Abstract

Observations of natural electromagnetic noise in the VLF range have been carried out at Syowa Station, Antarctica, since April, 1966. The VLF observation system is briefly described and the result on VLF emissions known as polar chorus is presented, based on the data obtained in 1966. It is confirmed that polar chorus in the auroral zone is a daytime phenomenon and that its occurrence culminates in the summer season. The statistical analysis indicates that a definite positive correlation exists between polar chorus activity and magnetic activity, especially during periods of moderate magnetic condition. Comparison of VLF data with magnetograms from low latitude stations reveals that VLF chorus variations are closely related to ssc, si and other worldwide magnetic changes, and that in several cases the chorus intensity decreases are associated with solar flares. Sudden impulse type magnetic field variations, which are thought to be caused by compression or expansion of the magnetosphere, are associated in most cases with polar chorus variation in the daytime, and a positive impulse is accompanied by a sudden enhancement or commencement of chorus, whereas a negative impulse is associated with a sudden decrease or fadeout of chorus emission. The center frequency of chorus tends to increase at the time of positive magnetic variations, and the rate of this frequency change is closely related to the magnitude of the corresponding magnetic variation. These characteristics are explained by electron cyclotron instability in the daytime magnetosphere, $L=6\sim10$.

1. Introduction

At the time of reopening of the Japanese Antarctic station, Syowa (69°02′S, 39°36′E ; -69.6°, 77.1°) by the Seventh Japanese Antarctic Research Expedition in 1966, the observation of natural electromagnetic noises in the very low frequency range as one of the projects for studying auroral zone upper-atmosphere phenomena was planned by the Geophysics Research Laboratory, University of Tokyo. The VLF observation system was designed for recording natural VLF noises with frequencies from 50 Hz to 50 kHz on the five formats, magnetic tape, 16 mm film and three paper charts. The observation was carried out during the nine-month period from April to December 1966. The purpose of this report is to present the result of analysis of polar chorus based on this VLF observation.

VLF emissions at high and middle latitudes have been classified into various types : hiss, chorus, periodic emissions, *etc.*, according to their spectral characteristics (GALLET, 1959 ; HELLIWELL, 1965). Hiss with spectrum of band-limited noise is usually observed at night and is closely related to the occurrence of some types of aurora (MARTIN *et al.*, 1960 ; MOROZUMI, 1963). In the daytime at high latitudes a quasi steady noise, occasionally associated with discrete emissions of rising tone, is usually observed in a band below 1.5 kHz. This type of emission, having a rather hiss-like spectrum as compared with chorus observed at middle latitudes, is known as polar chorus or ELF hiss (UNGSTRUP and JACKEROTT, 1963 ; TAYLOR and GURNETT, 1968). The center frequency of polar chorus is typically observed at about 700 Hz with a band width of a few hundred Hz (AARONS *et al.*, 1960 ; EGELAND *et al.*, 1965). The occurrence frequency shows a pronounced seasonal variation with a maximum in summer (UNGSTRUP and JACKEROTT, 1963 ; EGELAND *et al.*, 1965 ; HELLIWELL, 1965). The occurrence is concentrated in a narrow region along the dayside auroral zone, as shown statistically by ground observations (UNGSTRUP, 1967) and by the Injun 3 observation (TAYLOR and GURNETT, 1968). In connection with the generation mechanism of polar chorus it is of interest that this occurrence pattern resembles in some respects the electron precipitation pattern derived by HARTZ and BRICE (1967).

MOROZUMI (1965, 1966) reported that the variation of VLF chorus at high latitudes is closely related to storm sudden commencements and sudden impulses, concluding that the intensity of polar chorus increases at the time of ssc's or si's in the forenoon and decreases in the afternoon, both being associated with CNA increase. It was, however, pointed out by HAYASHI, KOKUBUN and OGUTI (1968), based on comparisons between VLF records at Syowa Station and magnetograms from low latitude stations, that decreases in chorus intensity are associated with negative sudden impulses in geomagnetic field and that such a forenoon-afternoon asymmetry is not found in the geomagnetic effect.

MOROZUMI (1967) reported that fluctuations in VLF chorus and CNA intensities are often found to be positively correlated. Observations made with the Injun 3 satellite of precipitating electrons and VLF chorus emissions have also revealed that precipitation of electrons is always accompanied by a group of VLF chorus emissions (OLIVEN and GURNETT, 1968). The association of corpuscular precipitation and the intensity variation of polar chorus on the occasion of ssc and si is very important, because they have characteristics closely correlative with the generation mechanism of polar chorus.

In this paper the characteristics of polar chorus observed at Syowa Station are examined statistically first. Relations between polar chorus variations and sudden impulse type magnetic field changes, ssc, si and other worldwide changes in geomagnetic field, are discussed in detail. The data used here are mainly chart records (speed, 6 cm/h) obtained with a narrow band VLF noise recorder with center frequencies at 0.75, 1, 2 and 4 kHz, and a frequency sweep analyzer operating in the range between 50 Hz and 1 kHz. The band width and sweep rate of this analyzer are 10 Hz and 100 Hz/min, respectively. Detailed descriptions of the instruments are presented in Appendix. Low latitude magnetograms from Moca (5.8°, 78.6° in geomagnetic coordinate), Kanoya (20.3°, 198.0°) and Tucson (40.6°, 312.1°) are examined for the identification of ssc's and si's and also other worldwide changes in geomagenetic field (NISHIDA and JACOBS, 1962), which may not be given in the usual reports from magnetic observatories.

2. Diurnal Variations in Polar Chorus Occurrence and Frequency

Polar chorus is a daytime phenomenon and is a quasi steady noise in a band below 1 kHz. A special type of chorus is also observed in the auroral zone at the post-breakup phase of aurora (MOROZUMI and HELLIWELL, 1966). UNGSTRUP (1966) reported that chorus emissions with a warbling or fluttering sound were associated with flaming aurora and that bursts of emissions were synchronized with flashes in a patchy glow type of aurora. During observations at Syowa Station in 1966, such a type of chorus was often observed at the recovery phase of polar substorm when flaming or pulsating aurora covered the zenith of Syowa Station. It was confirmed by visual observations at Syowa Station that bursts of emissions were closely related to rapid movements or appearances of patches in aurorae. These types of chorus emissions may be called "auroral chorus" and it is possible to distinguish them from polar chorus by spectral and occurrence characteristics. Discussions will, however, be made mainly on the characteristics of polar chorus in the present study.

The characteristics of polar chorus at Syowa Station are found to agree with those reported by UNGSTRUP and JACKEROTT (1963), and others. Fig. 1 gives diurnal variations of chorus emission occurrence at Syowa Station for each month from April to December, 1966. Polar chorus emissions are identified from the 0.75 kHz band chart records. Total duration (in minutes) of emission for each hour is adopted as an index of polar chorus activity. This selection of the 0.75 kHz band seems to give no significant error in statistical characteristics of chorus activity, though 0.75 kHz is a little high to represent the occurrence of polar chorus as will be shown later.

Maximum flux density in polar chorus events is usually in the order of 10^{-14} w/m^2 Hz. Events of flux density as low as 10^{-16} w/m^2 Hz could be scaled. Interferences of atmospherics, temporal increases of 50 Hz harmonics from power lines, effects of antenna vibration by strong wind and lower band auroral hiss are carefully eliminated, referring to records of the other high frequency channels. Auroral chorus activity cannot be excluded in this procedure, but the result shown in Fig. 1 is considered to represent polar chorus activity because of the shorter duration and the lower intensity of auroral chorus.

