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THE DIURNAL- AND SUNSPOT-CYCLE VARIATION OF THE LAYERS *E*, *F*1 AND *F*2 OF THE IONOSPHERE AS OBSERVED IN NORWAY DURING THE PERIOD 1932—1956.

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Summary. Standard methods have been applied in order to study the diurnal variation of the critical frequencies of the *E*- and the *F*1-layers, and the seasonal and sunspot-cycle variation of the critical frequencies of the *E*-, *F*1- and *F*2-layers and the transmission factor (*M* 3000)-*F*2. The study is based mainly upon observations obtained at Kjeller and at Tromsø, although for part of the study some recent observations from Spitzbergen are also included.

In order to study the variation of the critical frequencies of the *E*-, *F*1- and *F*2-layers with sunspot activity, observations obtained at the same time of the day and the same month for all years were selected. Reasonably good linear correlation between the critical frequencies and the 13-monthly running mean of the sunspot number, *W*, were obtained. The sensitivity of the critical frequency to sunspot activity for the *E*- and the *F*1-layers showed a clear maximum in the summer, in agreement with the Chapman-theory. The noon values of the sensitivity for the *F*2-layer showed a minimum in the summer both at Kjeller and at Tromsø.

The diurnal variations of f_0E and f_0F1 are found to obey reasonably a $\cos^n\chi$-law, and the exponent n is found to vary with season and latitude.

The spread of the daily observations from the monthly median values was studies by means of the observed quartile ranges deduced from the observed values of f_0F2 at Kjeller for those years when the observations have been made by the NDRE. The quartile range seems to increase with the magnitude of the monthly median value and with sunspot number. A greater spread was observed by night than by day.

Finally, the correlation between the transmission factor (*M*3000)-*F*2 and the sunspot number *W* was studied for each month separately, and was found to be rather good. A study of the seasonal variation of the transmission factor concludes the work.

1. Introduction. The maximum electron density of the three normal layers in the ionosphere is known to undergo considerable diurnal, seasonal and sunspot-cycle variation. The maximum electron density (N_m) for a layer can be measured by a radio echo method, based on the equation:

$$N_m = \frac{m}{4\,\pi\,e^2} \cdot (f_0)^2$$

where m and e is the mass and the charge of the electron, respectively, f_0 is the penetration frequency for the ordinary magneto-ionic component («*critical frequency*»).

It is the purpose of this report to present an integrated picture of the most important parameters from the observations made in Norway. We shall treat only the values of the critical frequencies for the three layers *E*, *F1* and *F2*, and the transmission factor for the *F2*-layer, (*M3000*)–*F2*. We shall limit ourselves to a study of the monthly median values of these parameters.

2. Observations. Ionospheric observations, using radio-echo techniques, were started in Norway during the Second International Polar Year in 1932 by Sir Edward Appleton, then a visitor at the Auroral Observatory in Tromsø. The results of these observations (Appleton, Naismith and Ingram [1]) clearly demonstrated the need for a continuation of ionospheric observations at a high latitude station such as Tromsø.

After the Second Polar Year regular ionospheric observations were started at Tromsø from 1936.

During the war observations were made by the German occupation forces both at Tromsø and at Kjeller. After the war the observations have been continued by the Norwegian Defence Research Establishment, at Tromsø in cooperation with the Auroral Observatory.

Before the observations were started at Kjeller by NDRE, a series of observations were made by the Royal Norwegian Air Force at the same place. All the data obtained by the various investigators have been published in the CRPL F-series.

I Tables 2.1 and 2.2 below we have listed the observers for the time periods and the parameters to be used in this analysis.

Before 1941 routine observations were made only for the hours 1000, 1200 and 1400 MET. From 1941 to 1945 somewhat more frequent observations were made. But regular hourly recordings were not started before the stations were taken over by the NDRE. Furthermore, in this analysis, the values of the critical frequencies before 1941 are monthly means, whilst for the later years the median values are used.

3. Variation of critical frequencies with sunspot activity. The seasonal and sunspot-cycle variation of the observed noon values of f_0E, f_0F1 and f_0F2 at Kjeller and Tromsø is shown in Fig. 1. There is a clear positive correlation between

