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The Effect of Low Energetic Electrons in the Polar Ionosphere*

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Abstract. Measurements of the dispersive Doppler effect of the 150/400 MHz signals of the five orbiting US-NNSS satellites provide with good accuracy, the integral electron content I of the ionosphere as a function of geographic latitude φ. The research reported here was based on I (φ)-curves calculated at Oulu, Finland and such from Lindau/Harz. They enable to study the behaviour of the main trough in I. Data from winter 1972 were compared with relevant *FoF2* data measured at Freiburg, FRG; Lindau, FRG; Juliusruh, GDR; Uppsala and Lycksele, Sweden; and Sodankylä, Finland. On November 11th 1971 an effect was observable which was not reported yet. The electron content I showed in the latitude range 60° to 65° N in the time interval from 1600 UT to 1700 UT a strong increase towards north. The relevant *FoF2* curve at 1700 UT showed a *reverse* behaviour. At earliest one hour later the *FoF2* showed again a trend similar to that of I. If the increase of I was caused by precipitating low energetic particles the above mentioned time delay of at least one hour leads to the conclusion that the increase was caused by precipitating electrons with energies less than 100 eV.

Key words: Precipitation — Electrons — Electron Content — Dispersive Doppler Effect — Satellite Beacons — Gradients — Critical Frequencies — Dayside Plasma Trough — Subpolar Ionosphere.

Introduction

The 150 and 400 MHz signals of the five orbiting US-NNSS satellites have been recorded at Lindau/Harz (FRG) since 1970 and at Oulu (Finland) since 1971. Identical measuring equipment has been used. The satellites have an almost circular polar orbit, the altitude is approximately 1100 km above the surface of the earth. The evaluation of the Dispersive Doppler Effect (DD) (Schmidt, Tauriainen, 1970; Ebel, Hartmann, Leitinger, Schmidt, Schödel, 1969; Hartmann, Oberländer, Schmidt, Schödel, 1972; Hartmann Tauriainen, 1973; Tyagi, 1973) yields with good accuracy the total electron content (TEC) I as a function of geographic latitude φ of the subionospheric point. The results presented here are based on total electron content data from Lindau and Oulu. They were selected thus that the geographic longitudes of the subionospheric points were located between 10° east and 25° east. The I (φ)-curves from winter 1971 are compared with the relevant *FoF2* data from Freiburg (FRG), Lindau (FRG), Juliusruh (GDR), Uppsala (Sweden), Lycksele (Sweden) and Sodankylä (Finland). A phenomenon which has not yet been observed is reported here.

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*To Prof. G. Pfotzer in honor of his 65th birthday.

1. Negative Horizontal Gradient

Due to the nearly circular polar orbits of the NNSS-satellites the horizontal gradient of the total electron content I can be defined as follows.

$$G_R \overset{!}{=} \mathrm{d}I/\mathrm{d}\varphi \neq O \tag{1}$$

where φ represents the geographic latitude of the relevant subionospheric point. If there would be a clear dependance from the zenith distance χ of the sun there should be observable a decrease in I with decreasing χ, e.g.

$$\mathrm{d}I/\mathrm{d}\varphi > O \quad \text{if} \quad \mathrm{d}\chi/\mathrm{d}\varphi < O \tag{2}$$

$$\mathrm{d}I/\mathrm{d}\varphi < O \quad \text{if} \quad \mathrm{d}\chi/\mathrm{d}\varphi > O \tag{2a}$$

Data which did not satisfy these conditions were selected for the following investigation. This phenomenon was defined "Negative horizontal gradient of the total electron content I".

Rai and Hook (1967) and Liszka (1969) reported variations of I during winter months. On magnetic quiet days as well as on disturbed days I (φ) displayed temporarily "unusual" behaviour. The recent detailed comparison between the negative horizontal gradient of I and *FoF2* data revealed an additional yet unknown effect.