It is seen in Fig. 1 that the maximum occurrence is around 13 h in local

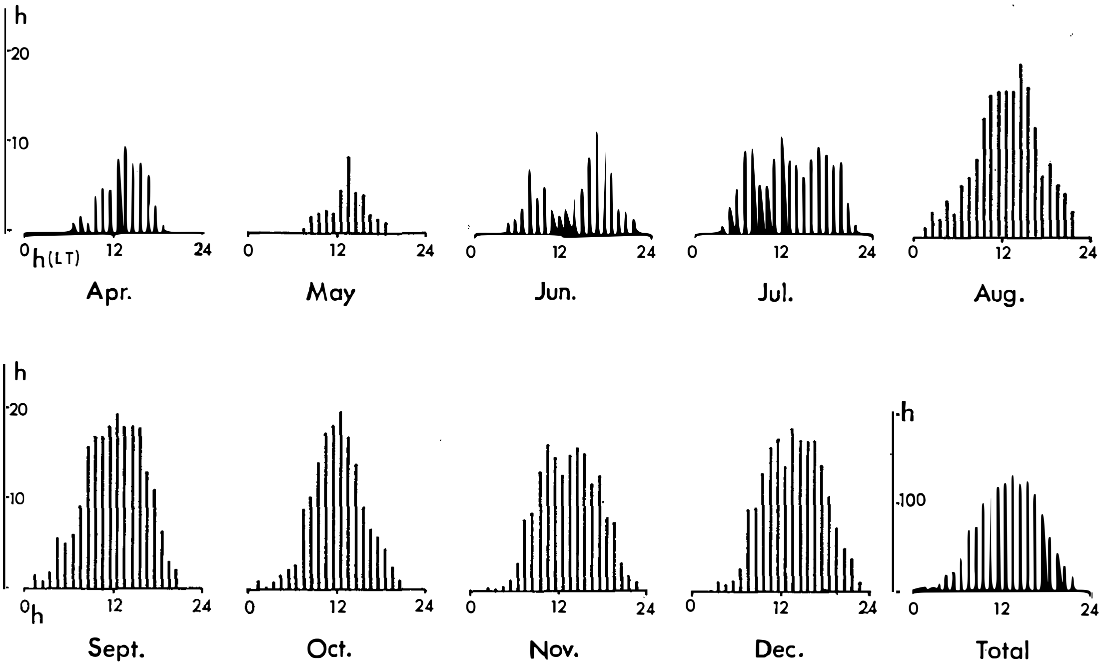

Fig. 1. Diurnal variation of polar chorus occurrence at Syowa Station in 1966.

time (10h 30m in geomagnetic local time) for each month and that the occurrence is larger in summer than in winter. These characteristics are consistent with the results reported by UNGSTRUP and JACKEROTT (1963). HELLIWELL (1965) also reported that the diurnal peak of VLF emission amplitude at a frequency of 0.75 kHz is observed at 10 h at Byrd Station ($\varphi_m = -70.4$) and that the intensity was maximum in November and minimum in May in 1962. Similar characteristics of polar chorus have recently been shown by MOROZUMI and HELLIWELL (1966). The VLF observation made by BÈGHIN (1967) in 1965 in Iceland, which is near the geomagnetic conjugate point of Syowa Station, also shows a diurnal variation consistent with the present result. The occurrence pattern of VLF emissions, derived from the Injun 3 satellite data (TAYLOR and GURNETT, 1968), agrees fairly well with the results obtained from ground observations mentioned above. It is important to note here that the occurrence of VLF emissions at satellite levels is not strongly dependent on the season (TAYLOR and GURNETT, 1968).

EGELAND *et al.* (1965) have shown that the maximum strength of polar chorus is found at 700 ± 100 Hz. The examination of the Syowa Station data reveals that the peak frequency of polar chorus shows a systematic diurnal variation in the period range between 400 and 800 Hz. The occurrence histogram of peak frequency, which was obtained using the sweep frequency analyzer record, is illustrated in Fig. 2. Examples of frequency spectra obtained with this analyzer are also given in Fig. 3. In Fig. 2 histograms of peak frequencies every hour are plotted for the cases of low magnetic activity $0 \leqq Kp \leqq 2-$, and moderate magnetic activity, $2_0 \leqq Kp \leqq 4_0$, during four months from September to December. The mean diurnal curves of peak frequencies are given in Fig. 4. It is found that the

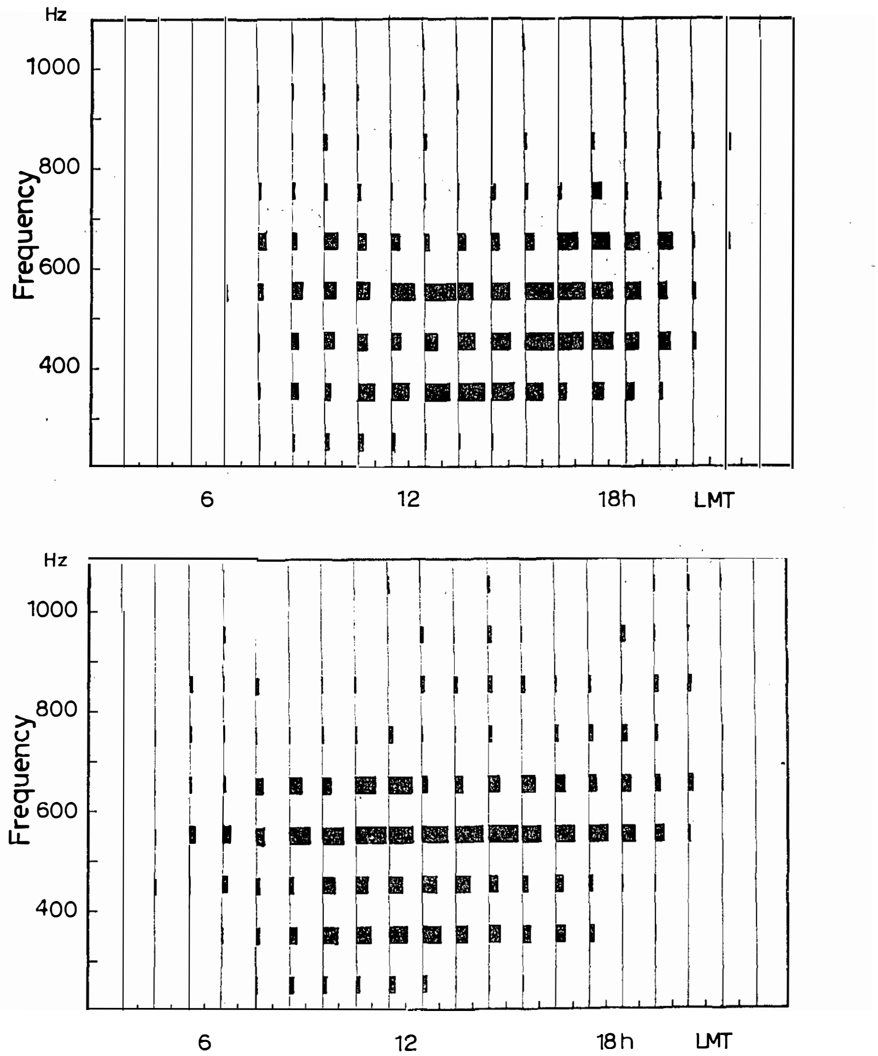

Fig. 2. Occurrence histograms of peak frequency during a period from September to December, 1966.
Upper : $0 \leqq Kp \leqq 2-$
Lower : $2_0 \leq Kp \leq 4-$