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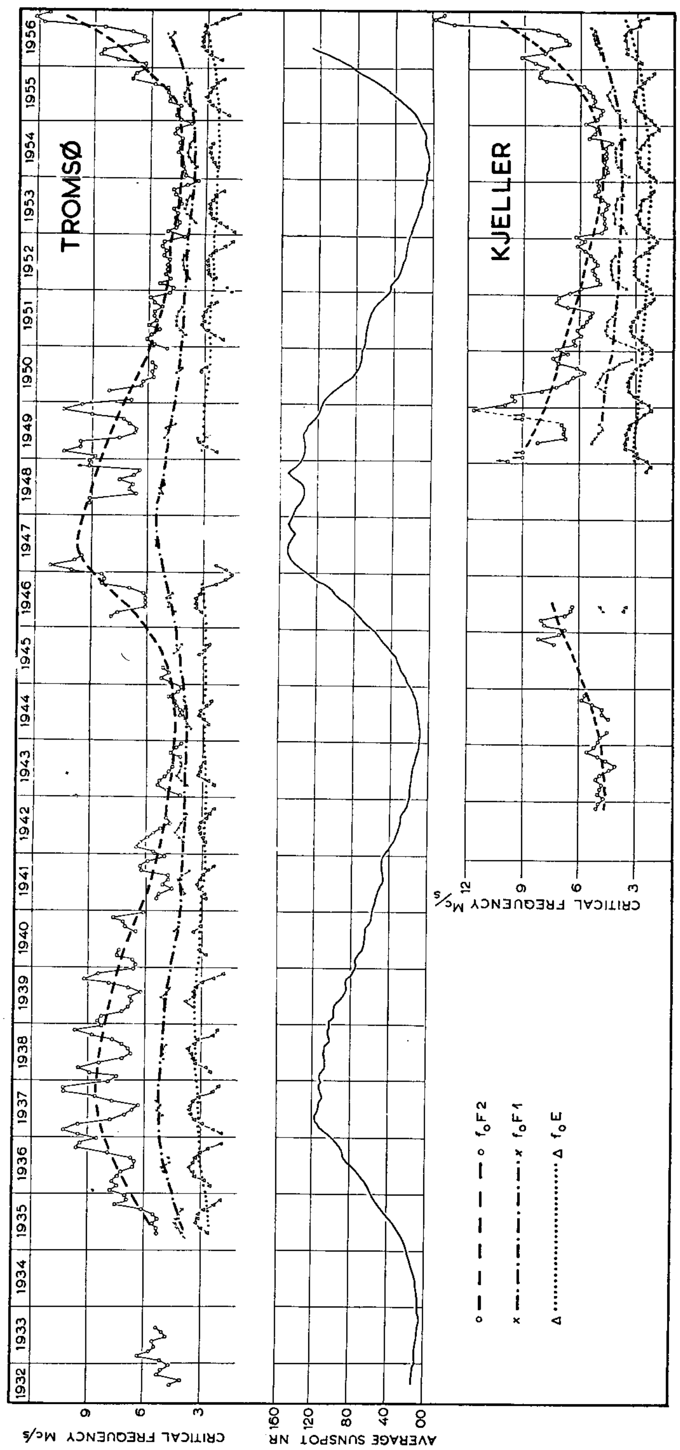

Fig. 1. The mean variation of the *noon* values of f_0F2, f_0F1 and f_0E observed at Tromsø (above), Kjeller (below) and a 13-monthly running mean of the relative sunspot number.

Table 2.1. *Observations at Tromsø* (69.7° N, 18.9° E).

Period	Parameters	Observers
Aug. 1932 — Aug. 1933	f_0F2	Appleton et al.
Apr. 1935 — Dec. 1940	all	Auroral Observatory
Jan. 1941 — Dec. 1945	f_0E and f_0F1	—,,—
Mar. 1941 — Apr. 1945	f_0F2	German Occupation Forces
Apr. 1946 — Dec. 1956	all	NDRE

Table 2.2. *Observations at Kjeller* (59.9° N, 11.0° E).

Period	Parameters	Observers
Nov. 1942 — Dec. 1944	f_0F2	German Occupation Forces
Oct. 1945 — Jun. 1946	all	Norwegian Air Force
Nov. 1948 — Dec. 1956	all	NDRE

the solar activity and the critical frequencies, and the seasonal variation increases with increasing sunspot activity.

According to the simplified formula of Chapman [2], the critical frequency for the *E*- and the *F1*-layer should vary as:

$$f_0\,(\Phi\,,\,d\,,\,\tau\,,\,W) = f_1\,(W)\cdot\cos^n\chi\,(\Phi\,,\,d\,,\,\tau) \tag{3.1}$$

where Φ is the hour angle (being zero at local noon), d the number of the day in the month, τ the number of the month, W the sunspot number, and χ the solar zenith angle. Equation (3.1) is expected to be roughly valid for values of $\chi \lesseqgtr 85°$.

In this section the variation of the critical frequency with solar activity will be studied, and in section 4. the variation with solar zenith angle will be treated.

The correlation between the critical frequency and sunspot activity will be studied, using a thirteen monthly running mean of the sunspot number ($\bar{W}$) to represent the sunspot activity. In order to eliminate the effect of varying solar zenith angle (see eq. 3.1), values of the critical frequencies obtained at the same hour and for the same month for all years will be selected for the study. Examples of the correlation plots are given in Figs. 2 to 5.

a. E- and F1-layers. In Fig. 2 the noon values of the critical frequencies for the *E*-layer are plotted against $\bar{W}$ for the twelve months of the year for the station at Tromsø. In the illustration (and also in Figs. 3 to 5 and Figs. 12 to 13) the following legend will be used:

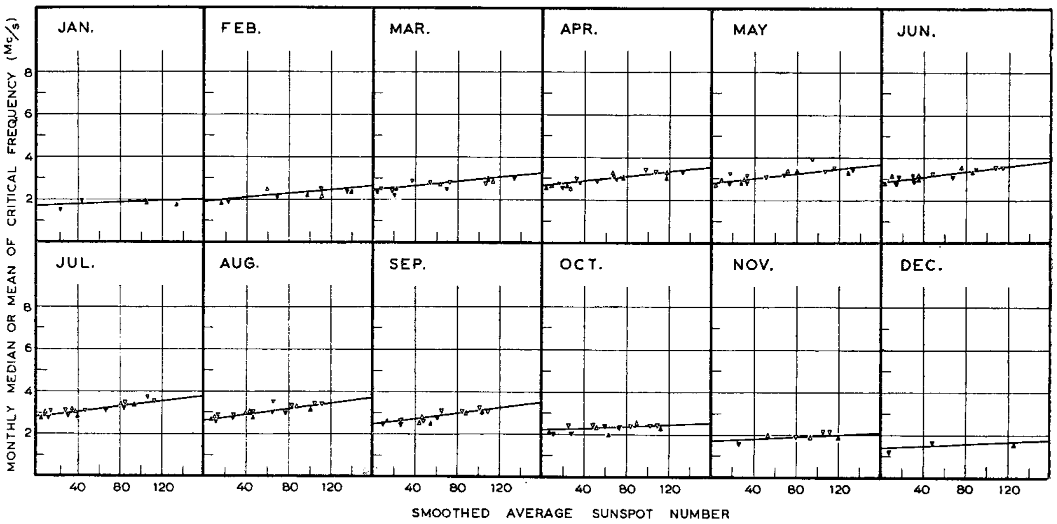

Fig. 2. Noon values of f_0E plotted against sunspot number for Tromsø.

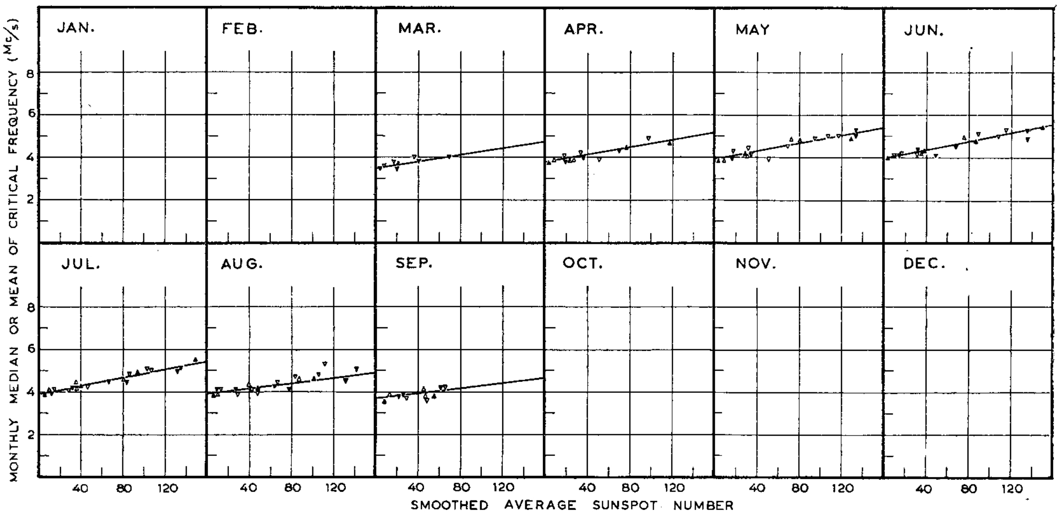

Fig. 3. Noon values of f_0F1 plotted against sunspot number for Tromsø.

Table 3.1. *Noon values of a* (Tabulated in thousandths of Mc/s).

	J	F	M	A	M	J	J	A	S	O	N	D
Kjeller:												
E-layer	2.0	5.5	4.5	6.0	5.0	4.5	4.5	4.5	5.0	4.5	2.5	2.0
F1-layer	—	1.0	5.0	7.5	10.0	9.0	8.5	6.0	5.0	5.5	—	—
Tromsø:												
E-layer	2.0	3.5	5.5	5.5	5.5	6.5	6.0	6.5	6.5	2.5	2.0	2.0
F1-layer	—	—	8.0	8.5	9.0	10.0	9.5	6.0	6.0	—	—	—

▲ — Data obtained by NDRE, increasing sunspot activity.
▼ — —,,— decreasing —,,—
△ — Older data, increasing sunspot activity.
▽ — —,,— decreasing —,,—

Similar plots are presented for the *F1*-layer in Fig. 3. We see that quite a good linear relationship is found between the parameters, and also that the sensitivity α, defined as:

$$\alpha = \frac{df_o}{dW}$$

is greater in the summer than in the winter in agreement with theory. This effect is more pronounced for the *F1*-layer than for the *E*-layer as will be seen from Table 3.1, where the deduced values of α are given for the twelve months of the year, for the two layers and for the two stations. It also follows from this table that there is little difference of the sensitivity between the two stations.

The correlation plots also show that the older data give higher frequencies at the same sunspot number than those observed by NDRE. It is difficult to decide whether this is a significant effect or an effect caused by changing of equipment and to some extent scaling procedure. The same effect is also found for the *F2*-layer.

b. F2-layer. For the *F2*-layer, correlation plots similar to those given in Figs. 2 and 3 have been made for the times 0000 and 1200 MET, and examples of these are given in Figs 4 and 5. It is beyond the scope of this paper to discuss whether there really exists a linear relationship between f_0F2 and $\overline{W}$, but we have tried to draw regression lines. The sensitivity index α is defined as the angular coefficient of these lines.