2. Results

a) Data from November 11th, 1971

Fig. 1 shows the electron contents I and critical frequencies *FoF2* as functions of the geographic latitude, respectively invariant latitude Λ. The I (φ)-curves represent data which were continuously measured therefore the lines are drawn fat. The critical frequencies were only available for Freiburg (FR), Lindau (LI), Juliusruh (JU), Uppsala (UP), Lycksele (LY), and Sodankylä (SO). This data was connected by a thin line in order to indicate that the thus drawn curve may deviate considerably from the actual continuous unknown *FoF2* (φ)-curve. If in the following the *FoF2* (φ)-curve is mentioned this special graphical representation is under consideration. The abscissa in the lower part of the figure represents the geographic latitude φ that in the upper part the invariant latitude Λ. The ordinate to the right displays the critical frequency *FoF2* in MHz, that to the left indicates the electron content I per m^2 [el/m^2] times 10^{-16}. Eight *FoF2* (φ)-curves between 1500 UT and 2200 UT and five I (φ)-curves are given. The first (fat dotted) was calculated from Lindau data of the NNSS satellite 30180 during its passage at 1600 UT. The second (solid line) was calculated from data of the satellite 30120, recorded in Oulu at 1700 UT. The last three curves were calculated from Lindau data of the satellites 30130—1932 UT —; 30130—2120 UT —; and 30140—2341 UT. This day had slight magnetic activity. During the measuring period the following *Kp*-indices were reported. 1) 12—15 UT $Kp = 3-$; 2) 15—18 UT $Kp = 2$; 3) 18—21 UT $Kp = 4+$; 4) 21—24 UT $Kp = 3-$. *Ap* was 16 that day. Rai and Hook (1967) defined similar observations

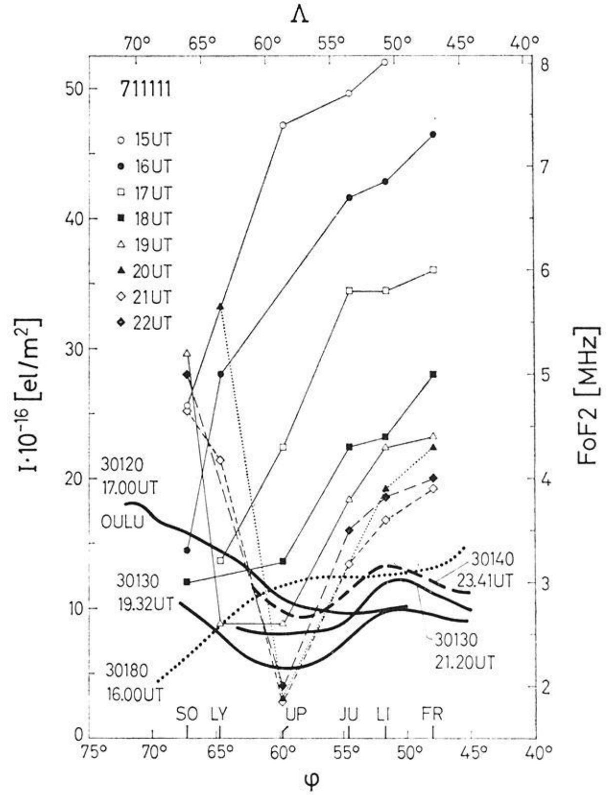

Fig. 1. Electron content I and critical frequency *FoF2* as a function of geographic latitude φ, respectively invariant latitude Λ within the latitude range 10° east and 25° east, calculated for Nov. 11th, 1971, in the time interval 1500 UT to 2400 UT. The ordinate to the right displays the critical frequency *FoF2* [*MHz*], that to the left indicates the electron content I per m² [el/m²] times 10^{-16}. $I(\varphi)$-curves denoted with Oulu were calculated with data measured in Oulu. Those without denotation were calculated with data measured in Lindau. The numbers 30120, 30130, 30140, 30180 and 30190 give the international nomenclature of the five US NNSS satellites. Time is given in Universal Time (UT). Local time in Lindau is Central European Time (CET) = UT + 1 hour. Local time in Oulu is Eastern Eropean Time (EET) = UT + 2 hours

"quiet" as long as *Ap* was less than 15 and the *K* index of College, Alaska, as well as *Kp* were less than 2.

