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Electron content measurements in the auroral zone using GPS: preliminary observations of the main trough and a survey of the degree of irregularity in summer

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Abstract—Ionospheric electron content was monitored from sites in or near Tromsø, Norway, for six months of 1993, using the transmissions from the satellites of the Global Positioning System (GPS). The data have been used for preliminary studies of two important phenomena of the high-latitude ionosphere: the main trough and the incidence of large irregularities. The latitude and motion of the trough were determined on several occasions during the spring period, and the results compared with previous data. Best agreement is with the formula of Collis and Haggstrom (1988). The incidence of large irregularities was surveyed during a four-month period, approximately from the summer solstice to the autumnal equinox, and the variation with time of day and magnetic activity has been determined. It was found that irregularities are considerably larger by night than by day, but that they are enhanced during both periods by increased magnetic activity. Statistical results are presented. It is suggested that these irregularities are the same as the "auroral blobs" previously studied by incoherent-scatter radar. Copyright © 1996 Elsevier Science Ltd

INTRODUCTION

The auroral ionosphere is the most disturbed and irregular region of the terrestrial ionosphere, being affected directly by charged particle precipitation, by instabilities produced by electric currents and by large scale convection, none of which affects the mid-latitude regions to any significant extent. The variations in the electron content of the ionosphere can be significant for various radio systems, for example in communications or radar, since the propagation delay is affected and irregularities cause scintillation phenomena. Such problems are likely to be more severe at high latitude, particularly in the auroral regions.

The GPS (Parkinson and Gilbert, 1983) is now the principal means for measuring the electron content of the terrestrial ionosphere. However, to be set beside the great advantage of availability there are also some disadvantages. One is the high cost of reception equipment. Another is the nature of the orbit, which gives tracks of limited duration—no more than 4 to 6 hours during which the ionospheric crossing point moves some 1000 km at ionospheric heights. The data therefore contain both time and space variations, which can present a complication in the interpretation of the data. In some cases, though, this could be an advantage.

The orbital inclination of 55° means that some satellites pass overhead at all latitudes up to 55°. Measurements at even higher latitudes can be made by siting a reception station closer to the pole. It is significant for our purpose that GPS enables observations of the electron content to be made in the auroral zone, something that has been difficult to achieve in the past. A further advantage over previous beacon satellites is that several GPS satellites are in view at any one time, allowing spaced measurements to be made simultaneously.

Probably the greatest problem is that each satellite has an individual "bias", due to a small relative time delay between the transmissions on the frequencies that are to be compared (for example, Sardon *et al.*, 1994). This makes it more difficult to obtain absolute values of the electron content, although relative values obtained from one and the same satellite are obviously not affected. Results from the present study depend on relative values only, and are not affected by the bias.

The present paper reports an exploratory inves-

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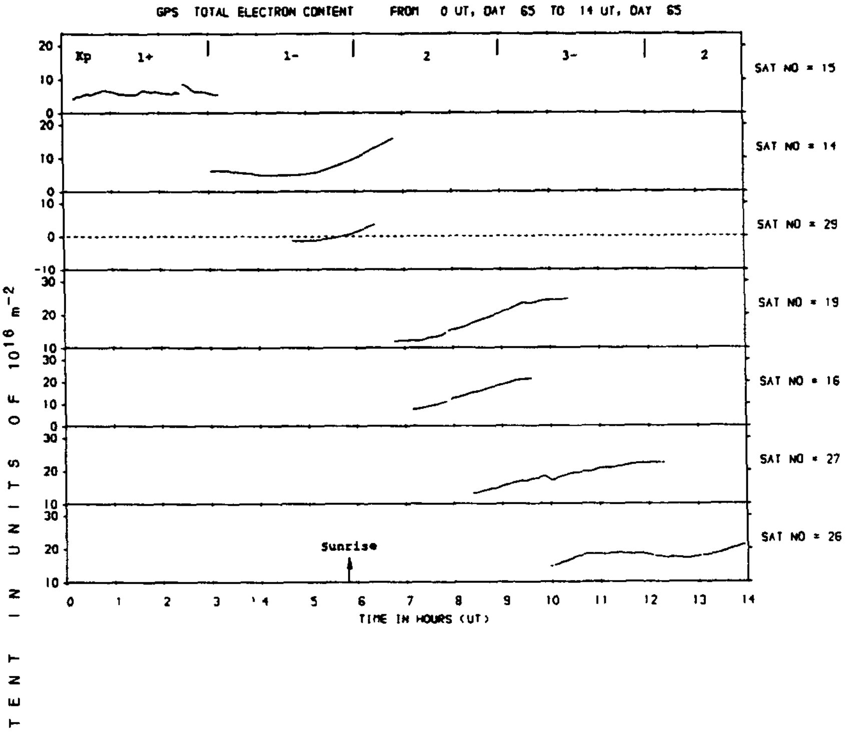
* Now in Engineering Department.

