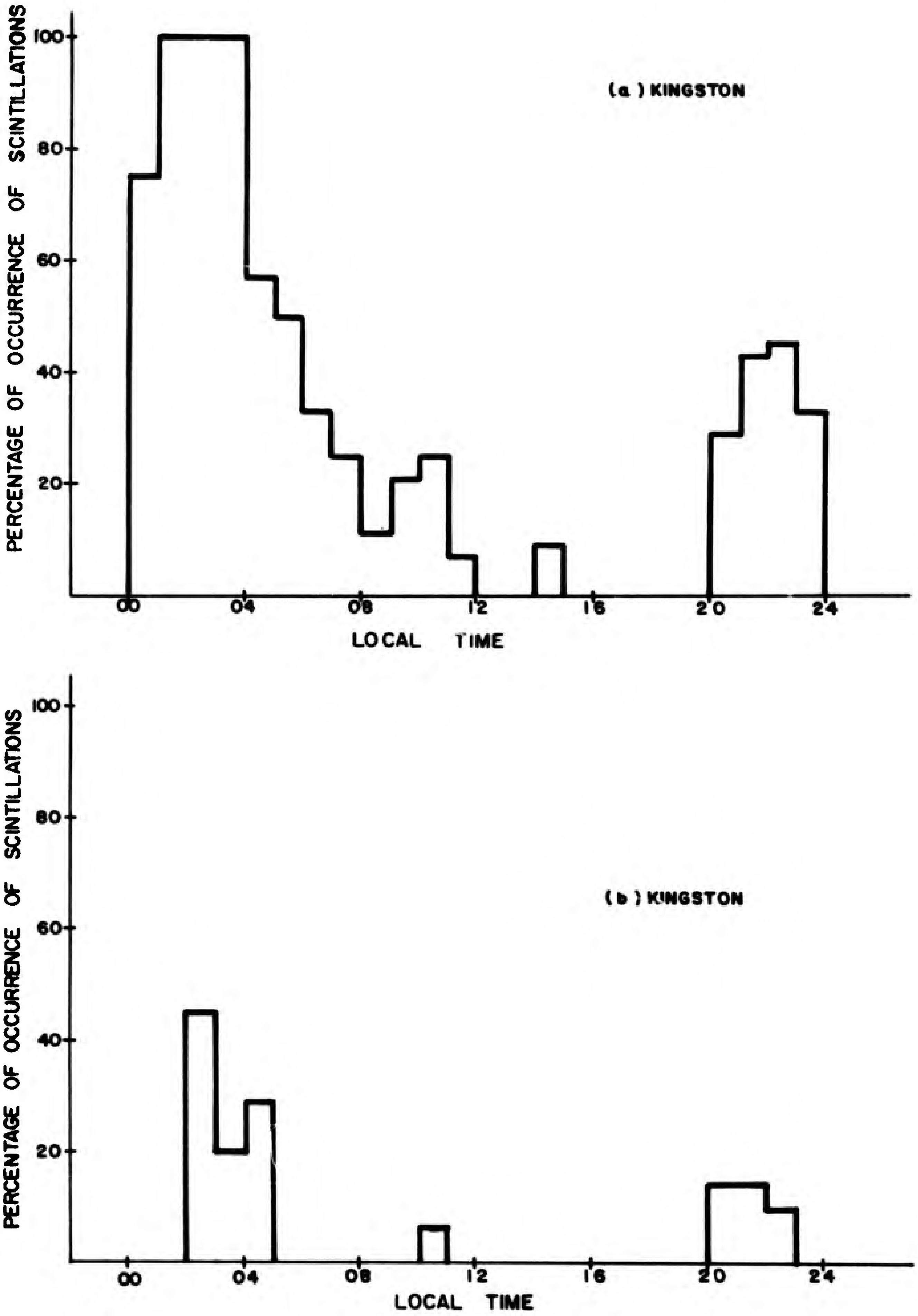

FIG. 5: PERCENTAGE OF OCCURRENCE OF (a) ALL SCINTILLATIONS AND (b) SEVERE SCINTILLATIONS AT KINGSTON, FOR THE PERIOD MARCH – JUNE 1965.