The two most important curves are the first and second $I\ (\varphi)$-curve. At 1600 UT $I\ (\varphi)$ shows in the latitude range 60° to 65° N a strong decrease. At 1700 UT $I\ (\varphi)$ shows a strong increase in this range. Sodankylä displays an increase in I from 6×10^{16} el/m² to 16×10^{16} el/m², e.g. by a factor of three. Stations further north exhibit an even stronger increase.

Similar increases of I were reported by Liszka (1966) in northern Scandinavia, by Rai and Hook (1967) in Alaska, and by Stuart (1972) in New Zealand. Liszka as well as Rai and Hook assumed that precipitating low energetic particles were the cause of this unusual increase. They had available only data from a single low orbiting satellite. Hence a denser time sequence of I (φ) data was impossible and thus comparisons with other ionosphere data like *FoF2* were very difficult. Due to the now orbiting five satellites these comparisons can be carried out more efficiently.

A comparison between the I (φ)-curves and the *FoF2* (φ)-curves reveals the following: The *FoF2*-curve at 1600 UT (black circles) decreases towards north like the relevant I(φ)-curve (dotted). The *FoF2*-curve at 1700 (open squares) *decreases* up to 65° N, the station Lycksele. The data from Sodankylä is missing, so there is no clear statement possible whether the curve is decreasing even further north. On some other days in November, magnetically quiet and disturbed ones, at 1700 the minimum of the trough was observed already overhead Lycksele, that means that at that time there is already an increase of the *FoF2*-curve from Lycksele towards Sodankylä. These increases of the critical frequencies were reported by several authors (Möller, 1967). The relevant I (φ)-curve at 1700 UT however *increases* within the whole measuring range (solid curve). The *FoF2* curve at 1800 UT (solid squares) shows in the range 60° to 70° latitude a very weak decrease. Recent new reductions of ionograms kindly supplied on request by Mr. A. Hedberg. (Uppsala) revealed that the *FoF2* data from Lycksele — which was missing at the time when the figure was drawn — was smaller than that from Sodankylä and Uppsala. This means that the actual *FoF2* curve decreases up to Lycksele and then starts again increasing towards north. The *FoF2*-curve at 1900 UT as well as the following three ones show clearly the well known trough. The third I (φ)-curve (1932 UT), the fourth (2120 UT), and the fifth (2141 UT) clearly reveal the trough in electron content I.

b) Discussion

The comparison of the I (φ)- and *FoF2* (φ)-curves yielded the following:

I) The electron content showed in the latitude range 60° to 65° N in the time interval from 1600 UT to 1700 UT a strong increase towards north. The relevant *FoF2* (φ)-curve at 1700 UT showed a *reverse* behaviour. At the earliest one hour later the *FoF2* showed again a trend similar to that of I (φ).

II) Overhead the station Lycksele the electron content I increased during this time interval by a factor of 1.7, however the cirtical frequency *FoF2* decreased by a factor of 1.5. There are no statements possible for the time interval 1700—1800 since there were no I and *FoF2* data available.

I and II lead to the conclusion that the behaviour of the I (φ)-curves and the *FoF2* (φ)-curves show a time delay of approximately *one* hour in the early evening. Roughly spoken *FoF2* lags behind I about one hour. If the increase of I (φ) was caused by precipitating low energetic particles the above mentioned time delay of at least one hour leads to the suggestion that the increase was caused by precipitating electrons with energies less than 100 eV. Electrons with higher energies would penetrate at least to the maximum of the *F2*-layer, e.g. the increase in I and *FoF2* should occur simultaneously. The increase of I towards north during early evening hours in winter was reported also by other authors, however this time delay between I and *FoF2* is reported the first time. Whether this phenomenon is only observable during medium or stronger magnetic activity or whether it is generally related with the formation phase of the trough cannot be decided yet due to the few data available for comparisons. However the first statement seems to be more likely. This is supported by statements presented by Chappell (1972) about regions of detached plasma in the dayside plasma trough. Mass spectrometers on board both OGO 3 and OGO 5 have measured masses of ambient plasma enhanced density levels that are detached from the main body of the plasmasphere. These masses of plasma are present across the dayside of the plasma trough, with particular concentration in the afternoon-dusk local time sector. Approximately 70% of the total number of detached plasma instances occurred following periods of moderate to high magnetic activity. ($Kp > 3^-$ in the previous 24 hours). Whether these regions of detached plasma can explain at least partially the above mentioned effect is not clear yet and needs further investigations.