frequency of emissions is lowest during the period of maximum emission activity and is higher on the average in higher magnetic activity. It is also evident that the time of minimum in frequency tends to shift to morning hours as magnetic activity increases. To examine this tendency the mean value of peak frequency during the period of maximum occurrence, from 9 h to 10 h in geomagnetic local time, is plotted against Kp for every day from September to December, and the number of days when no emission was recorded is also plotted. It is apparent in Fig. 5 that a tendency to show a peak frequency increases with Kp, and the occurrence of polar chorus is dominant in moderate magnetic activity, $1 \leqq Kp \leqq 5$.

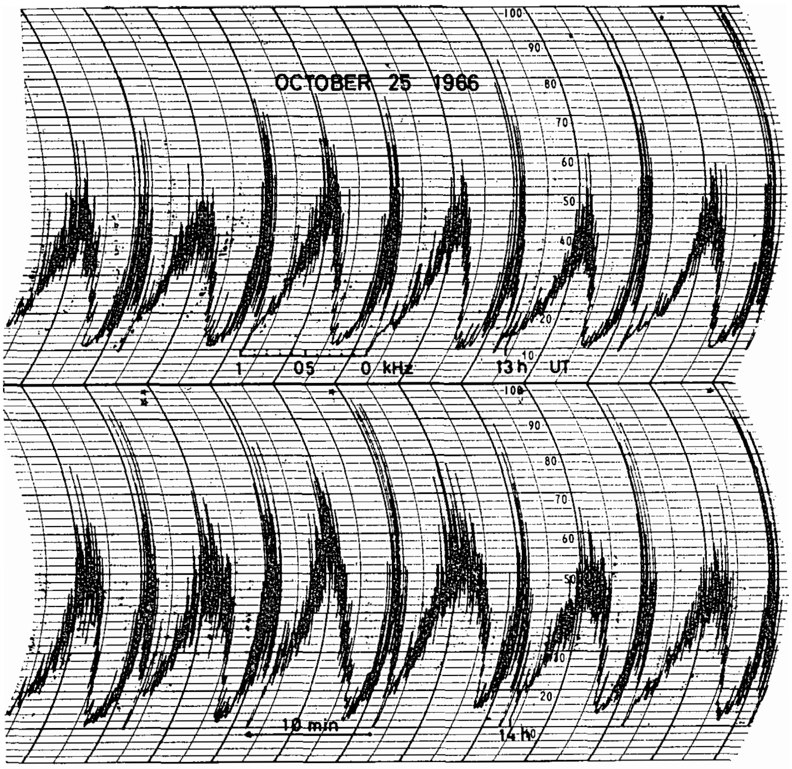

Fig. 3. The sweep analyzer record on October 25, 1966. A quasi-steady nature of polar chorus is evident.

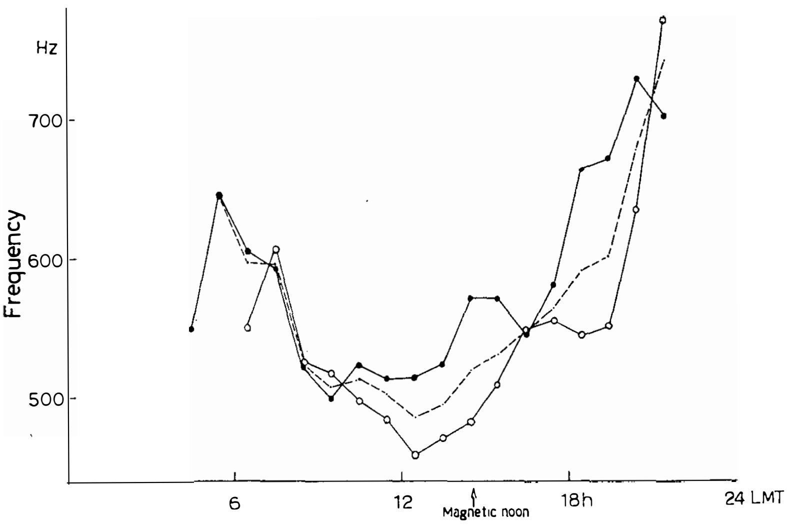

Fig. 4. Mean diurnal curves of peak frequency.

—◦— : $0 \leqq Kp \leq 2-$

—•— : $2_0 \leqq Kp \leqq 4-$

- - - - - : *all the events*

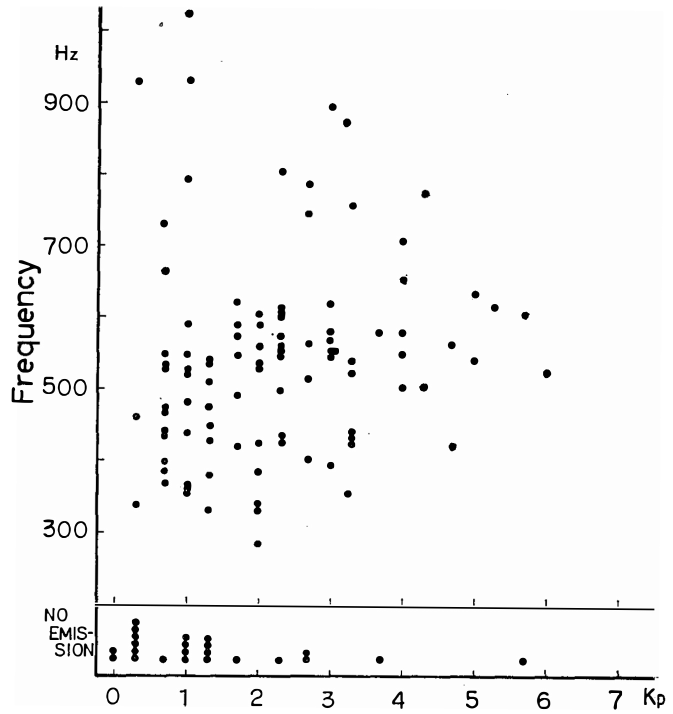

Fig. 5. Kp dependence of peak frequency during a period of maximum chorus occurrence.

3. Polar Chorus Occurrence and Geomagnetic Activity

Relations between VLF emissions and geomagnetic activity have been investigated by many workers using aural data, including ALLCOCK (1957), YOSHIDA and HATANAKA (1962), POPE (1963) and UNGSTRUP and JACKEROTT (1963). UNGSTRUP and JACKEROTT (1963) reported that a negative correlation exists between polar chorus and magnetic activity at the high-latitude station, Godhavn, and polar chorus often disappears during magnetically disturbed periods. However, the relationship between polar chorus and magnetic activity in the auroral zone has not been definitely clarified. The present analysis indicates that a definite positive correlation exists between the chorus activity at Syowa Station and the worldwide magnetic activity, especially in periods of moderate magnetic condition.