The seasonal variation of the noon- and the midnight values of α is shown in Fig. 6. We see that the noon values of the sensitivity do not follow a Chapman law, in fact the index shows a clear minimum in the summer when $\cos \chi$ has a maximum, and a clear maximum in the winter both at Kjeller and at Tromsø. There is no marked difference in α for the two stations, the difference in χ being approximately 10°. For the midnight values, on the other hand, there is a marked difference for the two sta-

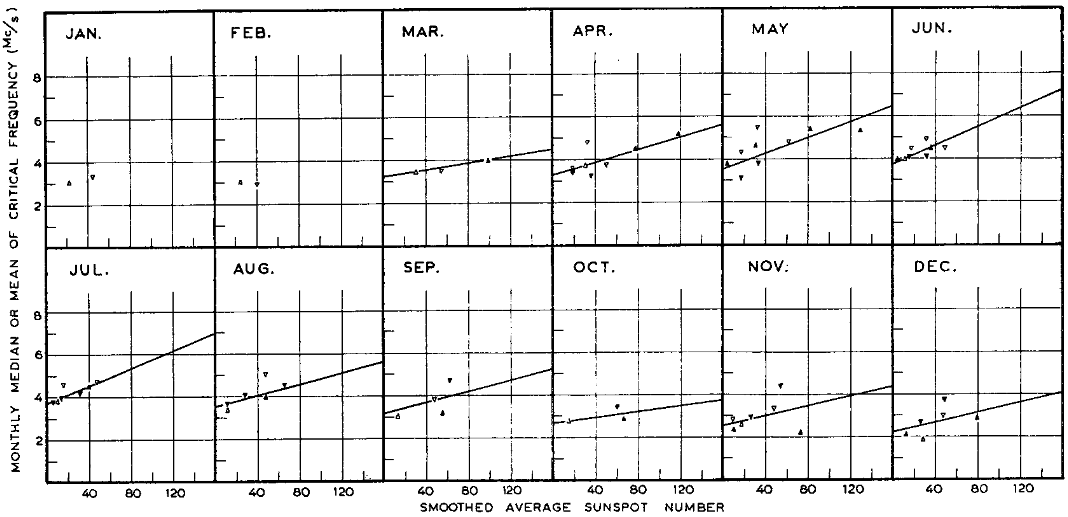

Fig. 4. Midnight values of f_0F2 plotted against sunspot number for Tromsø.

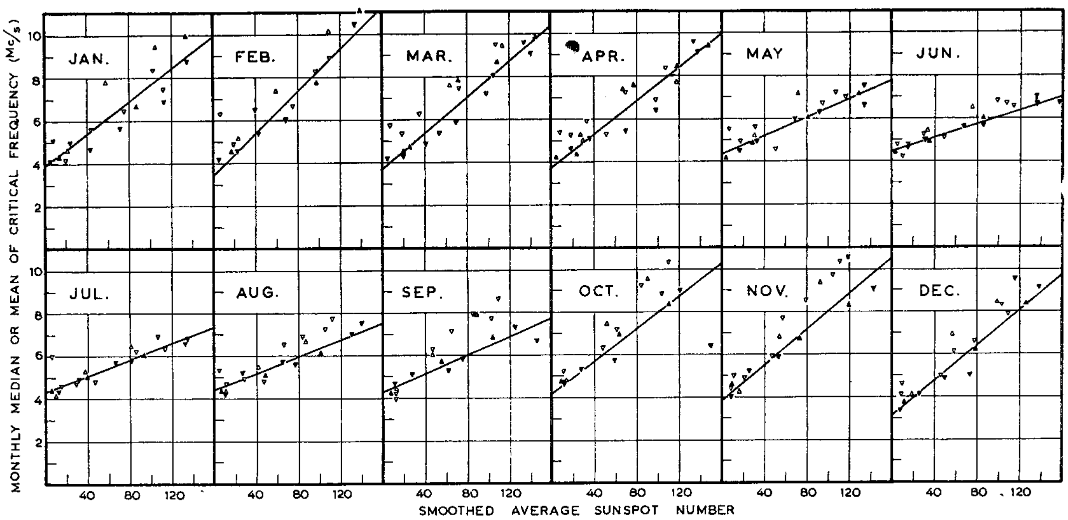

Fig. 5. Noon values of f_0F2 plotted against sunspot number for Tromsø.

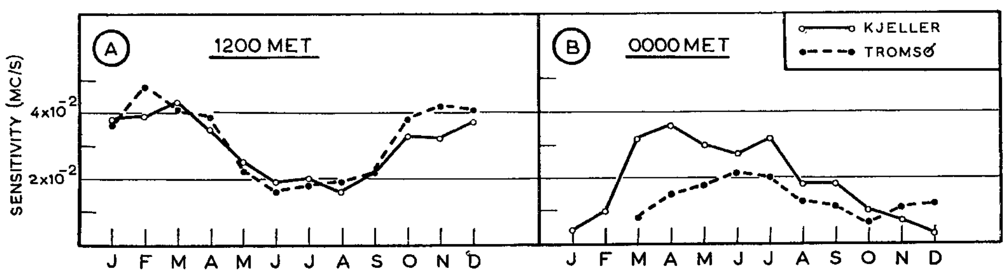

Fig. 6. Seasonal variation of the sensitivity of f_0F2 to sunspot activity.

tions. Here both curves show a clear maximum in the summer, and the values deduced at Kjeller are considerably higher then the Tromsø-values most of the year.

