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DAYTIME VALLEY IN THE F_1-REGION OBSERVED BY INCOHERENT SCATTER

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Abstract—Incoherent scatter data obtained at Saint-Santin have been analyzed between 1969 and 1972 in the height interval 120–200 km. The summer daytime electron density profiles show a maximum around 150 km followed by a minimum around 165 km, when the solar activity is low. The seasonal and solar cycle variations of this phenomena are discussed. When the daytime valley exists, the maximum density is *ca*. 20–30 per cent greater than the minimum value. The phenomenon cannot be fully explained on the basis of photochemical equilibrium. A wind-shear mechanism could play an important role.

1. INTRODUCTION

Although ionosondes have been in operation all over the world for many years, very little is known about the structure of the electron density profile in the transition zone between the E and F regions. Improvements have been achieved in the interpretation of ionograms, but most of the reduction methods now available are not capable of determining possible valleys in the electron density profiles. This is the case for all methods dealing with only one trace, usually the ordinary trace because it appears most frequently in the ionograms. All methods are based on the inversion of an integral equation. The difference arises in the inversion procedure, but the methods all imply that the unknown electron density profile is a monotonic function of height. Such an assumption not only ignores the possible existence of a valley, but also introduces serious errors when a valley is present.

In order to get a rough estimation of the width (altitude range necessary for the electron density to recover its value after the depression) and depth of the valley, it is necessary to apply a numerical analysis to both the ordinary and the extraordinary traces (Wright and Smith, 1967). Besides the fact that the analysis is difficult and needs special care, the two traces are not always recorded on the same ionogram. Very often both traces are missing in the lower part of the F region because of sporadic E blanketing.

Figure 1 shows an ionogram obtained very close to the incoherent scatter sounder at Saint-Santin. The F_1 and F_2 layers are clearly distinct and their critical frequencies are easily obtained with good accuracy. The E layer is easily visible from the beginning of the ionogram up to 3 MHz. At higher frequencies the E layer is screened by a sporadic E layer, with the consequence that the f_0E frequency cannot be read. The Es layer becomes semi-transparent at approximately 3·4 MHz and a stratification, generally called $E2$, appears. Ionograms made at intervals of 5 min have been recorded several days before and after 21 June 1973. During most of that period the stratification is not apparent because of blanketing. Sometimes the trace is so faint that it is difficult to decide whether the stratification exists or not.

The above facts show how it has always been difficult to decide from ionosonde observations whether or not a valley exists in the lower part of the F_1 region.

Early rocket measurements obtained from phase differences between two continuous waves have shown, without any doubt, a depression in the electron density at approximately 135 km, i.e. above the E layer maximum (Seddon, 1953; Jackson, 1956). Aono *et al.* (1962) and Oya and Obayashi (1967) report from several rocket experiments that sometimes the electron density profile increases continuously and almost smoothly above the f_0E height. Results from an inverse Seddon experiment in Sardinia, Italy, do not show any valley for a daylight rocket flight on 4 October 1967, but a clear valley appears at 160 km a few days later (Jacobs *et al.*, 1969). At higher temperate latitudes, rockets carrying high-frequency impedance probes have measured electron densities up to 170 km without observing a daytime valley in January and in July 1969 (Andreyeva *et al.*, 1971). On 8 and 12 June 1971, an impedance probe on board a Véronique rocket was launched in the afternoon from Kourou, French Guyana. The first flight showed a daytime valley at 163 km, whereas the second flight indicated a monotonic increase of the electron density between 130 and 180 km (Neske and Kist, 1973). Many rocket experiments at mid-latitude launching sites have been performed at different local times and under different solar activity conditions (Maeda, 1969, 1972). It appears, however, to be very difficult to detect any general feature of the valley which is sometimes shown by the observations. These results and many others indicate a sporadic existence of a daytime valley in the F_1 region.

The lack of continuous rocket data makes it difficult to analyze the geophysical characteristics and variations of the daytime valley in the F_1 region. However, the incoherent scatter sounder at Saint-Santin has been regularly measuring electron densities in the E and F regions since 1967, i.e. data are available for maximum and minimum solar activity conditions. Furthermore, this technique does not suffer from the difficulties encountered in ionogram analysis when a valley is present.