(a) Morning



(b) Evening

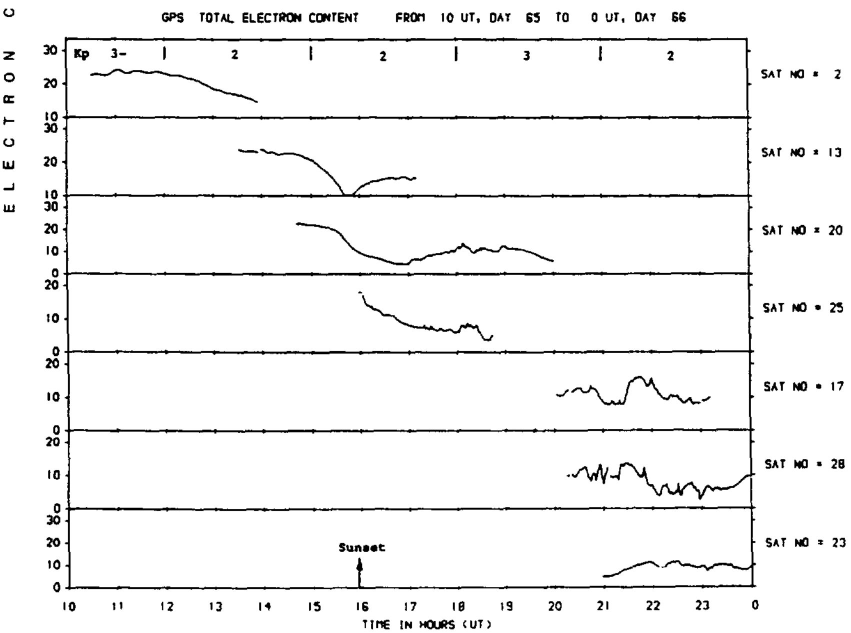


Fig. 1. Behaviour of the electron content on a magnetically quiet day (6 March 1993, $A_p = 8$) for (a) morning and (b) evening, showing a change of character after the trough. The number of the satellite being observed is marked to the right of each panel. The electron content has been corrected for obliquity at height 300 km by multiplying the slant value by the cosine of the zenith angle. Any negative values are due to the satellite bias.