In order to represent daily chorus activity at Syowa Station, an index, denoted here by Ch, is defined as the daily sum of periods when polar chorus is registered on the 750 Hz band time-amplitude records. Comparisons are made between Ch and the planetary magnetic index, Kp. In Fig. 6 are shown day to day variations of Ch and the daily sum of Kp, Σ Kp, from April to December, 1966, and smoothed curves of $\overline{\mathrm{Ch}}$ and $\overline{\Sigma\,\mathrm{Kp}}$ are also given. Smoothing was

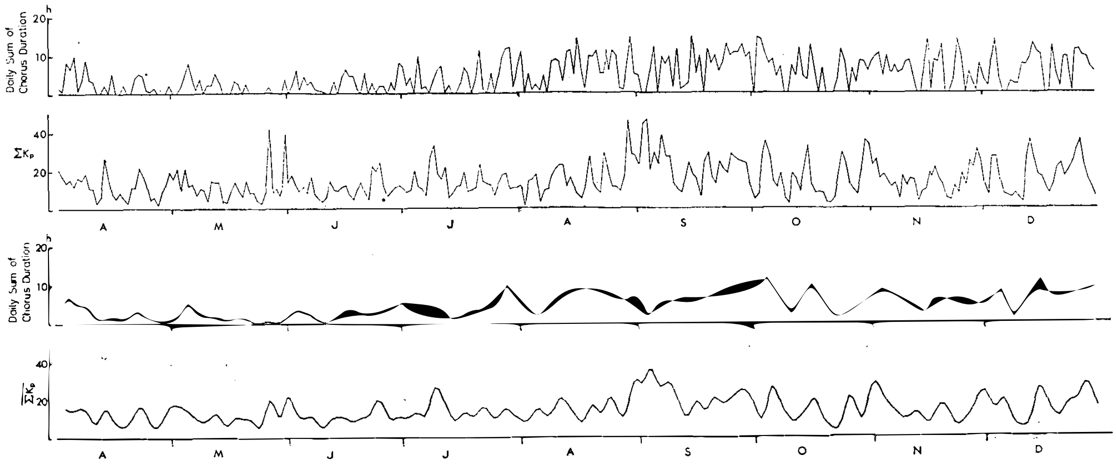

Fig. 6. Day to day variations of chorus activity at Syowa Station and magnetic activity.

carried out using a numerical low-pass filter of cosine type with a cutoff period of five days. A positive correlation is seen in the figures as a whole, except for the periods of magnetically disturbed condition (*e.g.* early in September and the end of November). A correspondence of peaks is obvious in some limited periods of moderate magnetic condition.

A cross correlation analysis is made to examine the relations between Ch and Kp in greater detail on the assumption that the index Ch represents polar chorus activity at 10 hours, universal time, when the occurrence frequency of polar chorus becomes maximum at Syowa Station. This assumption seems plausible considering that chorus occurrence is most probable at this time at Syowa Station, but diurnal variation effects cannot be entirely excluded from this procedure.

For calculation of cross correlation coefficients between Ch and Kp, a modified Kp, denoted here by Σ_s Kp, is represented successively by an eight point sum of Kp's about every three hours, universal time, namely Σ_s Kp's are given eight times more than Ch. Then cross-correlation coefficients with a time lag of three hours are calculated by sampling every eight interval of Σ_s Kp series.

Fig. 7 illustrates three correlation curves, between Ch and Σ_s Kp, between

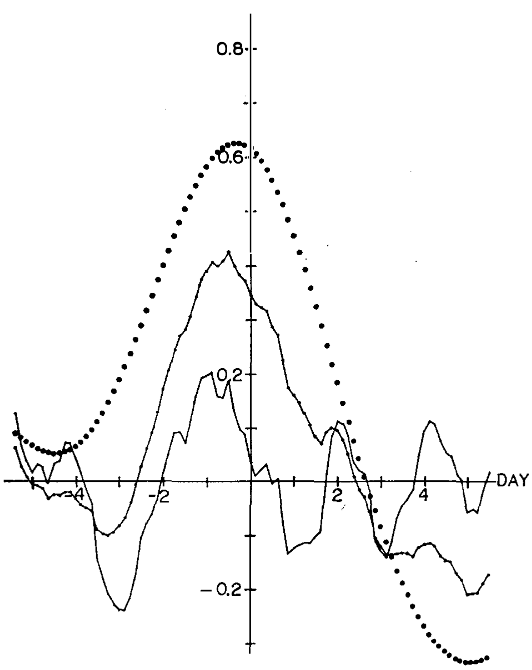

Fig. 7. Cross correlation curves between Ch and Σ_s Kp, calculated from four month period data.

—•— *Ch and Σ_s Kp*

······· *$\overline{Ch}$ and $\overline{\Sigma_s Kp}$*

——— *Ch–$\overline{Ch}$ and Σ_s Kp–$\overline{\Sigma_s Kp}$*

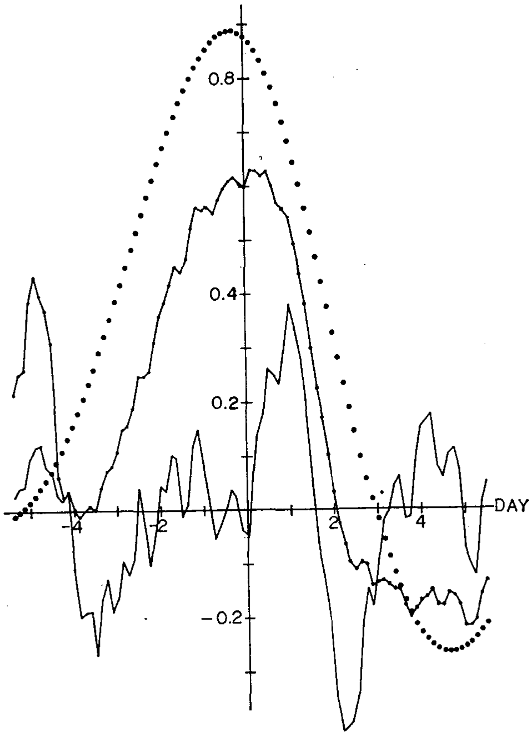

Fig. 8. Curves of thirty day data from September 20, similar to Fig. 7.

$\overline{\mathrm{Ch}}$ and $\Sigma_s \overline{\mathrm{Kp}}$, and between Ch–$\overline{\mathrm{Ch}}$ and Σ_s Kp–$\Sigma_s \overline{\mathrm{Kp}}$, of the data of four months since September, where $\overline{\mathrm{Ch}}$ and $\Sigma_s \overline{\mathrm{Kp}}$ denote smoothed indices with a cutoff of five days. In Fig. 8 are given similar curves for thirty days from September 20, showing a remarkable correlation. The maximum values of correlation coefficients in Fig. 7 are 0.42 for Ch and Σ_s Kp, 0.62 for $\overline{\mathrm{Ch}}$ and $\overline{\Sigma_s \mathrm{Kp}}$, 0.23 for Ch–$\overline{\mathrm{Ch}}$ and Σ_s Kp–$\overline{\Sigma_s \mathrm{Kp}}$, and those shown in Fig. 8 are 0.63 for Ch and Σ_s Kp, 0.88 for $\overline{\mathrm{Ch}}$ and $\Sigma_s \overline{\mathrm{Kp}}$, and 0.38 for Ch–$\overline{\mathrm{Ch}}$ and Σ_s Kp–$\overline{\Sigma_s \mathrm{Kp}}$.