In this paper the validity of the incoherent scatter data from Saint-Santin is discussed in relation to the daytime valley in the F_1 region. The geophysical characteristics of the valley observed at Saint-Santin are then presented as a function of solar activity, local time and seasons.

2. INCOHERENT SCATTER DATA

The incoherent scatter sounder at Saint-Santin (44°7N, 2°4E) emits a signal at 935 MHz through a narrow beam antenna (1°). In the same meridian 300 km to the north, the steerable antenna beam of a receiving station at Nançay intersects the emitting antenna beam at discrete altitudes between 90 and 600 km. The receiving signal due to scattering by electron density fluctuations is displayed as a frequency spectrum. Each frequency spectrum representative of an altitude is analysed to provide the electron concentration (n_e) proportional to the received power, the electron and ion temperatures (T_e, T_i) and a component of the ion drift obtained from the Doppler shift of the spectrum (Carru *et al.*, 1967).

The ion composition affects the shape of the spectrum and cannot be ignored especially in a transition region where the ratio $p = n(O^+)/n_e$ varies continuously from a small value in the E region to a value close to 1 at 250 km. The values of n_e, T_e and T_i deduced from the spectrum depend on the parameter p and are computed by assuming different values for p.

The estimated error on n_e, T_e and T_i is not larger than *ca.* 2–4 per cent, while the error in the ion drift is variable and more important. At each altitude the signal is integrated over 3–5 min depending on the signal-to-noise ratio. A profile, as shown in Fig. 2, is obtained in approximately half an hour. The rectangles define areas through which a

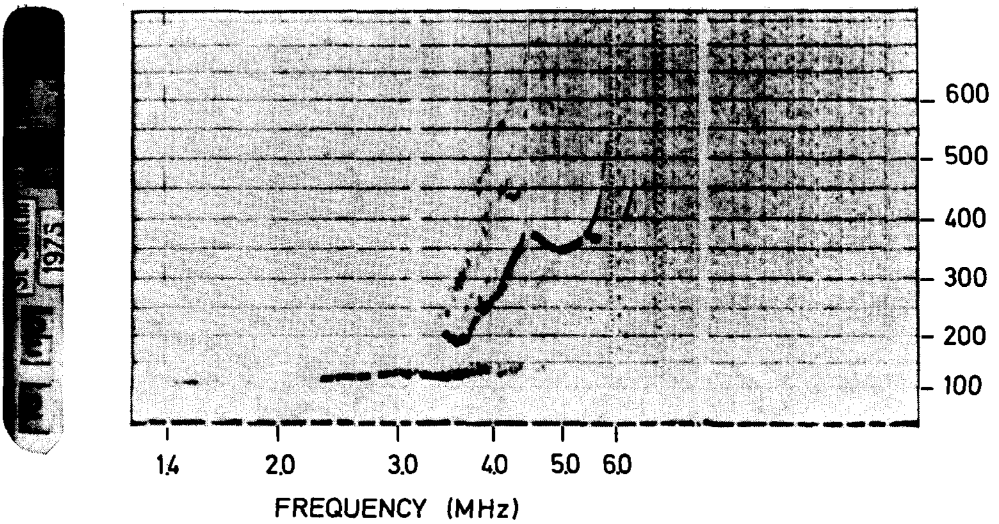

Fig. 1. An ionogram recorded at Saint-Santin on 21 June 1973.

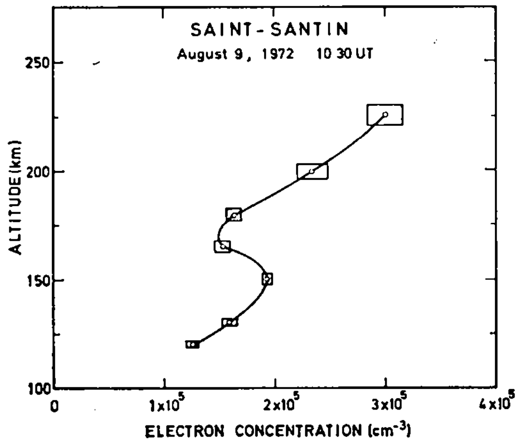

FIG. 2. ELECTRON DENSITY PROFILE IN THE TRANSITION REGION OBTAINED AT SAINT-SANTIN BY THE INCOHERENT SCATTER SOUNDER, 9 AUGUST 1972 AT 1030 U.T.