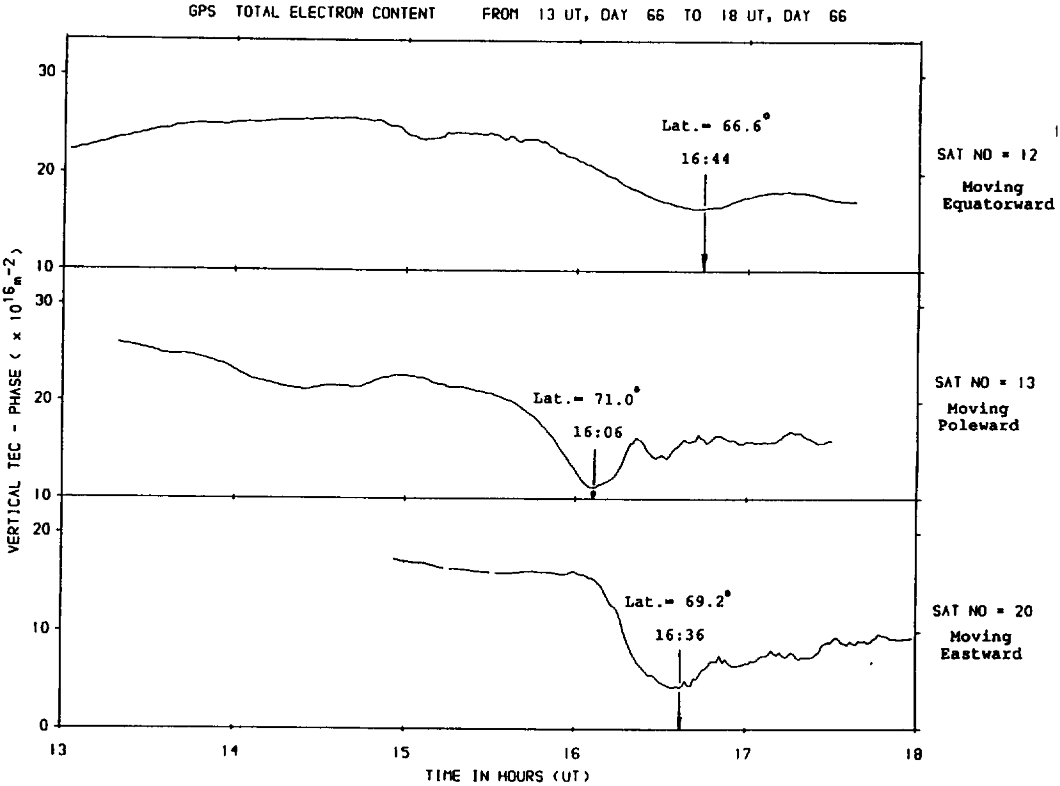


Fig. 2. Spaced observations of the trough on 7 March 1993 (day 66) using satellites 12, 13 and 20. The latitude and UT of each minimum is marked.

tigation of the application of GPS reception to studies of the electron content in the auroral region.

OBSERVATIONS

A GPS receiver (Osborne ICS-4Z) was operated at or near Tromsø from February to September 1993. The original site on the island of Ringvassøy (70.05°N, 19.04°E) proved to be unsuitable due to the unreliability of the mains power supply and, in June, the receiver was moved to Tromsø, some 40 km to the south. There it operated with minimal interruption, providing a virtually continuous data set of 4 months duration covering the period between summer solstice and autumnal equinox.

A PILOT STUDY—THE MAIN TROUGH

Observations

A pilot study was undertaken using 12 days from the Ringvassøy period (during March and April) in order to assess the value of the data and to indicate which topics should be selected for further study.

Figure 1a illustrates the behaviour of the electron content in the morning hours on a magnetically quiet day. Results for the afternoon and evening of the same day are shown in Fig. 1b. There is a striking change of character between day and night. Frequently, the day and night sections are separated by a major dip in the electron content. This is thought to be the main trough (Moffett and Quegan, 1983).

Spaced observations using three satellites (Fig. 2) show the trough occurring at different times in the different lines of sight, and from such cases we can get the position of the trough at different times and, thus, assuming an east-west extension, its motion in a north-south direction.

The sequence shown in Fig. 3 covered days of increasing magnetic disturbance. The trough appeared sooner at a given latitude on the more disturbed days. Drift speeds varied between 30 and 180 ms^{-1}.

Discussion

Several authors have published formulae relating the latitude of the trough to local time and magnetic