4. The diurnal variation of f_0E and f_0F1. In this section we will study the diurnal variation of the monthly medians of the critical frequencies for the *E*- and *F1*-layers, and calculate the exponent *n* in equation (3.1) from the observed values.

We assume that the diurnal variation of the solar zenith angle on the 15th of each month is representative for all days of the month, and define a quantity:

$$\Gamma(\Phi, \tau) = \frac{f_0(\Phi, \tau, W)_{med}}{f_0(o, \tau, \overline{W})_{med}} = \left[\frac{\cos\chi(\Phi, \tau)}{\cos\chi(o, \tau)}\right]^n$$

where $f_0(\Phi, \tau, \overline{W})_{med}$ is the monthly median value of the critical frequency. Plots therefore of $ln\ \Gamma(\Phi)$ against $ln \cos\chi$, for each month, should give straight lines, and the coefficient *n* may be obtained.

a. Observed results. We have deduced Γ-values for f_0E and f_0F1 for each hour of the day and the twelve months of the year. Such values have been deduced for each year when observations have been made by the NDRE, and the mean values $\overline{\Gamma}(\Phi, \tau)$ for those years have been determined.

The observed relationship between $ln\ \overline{\Gamma}(\Phi)$ and $ln \cos\chi$ at Kjeller are shown in Figs. 7 and 8 for the *E*- and *F1*-layers. Similar plots are also made for Tromsø. Quite a good linear relationship is observed when the solar zenith angle is less than 80 to 85°.

In order to study the seasonal variation of the coefficient *n* this is plotted as a function of month in Fig. 9 for the two stations and the two layers. n_E increases rapidly from February to April and so decreases more slowly. n_{F1}, which is considerably less than n_E, shows no marked variation in those months when the layer is observed.

There is a certain latitude variation both in n_E and in n_{F1} most of the year, increasing latitude giving decreasing *n*. In order to study this point more closely, values of *n* deduced from observations made at Longyearbyen, Spitzbergen (78.2° N, 15.6° E) have also been plotted in Fig. 9. This station has been in regular drift since June 1956. The values from Longyearbyen support the suggestion that *n* decreases with increasing latitude. The effect is most apparent for the *E*-layer. This latitude variation is in accordance with results of Scott [3]. Table 4.1 comprises the values of n^E and n_{F1} for some Canadian stations as observed in the months May, June and July 1949 and the values of the same parameters for the same months obtained from Fig. 9.

We have found that the variation of the critical frequencies for the *E*- and *F1*-layers may be described by equation (3.1), and that the coefficient *n* shows seasonal and latitude variation. In order to study whether there is any variation of *n* with the sunspot number $\overline{W}$, we have compared the observed values of $\Gamma(\Phi, \tau)$ for each year

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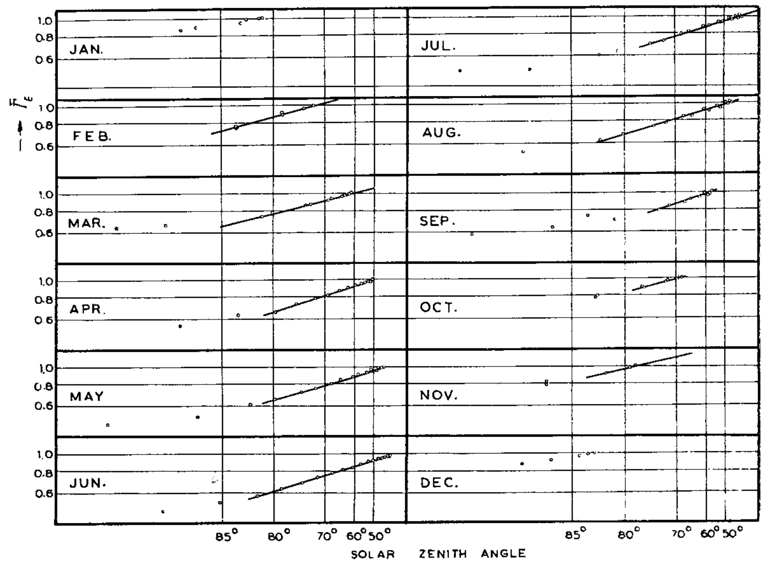

Fig. 7. The normalized critical frequency of the *E*-layer ($\overline{\Gamma}_E$) plotted against the solar zenith angle (χ) for Kjeller.