Tyagi (1974) used Stubbe's (1973) modified model to calculate I and $FoF2$ up to about 60°. Beyond that the ion- and heat-production due to precipitated electrons has been added to that program. The observed effect could not be explained satisfactorily by these model calculations. The model seems to be not very much suited for the study of transient phenomena. However if the EUV model which is used as the background for the calculation of ionization due to low energy precipitating electrons can be improved so as to reproduce the observed latitudinal gradients in the EUV ionization zone ($\leqslant 60°$ N), then it may be possible to reproduce both the trough and gradient reversal at the beginning and ending of trough formation using appropriate precipitating flux. The application of another model (Mayr *et al.*, 1972) was not taken into consideration due to a statement given by the authors that disagreement with experiment above 60° is to be expected. Above 60°, at the plasmapause and beyond, H^+ is depleted by electric field convection and polar wind escape which is not included in that study. A review on plasmapause — plasmasphere problems (Carpenter; Park, 1973) gave no indication that an applicable theoretical model of the plasmapause — trough region is available. This was supported by a very recent review about exospheric models of the topside ionosphere. (Lemaire, Scherer, 1974). Even if there are mainly the applications of kinetic theory to the collision-free domains of the terrestrial atmosphere are reviewed. Thus it seems fairly unlikely that an unambiguous theoretical explanation of this effect will be available in the near future.

c) Difficulties by Comparing the *I* and *FoF2* Data

The fact that in many cases the ionogram reductions from Uppsala, Lycksele and Sodankylä were not possible — mainly due to spread *F*-limited the number of comparisons drastically. Thus only this one clear effect could be presented. In cooperation with colleagues from Finland (University Oulu) and from Sweden (Uppsala) a coordinated measuring program of I and $FoF2$ has been started this winter to obtain more data. The problem of ionogram reduction however is still present. Nichol (1973) showed the close relation between the trough phenomenon in subpolar latitudes and the occurrence of spread *F*. This also explains the simultaneous observation of satellite scintillations which can be investigated also by using the signals of the NNSS satellites (Hartmann, 1972; Schmidt, 1972). During very strong scintillation cases the reduction of the dispersive Doppler effect (DD) for calculating I is also impossible. Due to the fairly high observing frequencies (150 MHz/400 MHz) the "I reduction" fails in much fewer cases than the "$FoF2$ reduction".

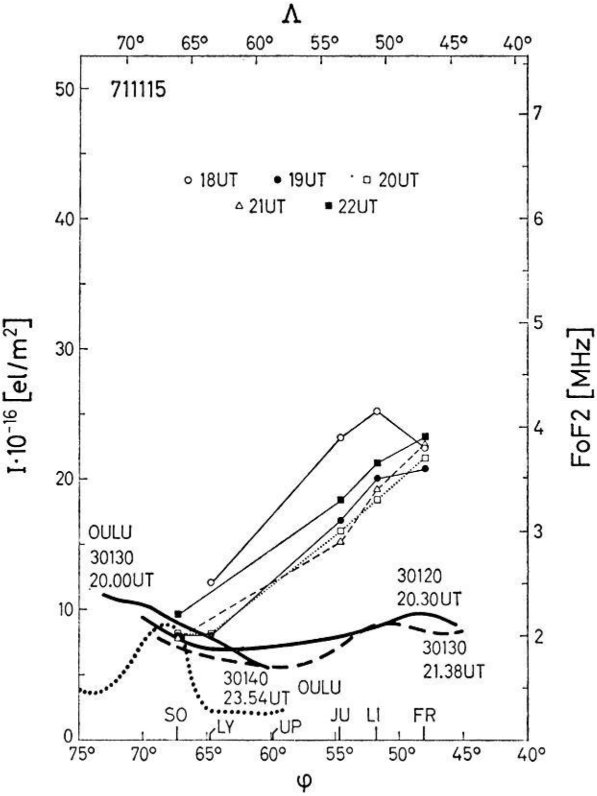

Fig. 2. Same nomenclature as for Fig. 1, however the I (φ)- and *FoF2* (φ)-curves were displayed for Nov. 15th, 1971, in the time interval 1800 UT–2400 UT