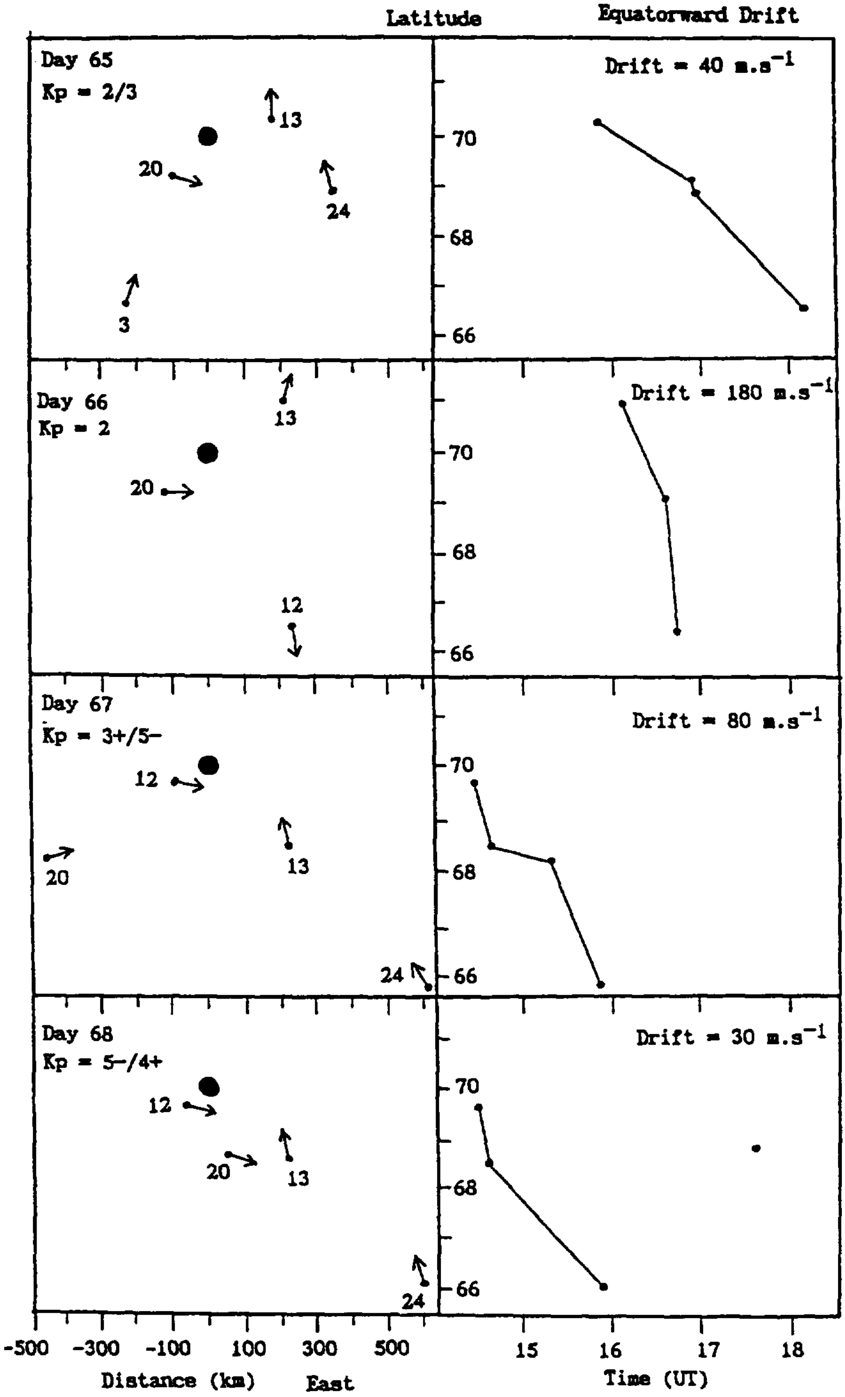


Fig. 3. An analysis of trough observations on four successive days, 6–9 March 1993. The diagrams on the left show the location of the observing station (solid circle) and the 300 km sub-satellite points of the satellites being observed with their directions of motion at the time of the trough crossing. The latitude is geographic The plots on the right show the variation of trough minimum against UT.