A correlation coefficient of 0.25 is significant to within one per cent for 100 degrees of freedom, corresponding to the former case, and that of 0.46 for 28 degrees of freedom, corresponding to the latter case. Another noteworthy point seen in these figures is a time lag of about seven hours between Ch and Σ_s Kp.

It can be concluded that polar chorus activity correlates with worldwide magnetic activity and has a time lag of about seven hours from worldwide magnetic activity. With respect to the time-lag, however, further examinations should be made using more chorus data, since chorus indices defined in the present study are determined by only one point data.

4. Polar Chorus and Worldwide Geomagnetic Variation

As mentioned above, polar chorus activity correlates with general magnetic activity. In order to make clear the physical mechanism of generation of polar chorus, an attempt is made to examine the effects of sudden impulse type magnetic changes on polar chorus.

With respect to storm sudden commencements, twenty one ssc's were selected on the basis that ten or more observatories reported them as ssc's during the period from April to December, 1966. Of them, thirteen occurred at local daytime at Syowa Station, and twelve cases were found to be accompanied by VLF chorus enhancements with one exception, which did not show an appreciable chorus enhancement. Fig. 9 shows sharp increases in chorus intensity at times of ssc's on October 15 and September 23, 1966. In both cases, intensity increases more than 10 db in 750 Hz band are associated with increases of approximately 30 gamma ssc variations. It is noteworthy that rise times of chorus intensity are shorter in these cases than those of ssc's.

MOROZUMI (1966) reported that ssc's or si's give rise to a decrease in VLF chorus intensity in the afternoon portion of the auroral zone. However, such a local time effect on the relation between ssc's and VLF chorus variations cannot be noted in this analysis. An example of VLF chorus decrease on September 13, 1963, in his paper corresponds to a negative si, and a definite increase in chorus intensity at the very beginning of magnetic field increase is seen in another example of ssc on September 27, 1963. Since the negative si in magnetic field is thought to be caused by expansion of the magnetosphere due to the change in momentum of solar wind, differences in positive and negative si effects on VLF chorus must be taken into careful consideration.

Comparisons between the VLF records at Syowa Station and the low latitude magnetograms show that si's and also worldwide changes in geomagnetic field, exhibiting features similar to ssc's and si's (NISHIDA and JACOBS, 1962), correspond to changes in chorus intensity in the daytime. In the following, the term "sudden impulse" is used for ssc, si and other worldwide changes.

On days of moderate geomagnetic activity, ten or more sudden impulse effects can often be found in VLF records. Examples of the effects of sudden impulses on polar chorus are shown in Figs. 10 and 11. Upward arrows indicate

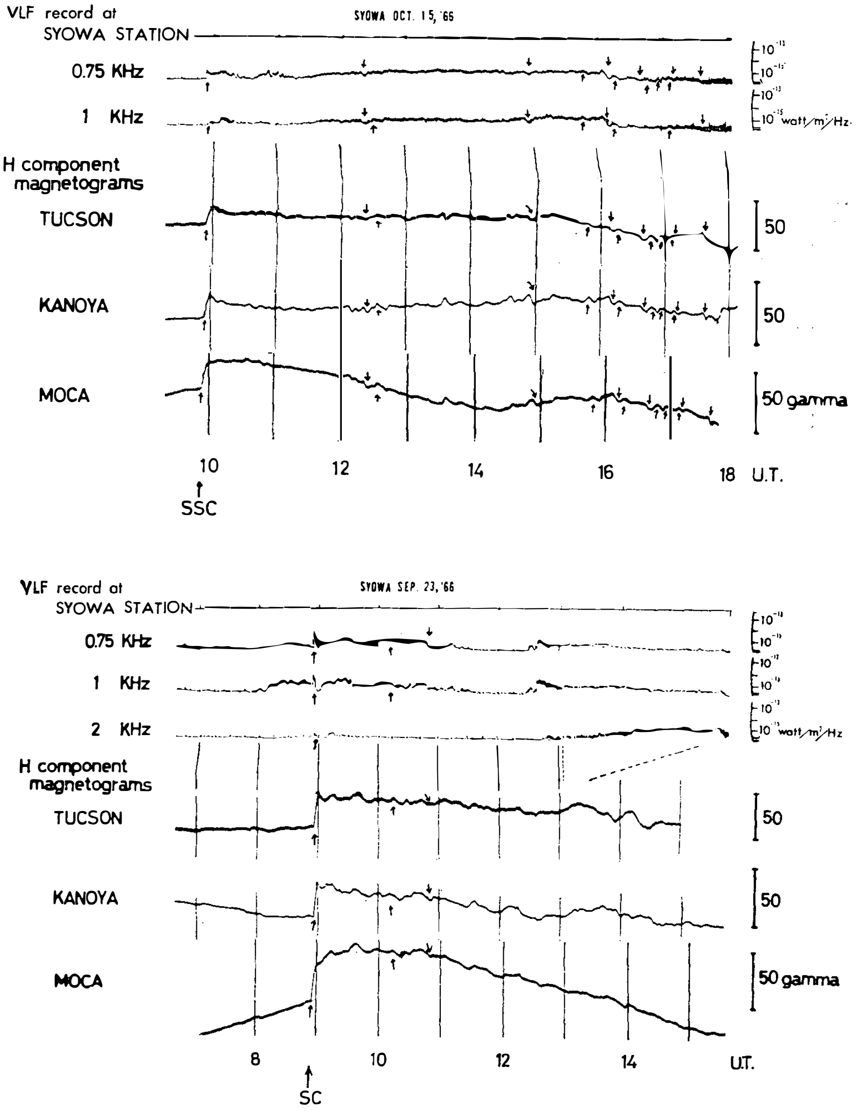

Fig. 9. Correlation between variations in polar chorus intensity in each frequency band and storm sudden commencements observed at Tucson, Kanoya and Moca on October 15 and on September 23, 1966. Upward arrows indicate corresponding peaks or increases in both phenomena, and downward arrows show troughs or decreases.

corresponding peaks or increases in both phenomena, and downward arrows show troughs or decreases in these figures. It is remarkable that a positive impulse gives rise to an increase in intensity in the 0.75 and 1 kHz bands, while a negative impulse corresponds to a decrease or disappearance. One of the most definite decreases at the time of a negative impulse was found at 09 h 06 m on September 24, shown in the left part of Fig. 10. Another example of chorus decrease is shown in Fig. 12. In these cases a sharp recovery is of interest in connection with the energy source of chorus generation. Similar decreases, associated with negative sudden impulses, are also found in VLF records at Byrd, Antarc-