A comparison with other satellite data, especially particle measurements was not possible since there were no such data available for the relevant time period. The following example may briefly show the difficulties of such comparisons. There were available particle data from INJUN 5 from February to June 1971 which should be compared with electron content data from the NNSS satellites. There were 42 cases, for which satellite INJUN 5 and one of the five NNSS satellites were observable — with respect to our station Lindau — in the range 10° longitude (east) ±15° and 52° latitude (north) ±10°, simultaneously within one hour time interval. Data are referred to the subsatellite points. The final comparison revealed that only for *one* day (Feb. 25) a true comparison of I data from the NNSS satellites and the particle data from INJUN 5 was possible. Further comparisons of the I (φ) data with bottom side data were also impossible.

Fig. 2 displays the electron content I and the critical frequency *FoF2* calculated for Nov. 15th, 1971 for the time interval 1800 UT to 2400 UT as a function of geographic latitude φ, respectively invariant latitude Λ. ($Ap = 2$). This is another example for an increase of I towards north (2000 UT) and a subsequent formation of the trough. Since *FoF2* data from Uppsala are missing for the time intervall 1800 UT

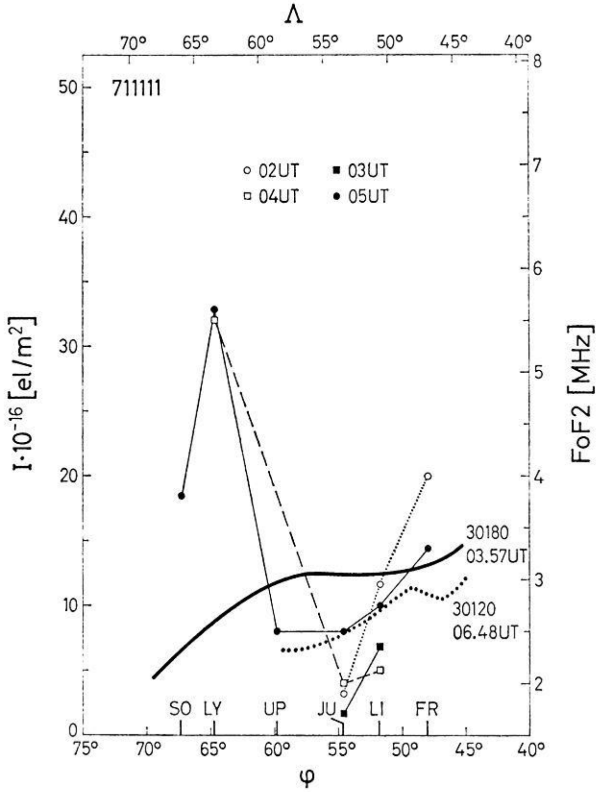

Fig. 3. Same nomenclature as for Fig. 1, however the I (φ)- and $FoF2$ (φ)-curves were displayed for Nov. 11th, 1971, in the time interval 0200 UT–0700 UT

—2200 UT and those from Lycksele for 2100 UT and 2200 UT no statement about a time lag between I and $FoF2$ is possible. This is just one example out of many similar cases.

Fig. 3 displays the electron content I and the critical frequency $FoF2$ again calculated for Nov. 11th, 1971 ($Ap = 16$) for the time interval 0200 UT to 0700 UT as a function of latitude. Both I (φ)-curves show a decrease towards north. The few $FoF2$ data available for this time period enable no reasonable comparison between I and $FoF2$. If the $FoF2$ (φ)-curve drawn for 0400 UT should represent to a first approximation the actual continuous $FoF2$ (φ) behaviour then we would have an increase in $FoF2$ in the range 60° to 65° N latitude but a decreasing I-curve. This would be a behaviour reverse to that observed in the early evening (Fig. 1).