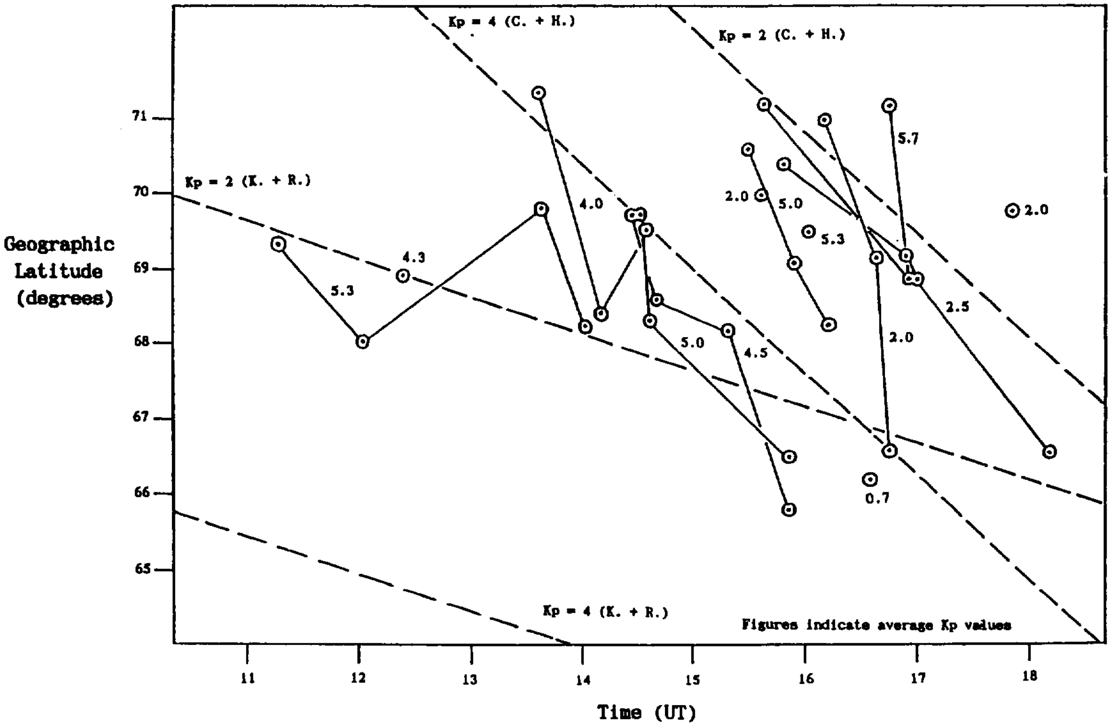


Fig. 4. Geographic latitudes of trough minima for 12 troughs observed in the pilot study. The dashed lines indicate the locations predicted by the formulae of Kohnlein and Raitt (1977) and Collis and Haggstrom (1988). Average K_p values are marked.

activity. The formula of Collis and Haggstrom (1988) agrees better than that of Kohnlein and Raitt (1977) with our present observations (Fig. 4). The difference is probably due to the method of observation. The Kohnlein and Raitt (1977) data were taken from a satellite in relatively low orbit, passing rapidly across the trough. Their formula therefore expresses an average of snapshops giving the location of the trough on separate occasions. Collis and Haggstrom (1988), on the other hand, tracked a number of troughs by incoherent-scatter radar and their formula expresses the motion of the troughs as well as their position. The present result also includes the trough motions. Figure 4 suggests that the rate of equatorward drift is greater than that due to the variation of the mean position of the trough with time of day.

IRREGULARITIES

Technique

A general survey of irregularities was made for the period when the data were almost continuous, June to September 1993. The tendency for there to be greater irregularity at night than by day had already been noted in the pilot study. It was also suspected that magnetic activity might be a factor in the incidence of irregularity.

In order to quantify the degree of irregularity a "roughness index" was devised:

$$R = \left(\frac{1}{3600}\right) \sum_{J=1}^{30} |\{I(J) - I(J+1)\}|$$

where I is the electron content and J is the number of the data sample between 1 and 30. The data samples are two minutes apart, and the formula gives the average change of content with time over periods of 1 hour, taking one second as the unit of time. It was applied to all passes having at least one UT hour of continuous data. Some 2000 values were derived in all.

Obviously, we expect that "rough" passes with large and rapid variations will produce a higher value of R than "smooth" passes. To provide a visual impression of the significance of the index, examples are shown in Fig. 5. We see that $R < 0.05$ means that the trace is essentially smooth, $R = 0.1$ to 0.2 means that there are irregularities of small magnitude, and $R > 0.5$ means there are large ones.