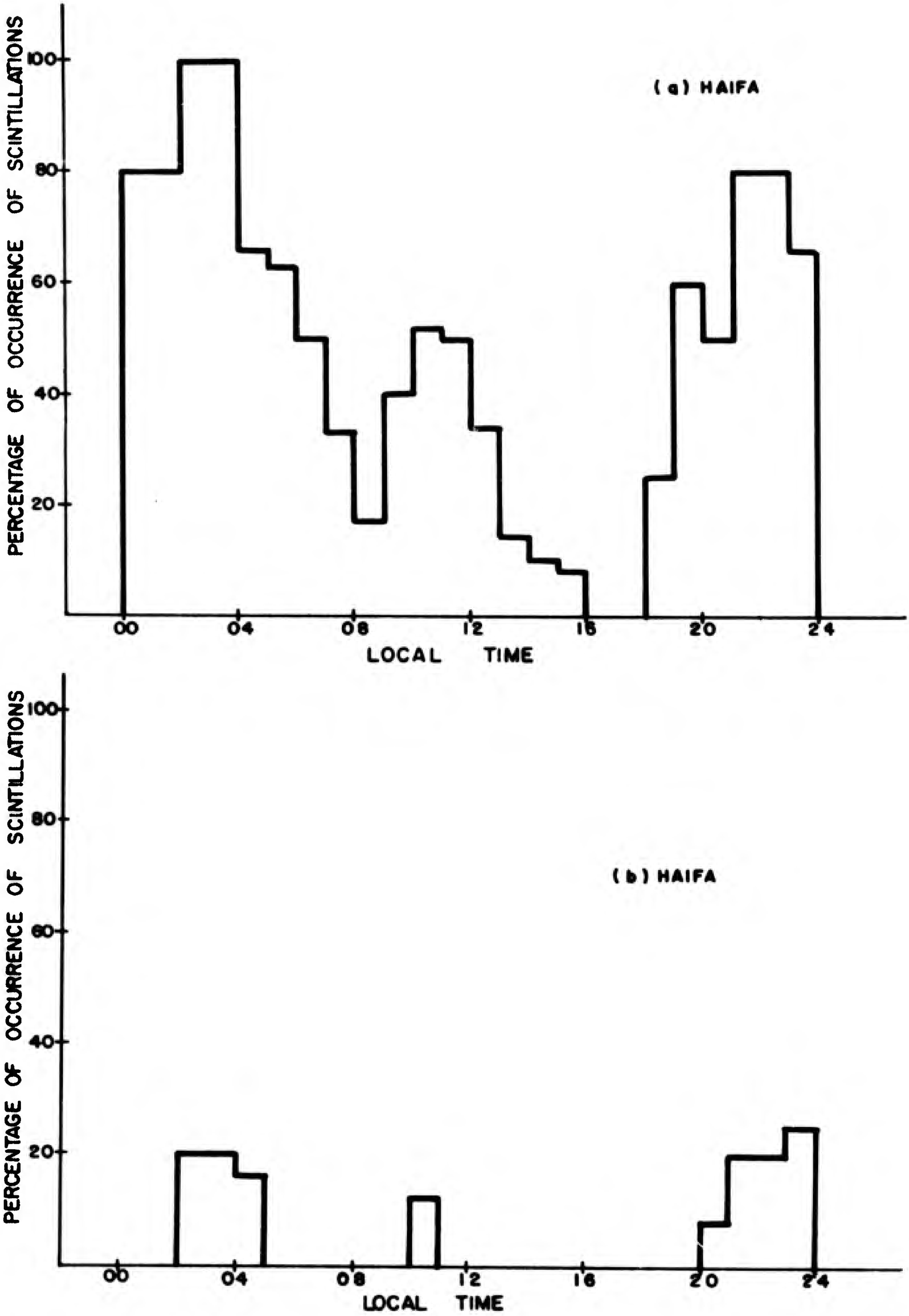

FIG. 6: PERCENTAGE OF OCCURRENCE OF (a) ALL SCINTILLATIONS AND (b) SEVERE SCINTILLATIONS AT HAIFA, FOR THE PERIOD MARCH-JUNE 1965.

ON THE VARIATION OF IONOSPHERIC ELECTRON CONTENT WITH THE SUNSPOT CYCLE

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INTRODUCTION

It is a well known fact that the ionospheric electron content N_t, as well as the critical frequency foF2 of the F2 layer, vary markedly with the solar cycle. The world wide results for the variation of the critical frequency with the sunspot number were summarized by Ratcliffe and Weekes (1960) as:

$$(\text{foF2})^2 \propto (1 + 0.02\,\overline{R})$$

where $\overline{R}$ is the mean Zurich sunspot number. It is of interest to find a similar relationship between the electron content and the sunspot number. Bhonsle, da Rosa and Garriott (1965) incorporating results of electron content from several midlatitude stations, found a linear relationship between the electron content and the sunspot number for $\overline{R} \geq 40$. They expressed this empirical relationship as:

$$N_t = a\left[1 + \frac{b}{a}(\overline{R} - 40)\right] \text{ elec/m}^2$$

where a and b are constants which are different for the different seasons. Yeh and Flaherty (1966) extended the above study to sunspot numbers smaller than 40, combining their results for the period 1961 - 1964 with values of electron content used by Bhonsle et al (1965). They arrived at the conclusion that the linear relationship between N_t and $\overline{R}$ does not hold anymore when results of electron content for $\overline{R} < 40$ are taken into account. Their results as well as the results used by Bhonsle et al (1965), for the declining phase of the solar cycle between the years 1958 - 1964, are shown in Figure 1.