Fig. 4 displays the electron content I and the critical frequency $FoF2$ calculated for Dec. 3rd, 1971 ($Ap = 4$) for the time interval 0900 UT—1500 UT as a function of latitude. I (φ) shows a behaviour which is abnormal for that time of day. It displays an increase towards north. $FoF2$ reveals very strong variations. The general tendency of the I (φ) and $FoF2$ (φ)-curve is pretty much the same.

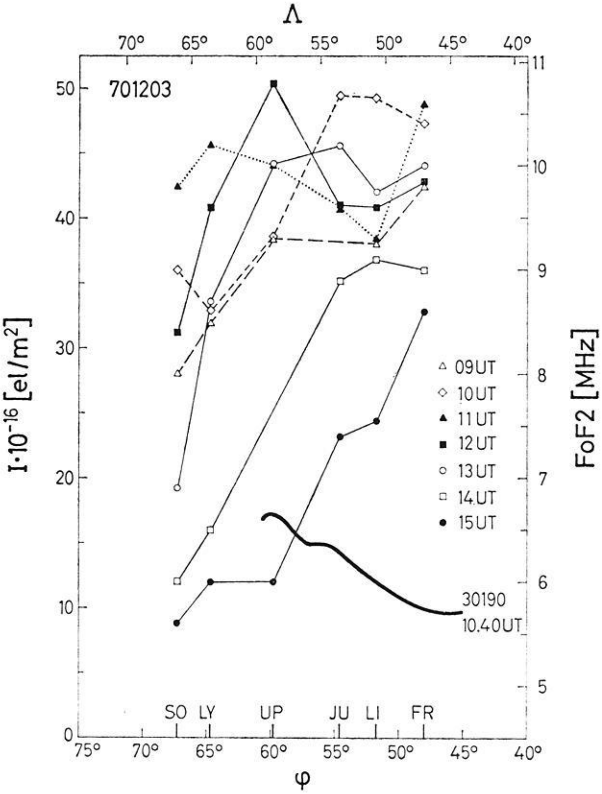

Fig. 4: Same nomenclature as for Fig. 1, however the *I* (φ)- and *FoF2* (φ)-curves were displayed for Dec. 3rd, 1971, in the time interval 0900 UT–1500 UT

d) Final Remarks

If, by the just planned coordinated measuring program, further data might be obtained which give further support of this pretented one hour time delay between *I* and *FoF2* during early evening hours in winter and if there will be a satisfactory theoretical explanation, then it seems to be possible to measure the effect of low energetic electrons (<100 eV) in subpolar regions by the described procedure. In our specific case the following data are required.

a) *I* (φ)-curves from Oulu and Lindau

b) *FoF2* data from Freiburg, Lindau, Juliusruh, Uppsala, Lycksele and Sodankylä.

Even if finally there will be not sufficient relevant data for this proposed comparison — due to spread *F*, satellite scintillations or other distortions — already the calculated *I* (φ)-curves may reveal new useful informations, especially if it is possible to gather data in a dense time sequence during the formation phase of the trough or also during its deformation phase. This seems to be very valuable for an improvement of the various theories about the trough formation and its relation to the plasmapause which are not yet in agreement.

The recently started investigations of irregularities in the polar ionosphere by means of holography (Schmidt, 1972), which are also based on observations of the 150 MHz and 400 MHz signals of the NNSS satellites should be carried out simultaneously. A cooperation with colleagues from Oulu has been already started.

These measurements should be supplemented by radar echoes measurements like those carried out by Hagfors *et al.* (1970). They showed that strong radar echoes occurred in the absence of observable electron precipitation but were in close time and spatial coincidence with proton precipitation, although the proton contribution to the ionization at the scattering height at 112 km was computed to be negligible compared with the solar ionization.

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