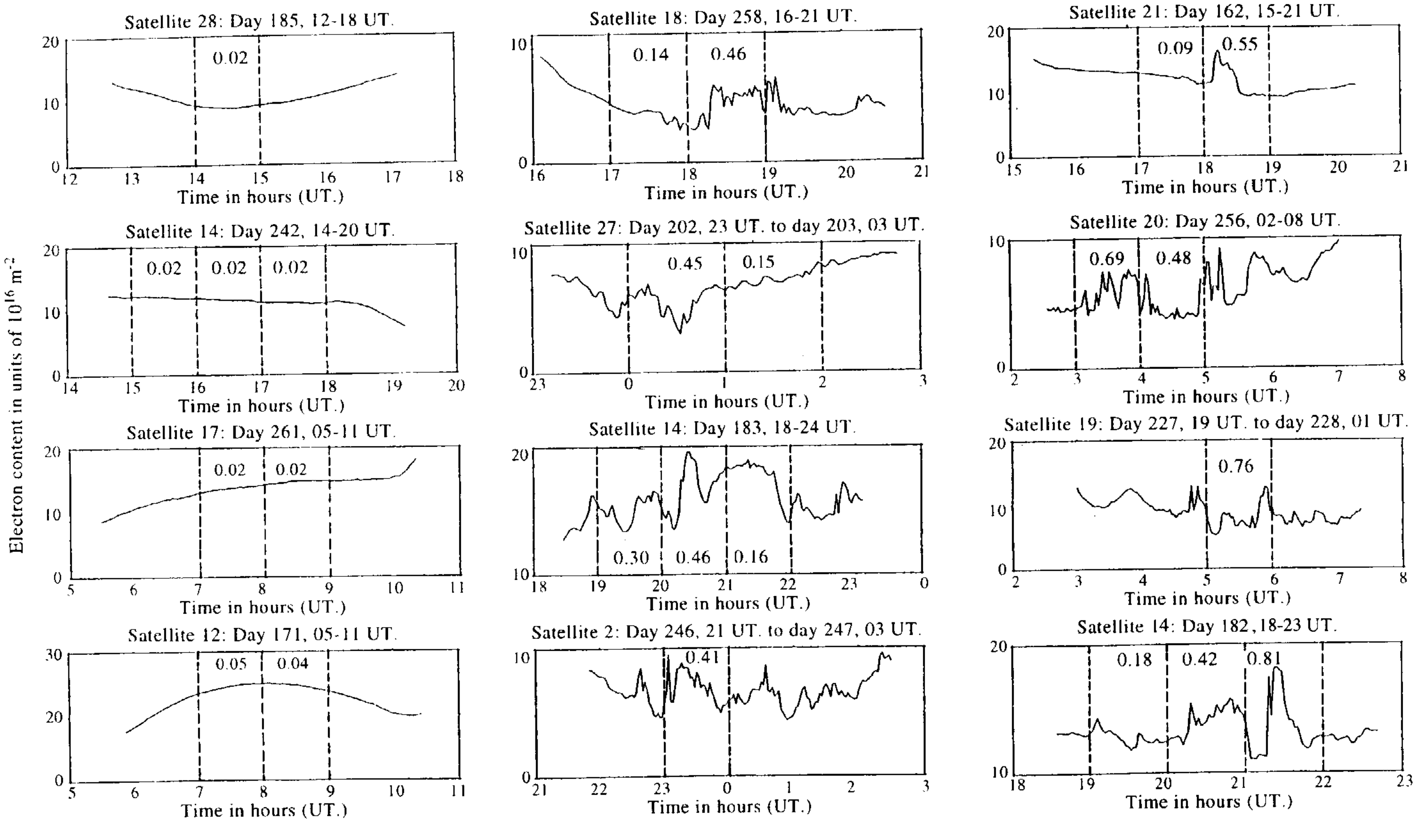


Fig. 5. Examples of traces to illustrate the significances of the Roughness Index: (a) $R < 0.05$; (b) $R = 0.05$–0.50; (c) $R > 0.50$. The vertical scale of each panel covers either 10 or 20 units of electron content. Individual values of R are inscribed within the hours to which they apply.

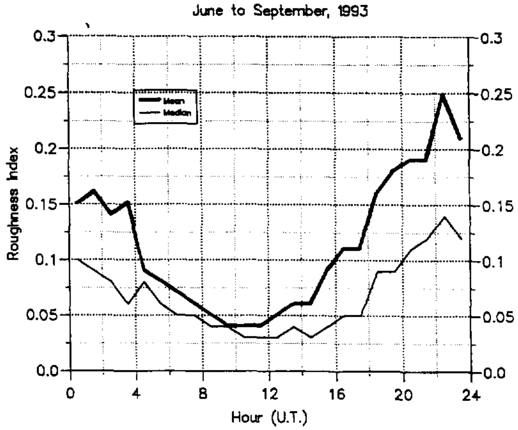


Fig. 6. Variation of hourly mean and median R with time of day, June to September 1993.