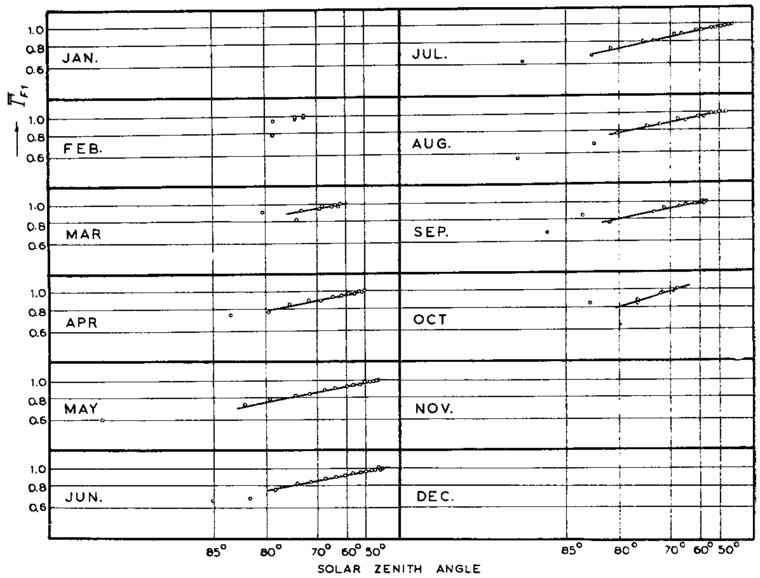

Fig. 8. The normalized critical frequency of the *F1*-layer ($\overline{\Gamma}_{F1}$) plotted against the solar zenith angle (χ) for Kjeller.

Table 4.1. *The mean cosine powers for the summer months.*

	Kjeller	Tromsø	Port. La Prairie	Baker Lake	Resolute Bay
n_E	0.33	0.30	0.27	0.25	0.25
n_{F1}	0.20	0.16	0.22	0.21	0.18

with the mean value for all years. According to URSI bulletin no 97 (1956) the year-to-year change of χ (Φ, τ) is only 4–5 $^0/_{00}$. If there were no connection between n and the sunspot activity, we could therefore assume that the diurnal variation of Γ (Φ, τ) would be the same from year to year. In our study we found that the departure from $\bar{\Gamma}$ never exceeded 5–6 %.

5. The spread of the observed values of f_0F2. In this paper only the monthly medians of the critical frequencies have been used. For radio-communication it is also of interest to study the deviation of the daily observations from the monthly medians. A short investigation of this kind has been made for the critical frequency of the *F2*-layer by means of the observed *quartile range.*

The quartile range $\triangle$ for a certain hour and month is defined as the frequency difference between the upper and lower quartiles of the observed values throughout the month. Only observations made at Kjeller at 0000 and 1200 MET have been treated.

In Fig. 10 the observed values of $\triangle$ are plotted against the median values of f_0F2 for the two hours. It is found that $\triangle$ increases with increasing frequency. The correlation coefficient at decreasing sunspot activity is found to be 0,55 and 0,58 for 0000 and 1200 respectively.

In the illustrations, lines are drawn for constant values of percentage spread, defined as:

$$S = 100 \frac{\triangle}{(f_0F2)_{med}}$$

We see that the observed values of f_0F2 show a greater spread by night than by day. For instance by night 50 %, and by day less than 10 % of all the observations give values of S greater than 30.

In Fig. 11 the deduced values of $\triangle$ are plotted against $\overline{W}$. It is found that $\triangle$ increases slightly with sunspot activity, but the correlation between the parameters is not very high. For decreasing sunspot activity the correlation coefficient is 0,40 and 0,43 for 0000 and 1200 MET respectively.

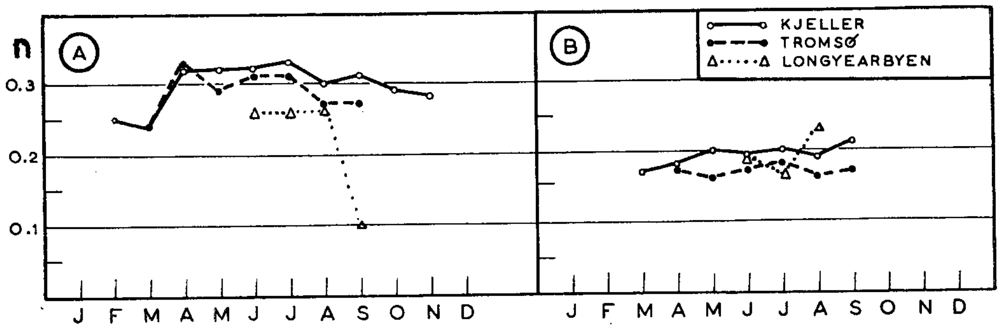

Fig. 9. The seasonal variation of the coefficient n. A refers to the E-layer and B to the $F1$-layer