mean profile is drawn. The horizontal width of the area corresponds to the range of n_e values for different values of p. The width is, of course larger than the real error in the measured electron density. The vertical width corresponds to the altitude range of the volume defined by the intersection of the lobes of the two antennae. It increases with altitude as does the volume, but the electron density which results from the addition of all scattered waves in the volume is more representative of the center than of the upper or lower sides. The altitude of the center is determined with an accuracy much better than 1 km. The rectangles actually describe the most pessimistic situation for the profile accuracy. The daytime maximum around 150 km and the minimum around 165 km are therefore unambiguously detected. Vertical profiles similar to Fig. 2 have been detected on many occasions.

3. COMPARISON BETWEEN IONOGRAM AND INCOHERENT SCATTER PROFILE

The irregularity observed in the altitude range 120–170 km (see Fig. 2) should also be apparent on ionograms. Since the techniques are different, a one to one agreement cannot be expected. The incoherent scatter measurements need a five minutes integration time at a particular altitude and half an hour for the whole profile, while the same altitude range is explored in a few seconds by an ionosonde. Moreover, the reflected signal of an ionosonde is very sensitive to the aspect of the reflection area, with the result that the intensity of the returned signal is sometimes very faint and below the noise level.

Nevertheless, simultaneous observations of the irregularity have been obtained. Figure 3 shows the ordinary trace of an ionogram of 21 June 1973, and the plasma frequency computed from the electron density profile measured by the incoherent scatter sounder at the same time. The maximum electron density of the irregularity is $1{\cdot}76 \times 10^5$ electrons/cm^3 and agrees very well with the $f_0E2 = 3{\cdot}8$ MHz ($1{\cdot}79 \times 10^5$ electrons/cm^3) of the ionogram. The comparison between f_0E and the maximum electron density of the E region obtained from incoherent scatter measurements is difficult due to the screening presence of a sporadic E layer. However, the critical frequency f_0E can be extrapolated and seems to be approximately equal to $3{\cdot}2$ MHz ($1{\cdot}26 \times 10^5$ electrons/cm^3). The corresponding value obtained by incoherent scatter is smaller, namely $1{\cdot}15 \times 10^5$ electrons/cm^3.

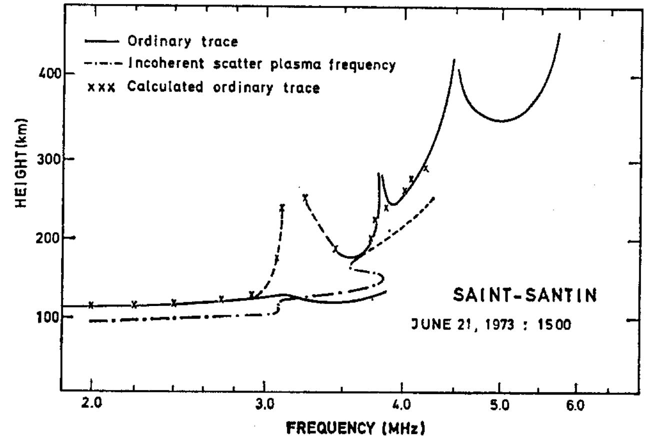

FIG. 3. COMPARISON BETWEEN ORDINARY TRACE CALCULATED FROM INCOHERENT SCATTER PROFILE AND ITS CORRESPONDING IONOGRAM ORDINARY TRACE.

From the electron density profile measured by incoherent sounder, the virtual heights of reflection have been calculated. The virtual heights of reflection are given by the integral equation

$$h'(f) = \int_0^{h(f)} \mu_0'(f, f_n, f_H, \theta)\, dh. \tag{1}$$

In this equation $\mu_0'(f, f_n, f_H, \theta)$ is the group refractive index for the ordinary wave (Budden, 1961), f_H is the electron gyrofrequency and θ is the angle between the vertical direction and the geomagnetic field. The last two quantities are assumed to be constant for a given location. The virtual height is a function of the observing frequency and of the plasma frequency f_n. With a change of variable, equation (1) can be written

$$h'(f) = \int_0^{f} \mu_0'(f, f_n) \frac{dh}{df_n}\, df_n. \tag{2}$$

Using the experimental n_e values, one obtains the function $h(f_n)$ by a least square method. The height dependence has been assumed linear or parabolic according to the shape of the electron profile. The whole $h(f_n)$ profile is therefore a series of linear and parabolic portions.