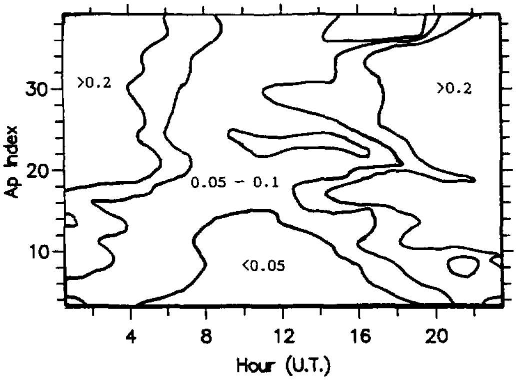


Fig. 7. Contour plot indicating variation of Roughness Index with A_p and time of day. Minor fluctuations of the contours are not significant.

Daily variation

Plots of roughness index against the time of day indicate that the magnitude of irregularity is considerably greater in the anti-sunward sector. Figure 6 shows the variation in terms of the hourly median and the mean values of R, here presented for all four months together because the results for individual months do not appear to be significantly different. The maximum occurs at 2200 UT and the minimum at 1000 or 1200 UT, i.e. close to magnetic midnight and noon, respectively. The ratio of maximum to minimum is about 6 and 5 for the mean and the median, respectively.

Influence of magnetic activity

In order to compare with magnetic activity, daily mean and median roughness indices have been plotted against A_p. There is a positive correlation, with a correlation coefficient of about 0.8. The regression equations are for the mean $R = 0.05 + 0.005\ A_p$ and for the median $R = 0.03 + 0.004\ A_p$.

To see whether the magnetic effect varies diurnally, three-dimensional plots were prepared. These include individual R values placed by the UT hour and the A_p for the day. Figure 7, which is a smoothed contour plot produced by UNIMAP graphics, shows a clear distinction between the sunward and anti-sunward sectors. The minor irregularities are no doubt statistical and of no significance, but some features are clear. Although R increases with A_p at all times of day, the effect is much stronger in the anti-sunward sector. In Fig. 7, those values are generally greater than 0.2 if A_p is enhanced, but note that values are smaller at low A_p, and it appears that R should be small if conditions are magnetically quiet. Values for the sunward sector are generally small (<0.1), but even lower values (< 0.05) occur when A_p is smaller than about 10. This plot includes all values from the period June to September, since the result appears to be essentially the same for each of the months studied.

The statistics of R for two four-hour periods, 2000–2400 UT and 0800–1200 UT, are shown in Fig. 8 for five levels of A_p. Plots (a) and (b) are on the same horizontal scale and illustrate the difference between those periods. In each, it can be seen that the values of R are generally greater when A_p is greater. Plot (c) is on an expanded horizontal scale to show the statistics of the sunward period more clearly. Here, R does not exceed 0.1 unless the magnetic activity is enhanced to some extent ($A_p > 10$). Below that, most values are no greater than 0.05.

Discussion

The irregularities studied above are not scintillations. As may be noted from Fig. 5, a typical duration is some tens of minutes and a typical magnitude is several units of 10^{16} m^{-2}. These figures suggest that the irregularities being observed are auroral "blobs", such as have previously been detected by incoherent scatter radar and whose horizontal scale is generally several tens of kilometres (Burns and Hargreaves, 1996). We therefore suggest that the present results may be taken to indicate the incidence of auroral blobs as a function of time of day and magnetic activity.