SOLAR CYCLE DEPENDENCE

The equivalent slab thickness of the ionosphere τ is defined as:

$$\tau = \frac{N_t}{N_{max}}$$

where N_{max} is the maximum electron density of the F2 layer and is related to the critical frequency foF2 according to $N_{max}\ \alpha (foF2)^2$. N_t could then be expressed as:

$$N_t = N_{max} \cdot \tau$$

If the slab thickness were independent of the solar activity, then N_t should vary linearly with $\overline{R}$ in the same form as N_{max} (or foF2)^2) i.e.

$$N_t\ \alpha (1 + 0.02\ \overline{R})$$

it is well known that τ is not independent of the solar cycle and Bhonsle et al (1965) found the following relationship between the slab thickness and the sunspot number for the declining phase of the solar cycle:

$$\tau\ \alpha (1 + 0.005\ \overline{R})$$

Using this relationship for τ, N_t should then vary according to:

$$N_t\ \alpha (1 + 0.02\ \overline{R})\ (1 + 0.005\ \overline{R})$$

$$\text{or} \quad N_t\ \alpha (1 + 0.025\ \overline{R} + 0.0001\ \overline{R^2})$$

Fitting a curve of the above form to the results of Figure 1, the relationship between N_t and $\overline{R}$ for the various seasons may be written as:

$$N_t = (1 + 0.025\,\overline{R} + 0.0001\,\overline{R}\,) \times 10^{17} \text{ elec/m}^2 \quad \text{for equinox}$$

$$N_t = 0\ 75\,(1 + 0.025\,\overline{R} + 0.0001\,\overline{R}\,) \times 10^{17} \text{ elec/m}^2 \quad \text{for winter}$$

and $$N_t = 0.5\,(1 + 0.025\,\overline{R} + 0.0001\,\overline{R^2}) \times 10^{17} \text{ elec/m}^2 \quad \text{for summer}$$

There appears to be a good agreement between the empirical curves and the experimental results. The double-humped nature of the seasonal dependence of electron content is apparent from Figure 1. It can be seen that the seasonal dependence becomes more pronounced with the increase in the solar activity.

Results of midday maximum electron content at Haifa for the period 1964 - 1967, at the increasing phase of the solar cycle, are plotted in Figure 2 versus the mean sunspot number. Again a curve of the form $(1 + 0.025\,\overline{R} + 0.0001\,\overline{R^2})$ has been fitted to the experimental results and the relationship between N_t and $\overline{R}$ can be described as:

$$N_t = 1.15\,(1 + 0.025\,\overline{R} + 0.0001\,\overline{R^2}) \times 10^{17} \text{ elec/m}^2 \quad \text{for equinox}$$

and $$N_t = 0.7\,(1 + 0.025\,\overline{R} + 0.0001\,\overline{R^2}) \times 10^{17} \text{ elec/m}^2 \quad \text{for winter}$$

The summer season results were not included as not enough data was available for the season.

Results of the variation of N_t at Haifa for the increasing phase of the sunspot cycle are rather similar to results obtained at midlatitude stations at the declining phase of the solar cycle. It seems that the seasonal dependence is more pronounced at Haifa which is at rather low latitude (32,9° N) than at the midlatitude stations, mentioned by Bhonsle et al (1965), and by Yeh and Falherty (1966).

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J. Geophys. Res., 71, 4557 - 4570, 1960.