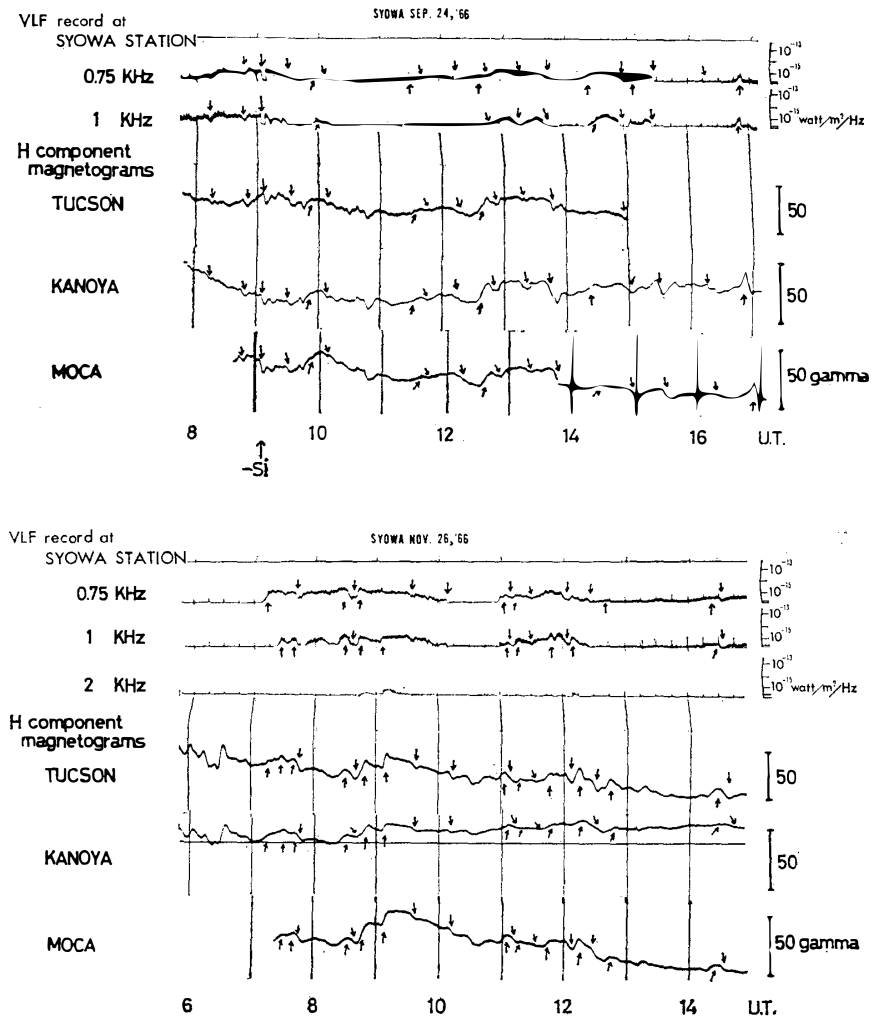

Fig. 10. Typical effects of worldwide changes in magnetic field on polar chorus intensity (similar to Fig. 9). A distinct negative sudden impulse effect is seen in the left part of the upper figure.

tica, published by MOROZUMI and HELLIWELL (1966). The magnitude of the geomagnetic variation is not always closely correlated with a simultaneous intensity variation in chorus. It is also important to note that not only a rapid magnetic variation such as ssc, but also a much slower worldwide coherent magnetic variation is associated with polar chorus variations.

An interesting feature is also seen in Fig. 11, where chorus intensity decreases in the 0.75 kHz band, while an increase occurs in both the 1 and 2 kHz bands, as in the case of a positive impulse at 10h 17m on September 27. This indicates that a sudden impulse affectes not only intensity but also frequency. Examples of frequency variations at times of ssc's and si's are shown in Fig. 13. A typical example of such a frequency variation associated with ssc is shown in greater

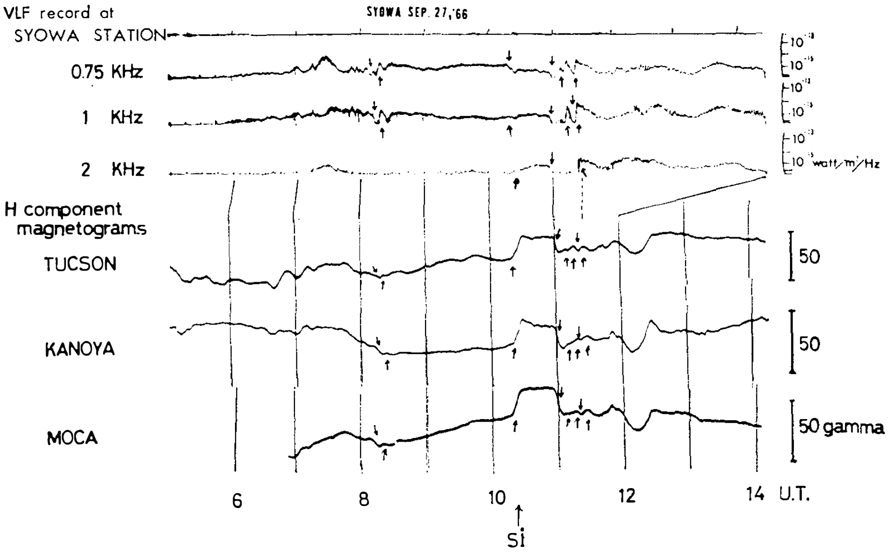

Fig. 11. Relation between variations in polar chorus intensity and geomagnetic variations (similar to Fig. 9 and 10). The effect of frequency change at the time of a sudden impulse is easily seen.

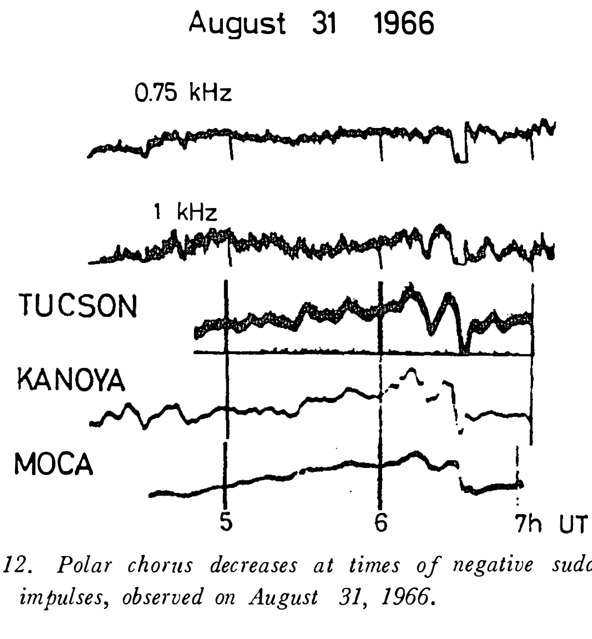

Fig. 12. Polar chorus decreases at times of negative sudden impulses, observed on August 31, 1966.

detail in Fig. 14a (dynamic spectrum), and Fig. 12b (relative intensity variation in each frequency band). This tendency was quantitatively examined for definite cases of sudden impulses, using records of the frequency sweep analyzer. The rate of frequency change associated with a sudden impulse $\Delta f/f_1$ (f_1, the center frequency of chorus just before a sudden impulse ; f_2, the center frequency of the first sweep after the impulse ; $\Delta f = f_2 - f_1$) is plotted against the magnitude of the magnetic variation in the horizontal component at Moca, ΔB (in γ), in Fig. 15. An approximate linear relation between $\Delta f/f_1$ and ΔB is obtained as