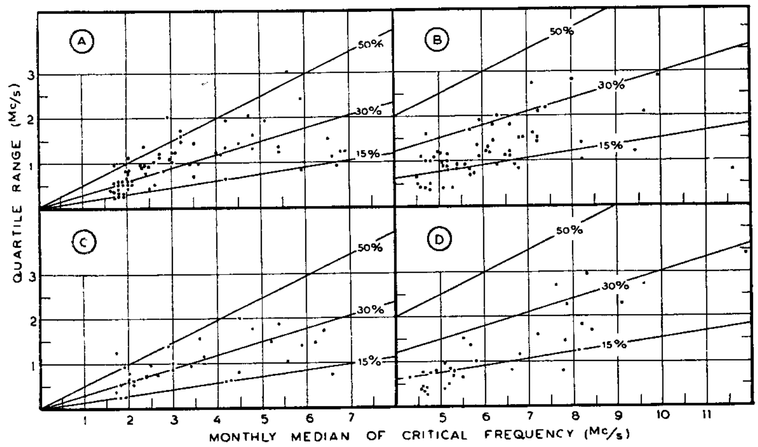

Fig. 10. Quartile range plotted against the monthly median value of f_0F2 for Kjeller. A: midnight-values and B: noon-values at decreasing sunspot activity, C: midnight-values and D: noon-values at increasing sunspot activity.

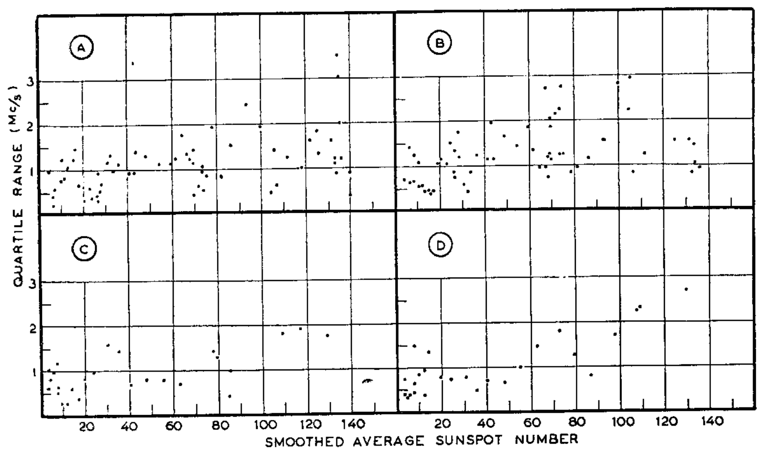

Fig. 11. Quartile range of f_0F2 plotted against sunspot number for Kjeller (See Fig. (10)).

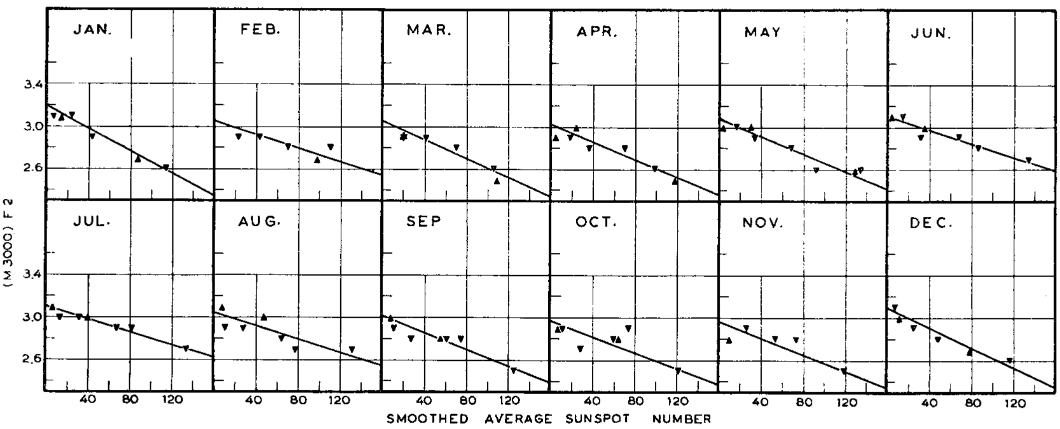

Fig. 12. Midnight-values of the transmission factor $(M3000)$–$F2$ plotted against sunspot number for Kjeller.

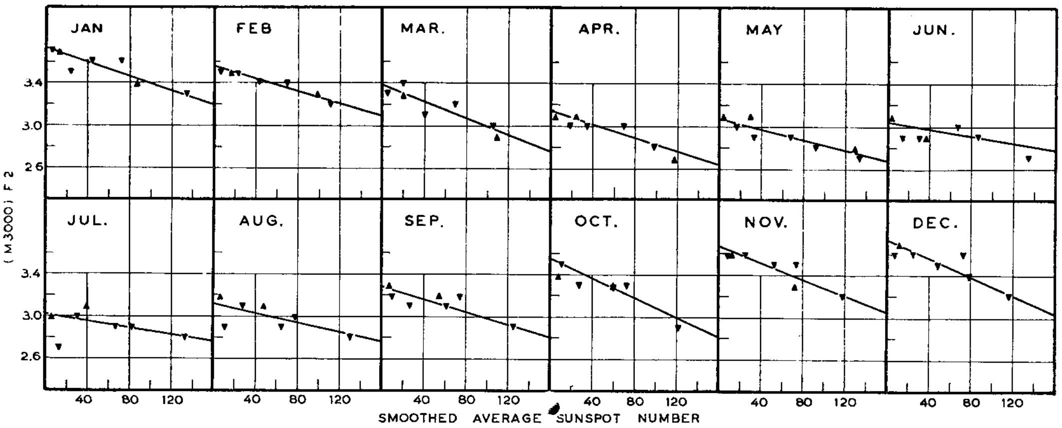

Fig. 13. Noon-values of the transmission factor $(M3000)$–$F2$ plotted against sunspot number for Kjeller.