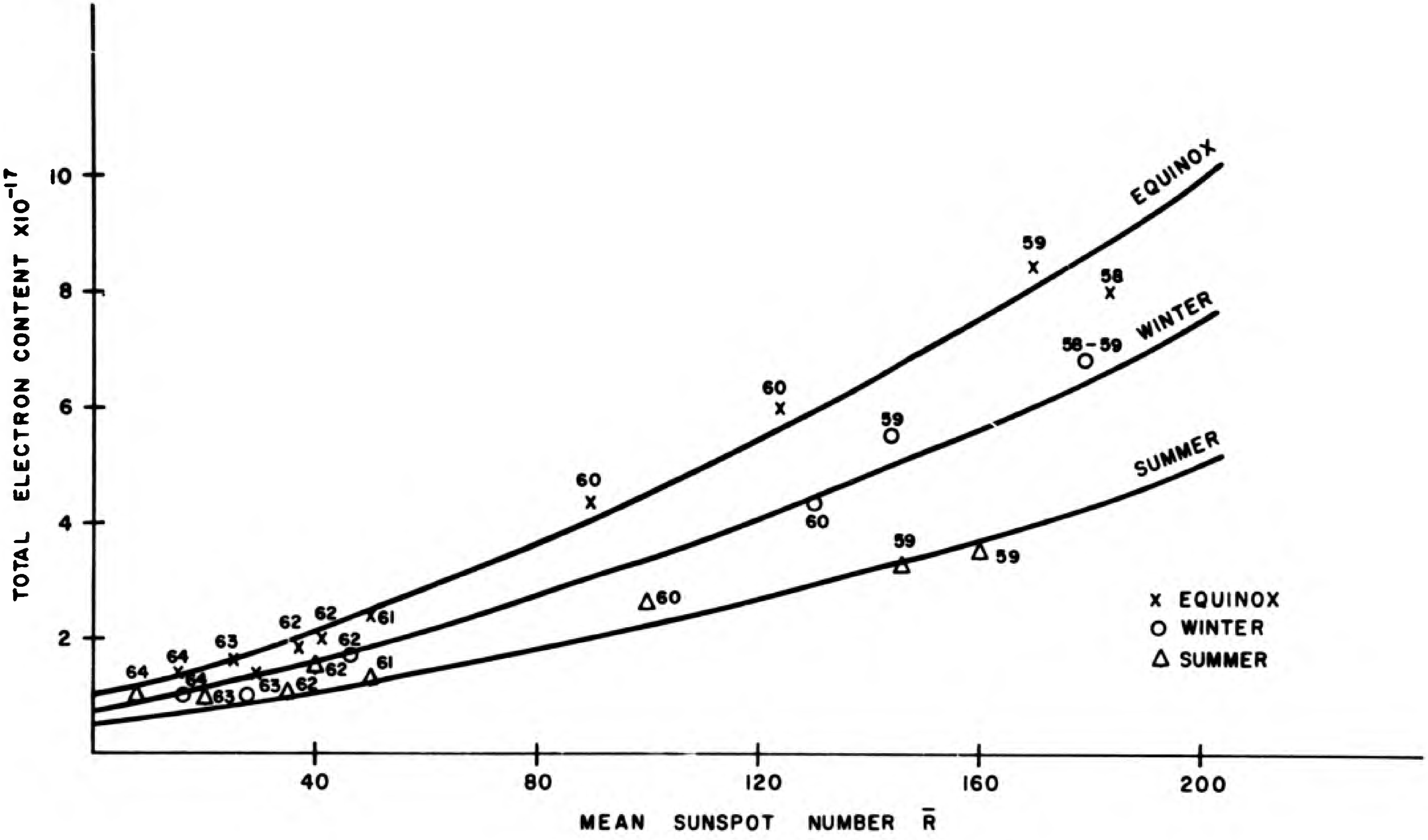

FIGURE 1: SOLAR CYCLE VARIATION OF AVERAGE MIDDAY ELECTRON CONTENT OF THE IONOSPHERE VALUES ARE FROM BHONSLE et al (1965) AND YEH AND FLAHERTY (1966) CURVES ARE DRAWN ACCORDING TO $(1+0.025\,\bar{R}+0.0001\,\bar{R}^2)$