The results of the computation are represented by the crosses on Fig. 3. The agreement between the computed and the observed trace is sufficiently good to demonstrate that the incoherent scatter profile represents a real physical situation.

4. GEOPHYSICAL CHARACTERISTICS OF THE DAYTIME VALLEY

In order to study, in some detail, the behavior of the transition between the E and F regions, 60 days of incoherent scatter observations at Saint-Santin have been considered from 1969 to 1972. The general conclusions of such a study can be summarized from the typical profiles shown on Figs. 4, 5 and 6. These profiles are chosen to represent high and low solar activity conditions as well as winter and summer conditions.

Figure 4 shows three daytime profiles observed on 6 February 1969. The electron concentration increases monotonically with height up to the F_2 maximum. The profiles given

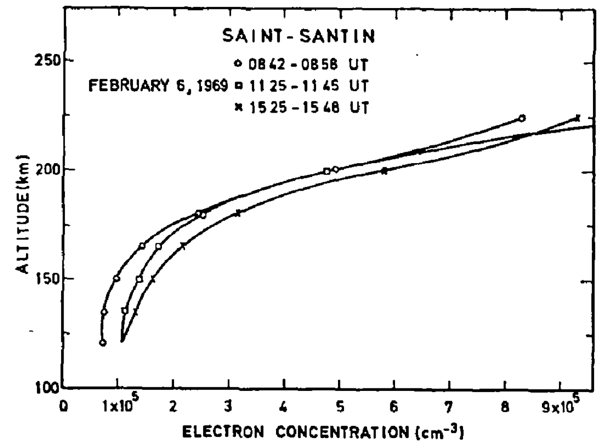

FIG. 4. ELECTRON DENSITY PROFILES IN THE TRANSITION REGION IN FEBRUARY 1969 FOR A HIGH SOLAR ACTIVITY.

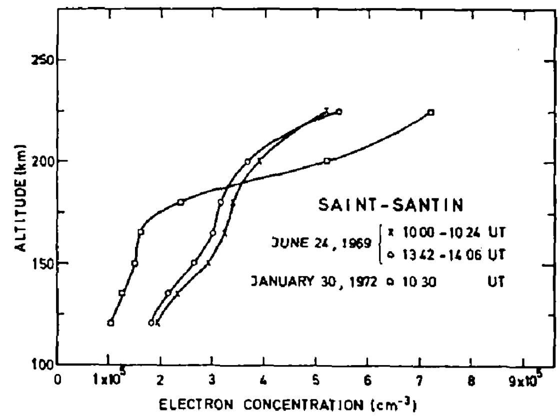

FIG. 5. ELECTRON DENSITY PROFILES IN THE TRANSITION REGION IN JUNE 1969 AND JANUARY 1972.

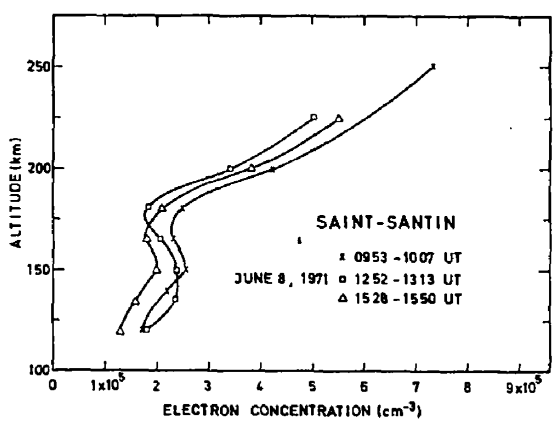

FIG. 6. ELECTRON DENSITY PROFILES IN THE TRANSITION REGION IN JUNE 1971.