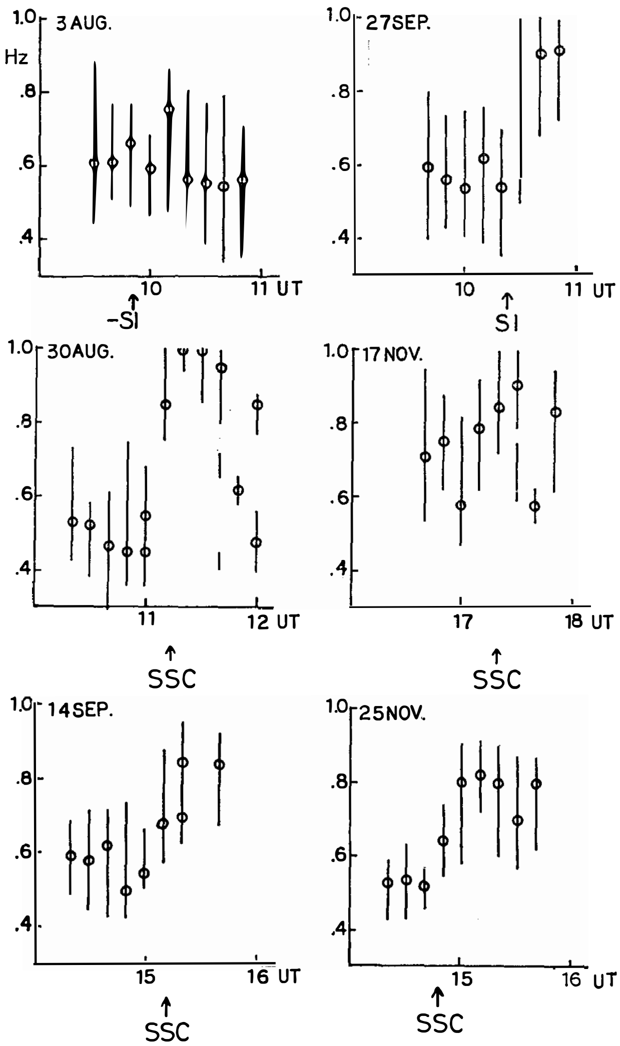

Fig. 13. Frequency changes of polar chorus at times of ssc's and si's, obtained from the frequency sweep analyzer. Circles represent the frequency of the spectral peak.

$$f/f_1 = 5/3\ \Delta B\ (\%).$$

Another interesting feature found in this analysis is the time difference of the beginnings of these variations. It is found by comparisons between the micro-pulsation records and the VLF records at Syowa Station that beginnings of chorus variations do not coincide with those of geomagnetic sudden impulses. Beginnings of distinct sudden impulses are determined from rapid-run induction magneto-grams at Syowa Station, and those of corresponding VLF variations are read from the 0.75 kHz band records with an error of about $\pm$ 20 seconds. Fig. 16 gives the time difference, $T_{750} - T_{si}$' against local time, where T_{750} and T_{si} denote commencement times of VLF chorus and magnetic variations. For all cases examined here, chorus variations are found to occur at least 30 seconds earlier than magnetic impulses. A small local time effect on the time difference is noted in Fig. 14 but a gerat deal of data appears to be necessary to clarify whether this local time effect is significant.

The obtained result is briefly summarized as follows :

1. In the daytime, a sudden impulse in geomagnetic field is frequently accompanied by a polar chorus variation ; positive impulses correspond to sudden enhancements of commencements of chorus emission, and negative impulses to sudden decreases or fade-outs. Chorus variations associated with sudden impulses are not found at night.

2. Chorus variation occurs about 30 seconds or more before the magnetic impulse.

3. Frequency variations are linearly related to the magnitude of sudden impulses.

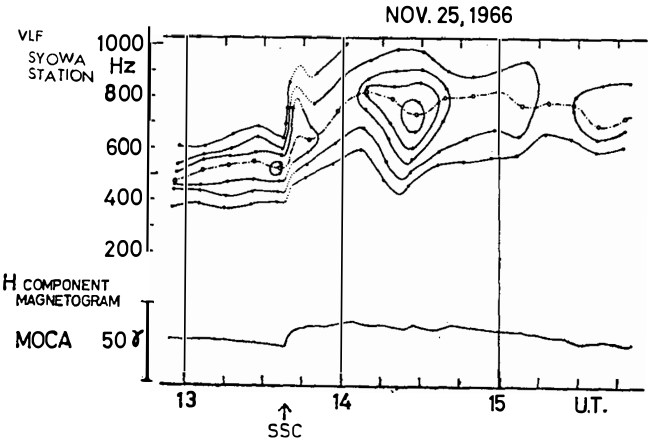

Fig. 14 (a). Dynamic spectrum of polar chorus at the time of ssc on November 25, 1966. Data points were obtained mainly from the frequency sweep analyzer record. Variation in peak frequency is indicated by open circles.

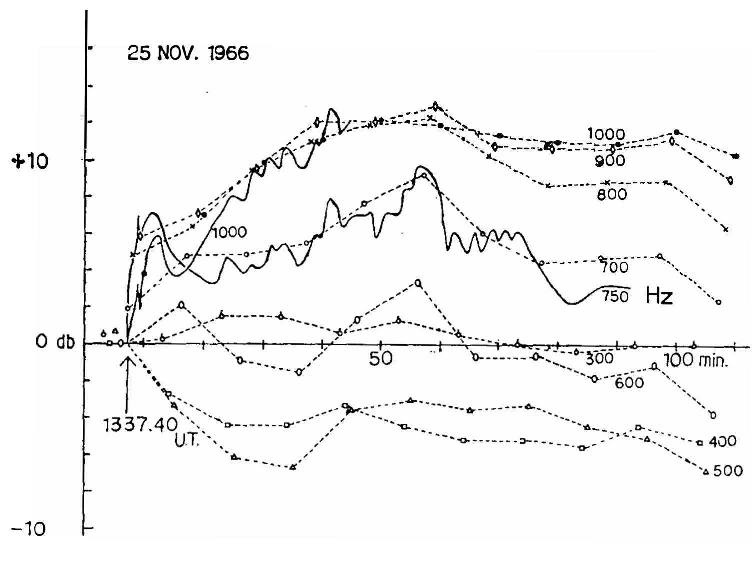

Fig. 14 (b). Variation in intensity, normalized to intensities just before ssc in various frequency bands for the same event shown in Fig. 14a. Continuous lines were reproduced from the record obtained with the narrow band continuous monitor, and others from frequency sweep analyzer.

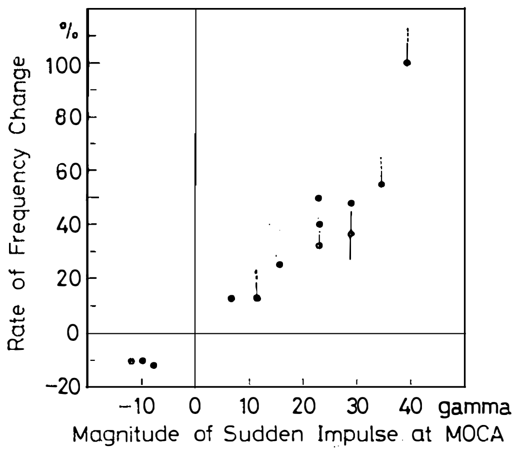

Fig. 15. Plots of the rate of frequency change associated with sudden impulses. The error bar represents the uncertainty in peak frequency, especially when the peak frequency was outside the range of the frequency sweep analyzer.