The results on the variation of roughness index with magnetic activity and time of day (as Fig. 6, for example) are almost the same for each of the four months, June to September. At first sight this is remarkable. Sunrise and sunset times vary greatly at auroral latitudes between solstice and equinox. In the

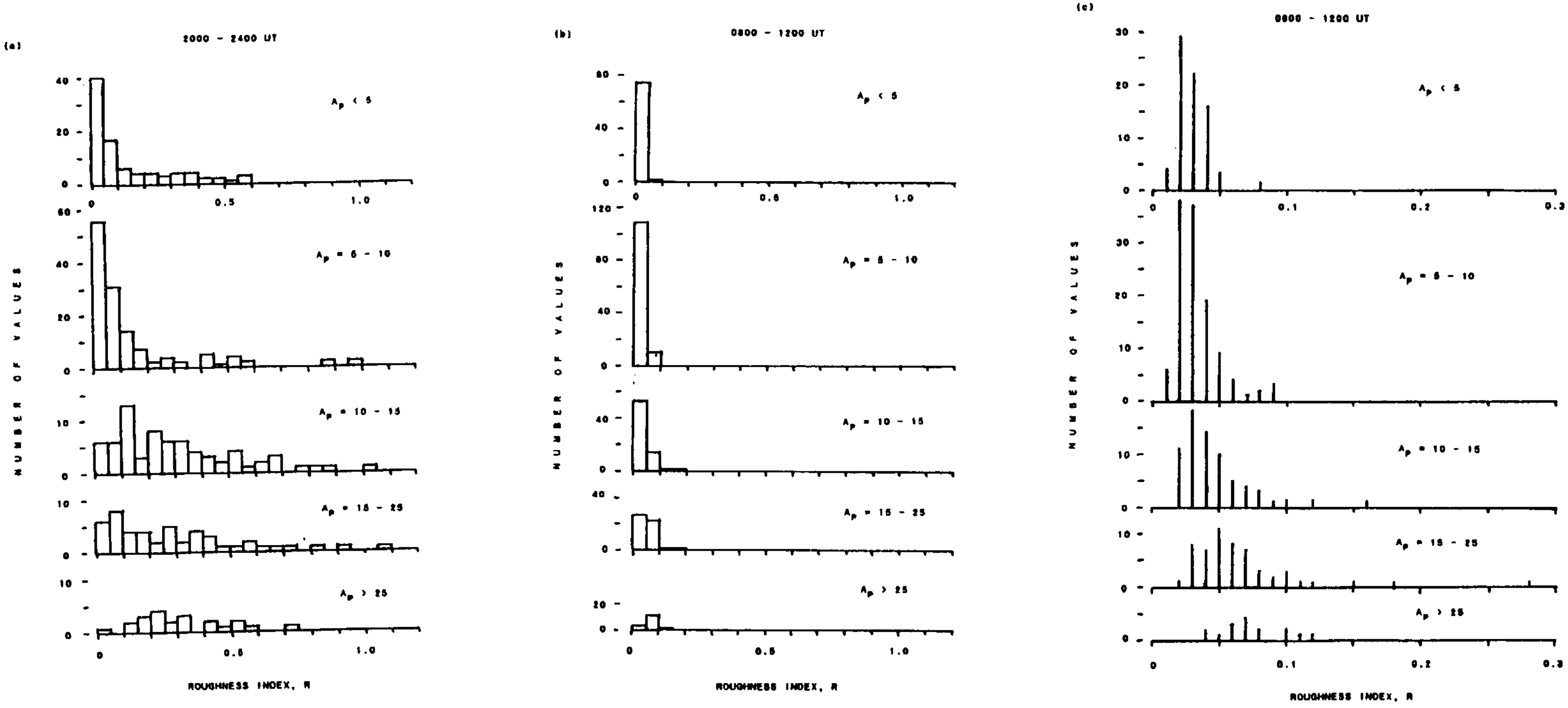


Fig. 8. Distributions of Roughness Index at five levels of A_p. (a) 2000–2400 UT; (b) 0800–1200 UT; (c) 0800–1200 UT with expanded scale of R.

middle of September, sunrise is at about 0400 UT and sunset is at about 1715 UT. But there is no ground darkness at all on 15 June or 15 July. Plainly, solar illumination is not a factor controlling the degree of irregularity. We presume, therefore, that the daily variation is due to geomagnetic effects, and is probably related to the circulation pattern of the polar F region. This would be consistent with what is known of the source of auroral blobs. Whether the daily variation would be different in winter, when there is little solar illumination at any time, is not known.

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