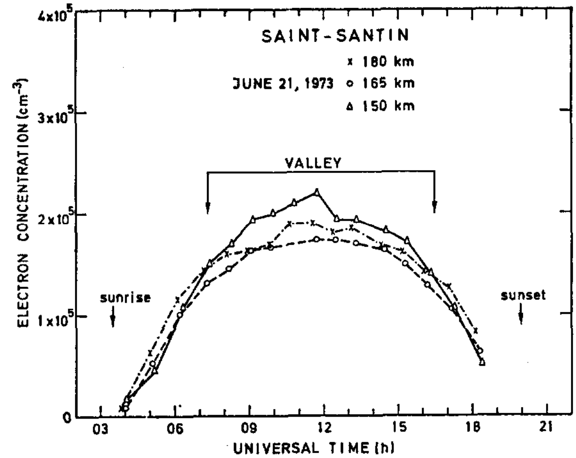

FIG. 7. DAILY VARIATION OF THE ELECTRON DENSITY AT 150 km, 165 km AND THE 180 km ON 21 JUNE 1973.

on Fig. 4 refer to high solar activity and winter conditions, when the F_1 layer is not present. The two profiles of 24 June 1969, shown on Fig. 5 are also characteristic of high solar activity, but they correspond to summer conditions. A point of inflexion now appears around 170 km. For high solar activity, an F_1 ledge is observed only under summer conditions, but no definite maximum or minimum can be seen on the vertical profile.

When solar activity decreases, the electron density gradient decreases between 120 and 170 km for winter conditions. This can be seen by comparing the winter 1969 profiles of Fig. 4 with the 30 January, 1972 profile of Fig. 5. Such a general trend is found on all the 26 winter days' observations made between 1969 and 1972.

A more fundamental change in the summer profile is found when solar activity decreases. The F_1 *ledge* shown on Fig. 5 is converted into a real F_1 *valley* (see Fig. 6) with a maximum around 150 km, followed by a density minimum around 170 km. Such a daytime valley has been permanently observed at Saint-Santin during summer 1971 and 1972. This is not necessarily a local phenomenon, since from the few quiet-day summer records of 1971 obtained at Chatanika in the auroral zone, Bates and Hunsucker (1974) suggest that a distinct valley between the F_1 and F_2 regions is not uncommon.

When the valley is present, it is interesting to study its daily evolution. Figure 7 shows the time dependence of the electron concentration at 150, 165 and 180 km for 21 June 1973, i.e. for low solar activity conditions. One can see that the 150 km concentration is higher than the 165 and 180 km values between approximately 07:00 and 16:00 hr. The valley appears, therefore, several hours after sunrise and it disappears several hours before sunset. The deepest valley is observed around noon when the solar distance is minimum. It is clear that we are dealing with a permanent summer daytime phenomenon for low solar activity conditions.

The long term variations of the F_1 valley at Saint-Santin can be analysed given a valley parameter $\bar{\delta}$ defined by

$$\bar{\delta} = 100 \times (n_{150} - n_{165})/n_{150}, \tag{3}$$

where n_{150} and n_{165} are the average electron densities between 10:00 and 14:00 hr, at 150 and 165 km, respectively. The parameter $\bar{\delta}$ is positive when a valley exists above 150 km,

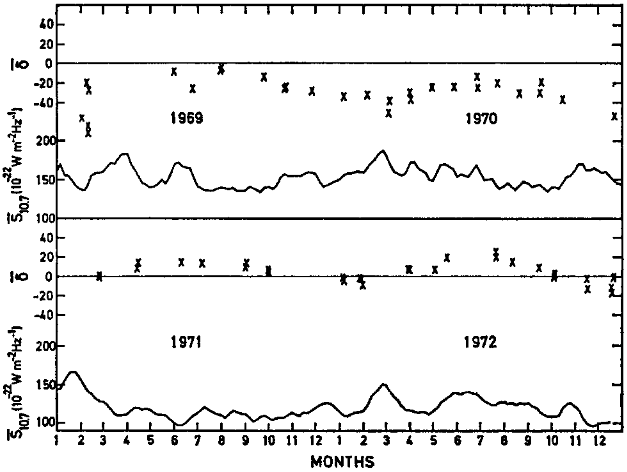

FIG. 8. $\bar{\delta}$ PARAMETER VARIATION AS THE FUNCTION OF TIME FROM 1969 TO 1972, COMPARED WITH 10·7 cm FLUX AVERAGED OVER ONE SOLAR ROTATION.

and it is negative when the concentration increases monotonically above 150 km. A positive $\bar{\delta}$ gives the average percentage depth of the valley.