6. Variation of $(M3000)$–$F2$ with sunspot activity. The transmission factor $(M3000)$–$F2$ is defined as:

$$(M3000)\text{–}F2 = \frac{MUF\,(3000)F\,2}{f_0F\,2}$$

where $MUF(3000)F2$ is the maximum usable frequency for radio communication over 3000 km via the $F2$-layer. This parameter has been scaled in the time period when observations have been made by the NDRE. The method introduced by Smith [4] has been used to evaluate the parameters.

In Figs. 12 and 13 are shown correlation plots between $\overline{W}$ and the monthly median of the noon- and midnight-values of $(M3000)$–$F2$, respectively, observed at Kjeller. Similar plots have been made for the values obtained at Tromsø. A good

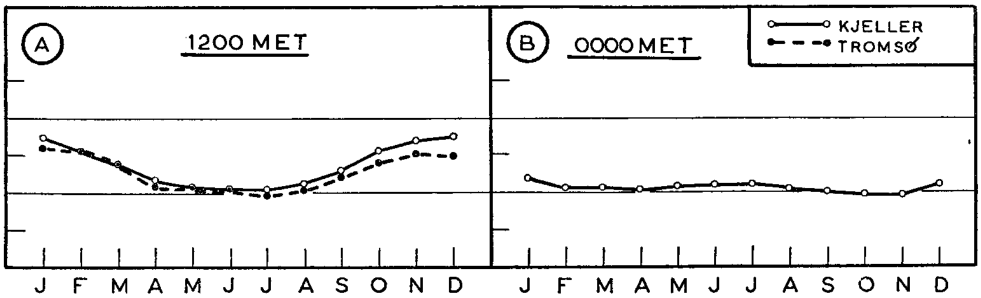

Fig. 14. $(M3000)$–$F2$ when reduced to zerosunspot number.

linear relationship is found between the parameters. This result is in agreement with the conclusion of Eyfrig [5] for observations at Huancayo. He found correlation coefficients between –0,90 and –0.99. It therefore seems reasonable to assume that the variation of the monthly median value of M may be described by the following formula:

$$M(\Phi, \tau, \overline{W}) = A(\Phi, \tau) - B(\Phi, \tau) \cdot \overline{W}, \tag{6.1}$$

where A and B varies with the hour angle Φ, number of the month τ, and with geographical latitude and longitude. This is the same assumption as made by Theissen [6].

The seasonal variation of A is shown in Fig. 14. We see that the noon values have a quasi-cosinusoidal variation.

It seems therefore reasonable to write:

$$A(O, \tau) = a - b \cos \chi \ (O, \tau). \tag{6.2}$$

where $\chi(O, \tau)$ is the solar zenith distance at noon. The correlation between $\chi(O, \tau)$ and A is a good as — 0,98 and — 0,92 for Kjeller and Tromsø respectively. The values of a and b deduced for the two stations are:

	a	b
Kjeller	3,88	1,05
Tromsø	3,65	0,86

The variation of the midnight values of A are shown only for Kjeller. No marked seasonal variation is observed.

In Fig. 15 the calculated values of B are plotted, and it is found that B has a more complex seasonal variation than A. The noon values of B show a maximum in March and October and a minimum in the summer at both stations. The midnight values of B are only plotted for Kjeller. A clear minimum is found in the summer and a more

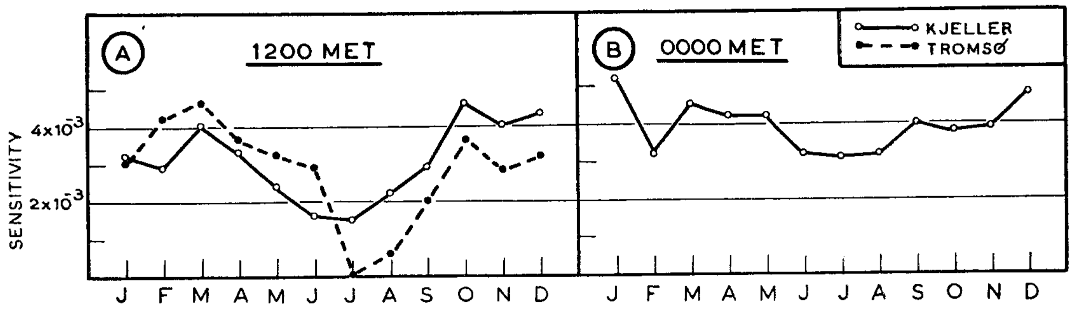

Fig. 15. Seasonal variation of the sensitivity of $(M3000)$–$F2$ to sunspot activity.

doubtful in February, and a well defined maximum occurs in January. The seasonal variation of B is greater for the noon values than for the midnight values.

The observed seasonal variations of A and B are in good agreement with those deduced by Theissen [6], who worked only with stations at lower latitude.

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