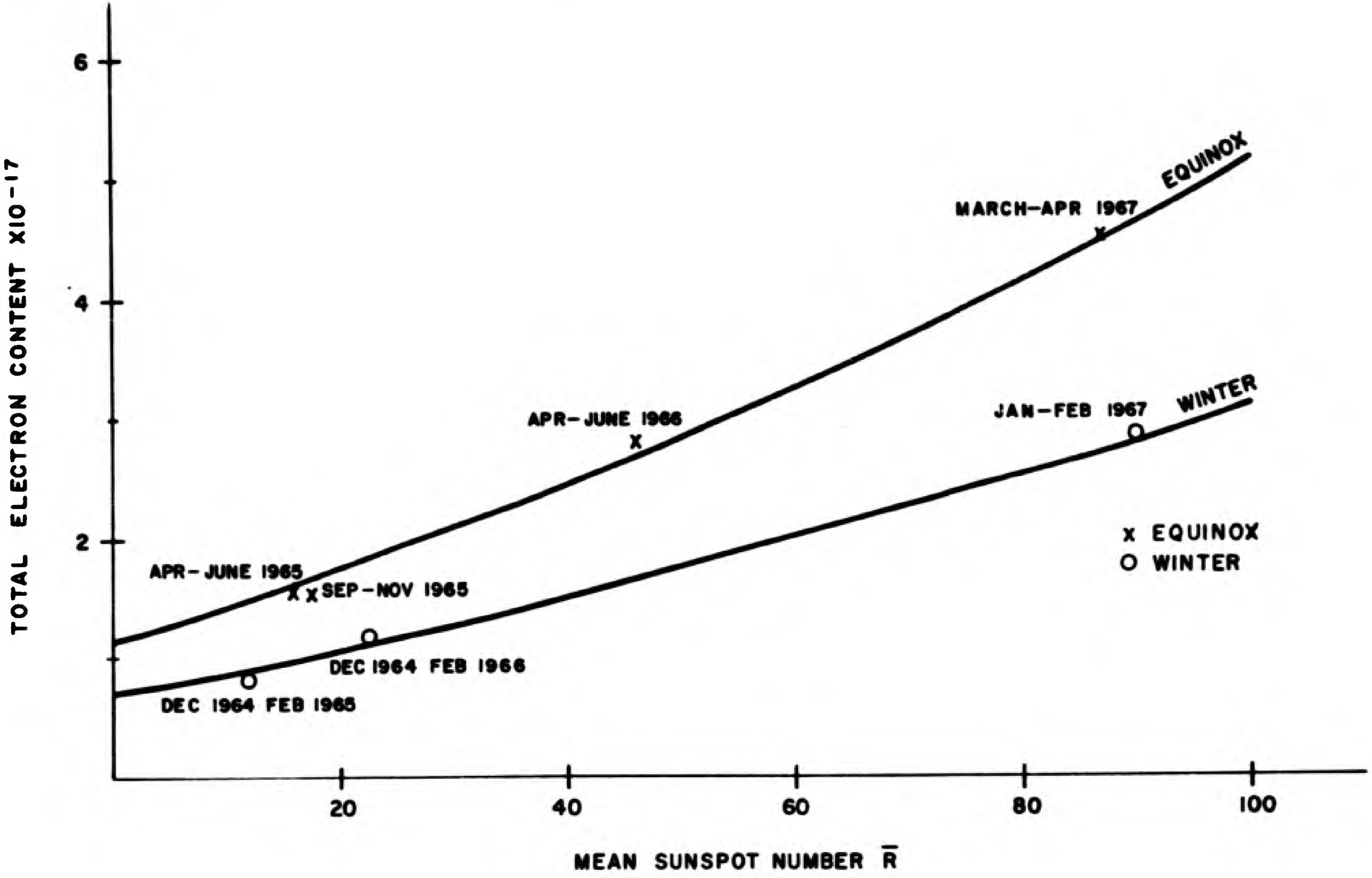

FIGURE 2: SOLAR CYCLE VARIATION OF AVERAGE MIDDAY ELECTRON CONTENT AT HAIFA.

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13. ABSTRACT

Results of measurements of electron content, of ionospheric slab thickness and of scintillations from three low latitude stations are presented. The three stations are Nairobi (Kenya),Kingston (Jamaica), and Haifa (Israel). Measurements were made at the three stations, of the Faraday polarization rotation of radio signals from the ionospheric beacon satellites S-66 and BE-C, during the period March-June 1965. The results show similar diurnal variations of electron content for the three stations, with a ratio of daytime maximum to predawn minimum of 8-10. Large variation in daytime values of electron content appear between Nairobi and Haifa, indicating large latitudinal gradients. The daytime values at Kingston and Haifa differ by about 25%. There are similar results of slab thickness and of scintillation occurrence at Haifa and Kingston, while at Nairobi the slab thickness values are lower and there is an increase in the percentage of scintillation occurrence, in comparison to the other two stations.

Results of electron content for the declining phase of the solar cycle for mid-latitude stations show a marked dependence on the sunspot number. The relationship between electron content and the sunspot number was found to be $N_T \alpha (1+0.025 \overline{R} + 0.0001 \overline{R}^2)$. Results of electron content at Haifa for the increasing phase of the sunspot cycle show similar relationship between electron content and sunspot number.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Electron Content						
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Transverse propagation						
Slab thickness						
Scintillations						
Ionospheric Beacon Satellites						