In Fig. 8 the valley parameter $\bar{\delta}$ is plotted as a function of time for the years 1969–1972, i.e. for a declining phase of the solar cycle. One can see that the daytime valley is never present in 1969 or in 1970, when the annual average of the 10·7 cm solar flux is of the order of 155×10^{-22} Wm^{-2}/Hz. A summer daytime valley appears in 1971 and in 1972, when the 10·7 cm flux is about 120×10^{-22} Wm^{-2}/Hz. The maximum hourly value of the valley depth is 20–30 per cent for summer noon during low solar activity. Figure 8 clearly shows that the valley disappears in winter for any level of solar activity. The strong negative values for the winters under higher sunspot activity correspond to large electron density gradients, whereas the slightly negative values for summers having high sunspot number or for winters having low sunspot number correspond to a point of inflexion in the F_1 profile. It appears, therefore, that the daytime valley is a seasonal phenomenon which strongly depends on solar activity. From the present data, no particular correlation could be found with geomagnetic activity.

In summary, the analysis of the incoherent scatter data obtained at Saint-Santin during the declining phase of the last solar cycle, clearly indicates the permanent presence of a daytime valley in the F_1 region during summer, when the solar activity is low.

5. DISCUSSION OF THE RESULTS

Under photochemical equilibrium conditions, the splitting of the F layer into an F_1 and an F_2 component is usually attributed to the transition from a square-law formula αn_e^2 to a linear formula βn_e (Ratcliffe, 1956). This corresponds actually to the transition from the molecular ions O_2^+ and NO^+ to the atomic ion O^+. The consequences of this theory are clearly described by Rishbeth and Garriott (1969). From classical soundings at mid-latitude stations, it appears that the F_1 region is most prominent around noon and is more commonly observed in summer than in winter. This is a consequence of the fact that the splitting in the F region decreases as the solar zenith angle increases. Finally, since the occurrence of an F_1 region is favored by low ion production, it is normal to observe an F_1 region more frequently at sunspot minimum than at sunspot maximum.

These well known seasonal and solar cycle variations of the F_1 region are qualitatively identical to the general trend of the daytime valley observed at Saint-Santin. Several attempts have been made to reproduce theoretically the daytime valley under photochemical equilibrium conditions. But, even with very low atomic oxygen concentrations and very low solar u.v. fluxes, it was impossible to obtain a valley depth larger than a few per cent, whereas the observations indicate a valley depth of 20–30 per cent. It is clear, therefore, that seasonal and solar cycle variations of the photochemical distribution cannot account for the present observed results. Photochemistry alone can lead to an F_1 *ledge*, but not to the observed F_1 *valley*.

However, using a photoequilibrium theory, Maeda (1972) deduces the presence of a summer daytime maximum at about 170 km, when the sunspot number is less than 30. On the other hand, in our observations, the maximum occurs at 150 km and during the summer months in 1971 and 1972, when the mean sunspot number was respectively 64 and 80. Furthermore, the recent solutions of the coupled momentum and continuity equations for NO^+, O_2^+ and O^+ obtained by Schunk and Walker (1973) do not show a daytime valley in the F region, although an F_1 ledge is present.

It appears, therefore, that other factors must be involved in a realistic explanation of the observed phenomenon. It is known (see Axford and Cunnold, 1966) that, between 80 and 120 km, shears in the east–west component of the horizontal wind can produce sporadic E layers. Since the ion neutral collision frequency becomes progressively smaller than the gyrofrequency above 120 km, an effective shear mechanism in the F_1 region is then related to the north-south component of the horizontal wind. Effects of electric fields can also not be excluded *a priori*. We suggest, therefore, that the vertical component of the wind shear should not be neglected in a complete analysis of the F_1 valley. It remains to relate quantitatively the valley parameters with an appropriate wind model and it is necessary to show the compatibility of such a model with the winds actually observed at the same time as the valley.

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