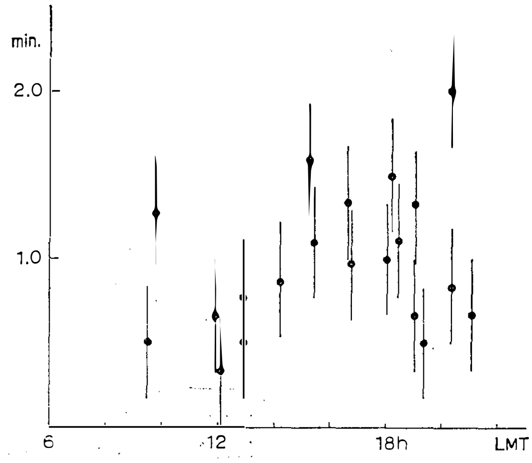

Fig. 16. The time difference, $T_{750}-T_{si}$ *against local time.*

5. Solar Flare Effect on VLF Chorus

No report has yet been presented on the solar flare effect on VLF emissions, though relations between VLF emissions and magnetic activity, CNA, *etc.*, have been already mentioned. By comparing the VLF records at Syowa Station with the magnetograms from low latitude stations, chorus intensity decreases were found to be associated with solar flares in several cases. Increases in the H component of geomagnetic field in the daylight hemisphere are accompanied by decreases in VLF chorus intensity at Syowa Station. Fig. 17 illustrates an example of such an effect observed at 12h 08m on September 19, 1966. The solar flare effect of magnetic variation was clearly found at Moca, but the simultaneous changes in the H component were not appreciable at Kanoya and Tucson in the evening and night. About 10db decreases in the 0.75, 1 and 2kHz bands of VLF noise intensity were observed, as compared with levels before the solar flare. The duration of chorus decrease was nearly the same as that of the

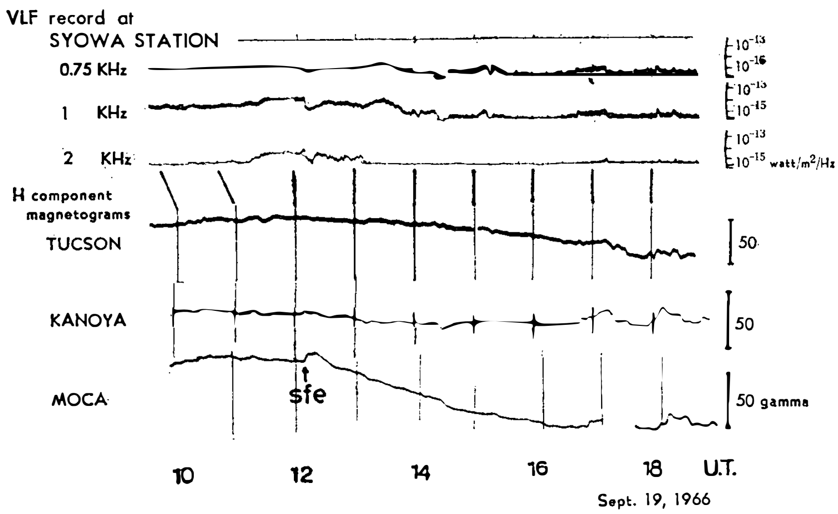

Fig. 17. VLF noise intensities in the 0.75, 1 and 2 kHz bands at Syowa Station, and magnetograms from low-latitude stations on September 19, 1966.

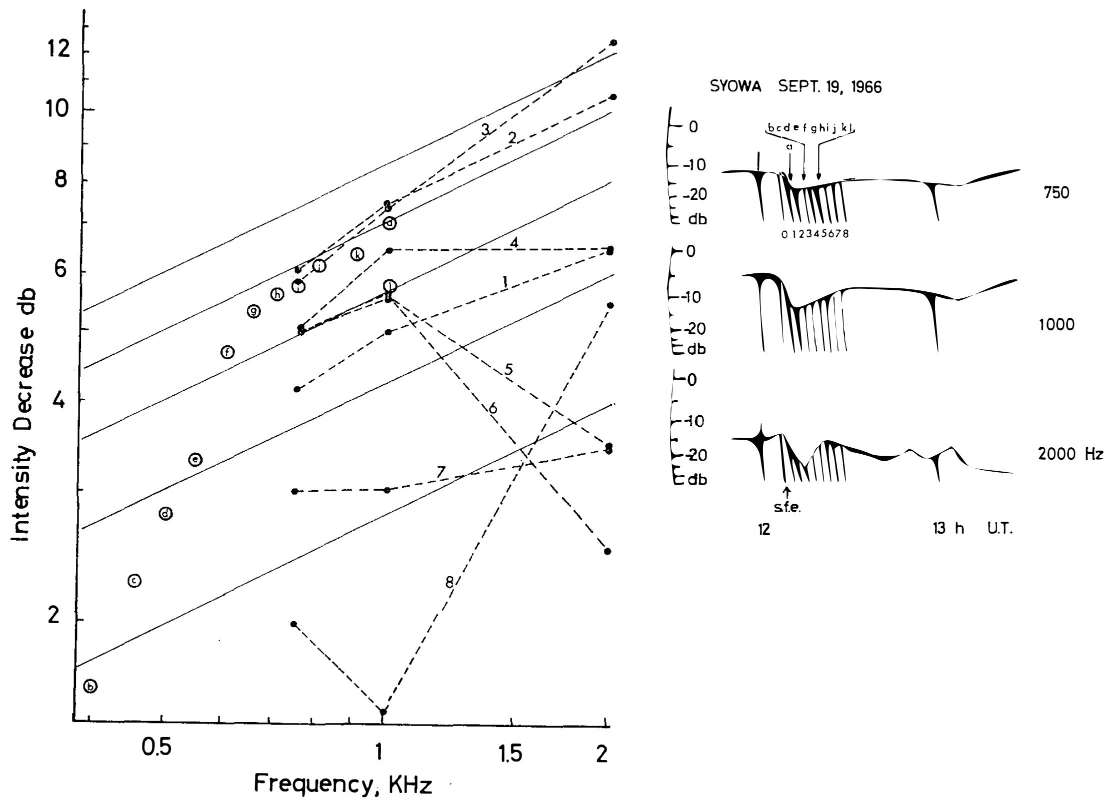

Fig. 18. Frequenay dependence of VLF noise decreases at the time of the solar flare on September 19, 1966.

geomagnetic effect. The frequency dependence of chorus decrease was examined in the frequency range, 0.4–2 kHz, using the narrow band and sweep analyzer records. The result of the case shown in Fig. 17 is given in Fig. 18. The alphabetical points show frequency dependence obtained from the sweep analyzer, and the broken curves from the band limited record shown on the right of the figure. In the frequency range between 600 Hz and 2 kHz, the observed frequency dependence seems to be almost parallel to the solid curve, $A \propto \sqrt{f}$, in the maximum stage of the solar flare effect, where A and f denote the intensity decrease in db and frequency.

The absorption of whistler mode wave in the ionosphere has been discussed by ONDOH (1963) and HELLIWELL (1965). The calculation for various model electron density distributions in the ionosphere shows that the total absorption of whistler mode wave through the ionosphere, due to electron collisions, is approximately proportional to the square root of frequency (HELLIWELL, 1965), and the contribution from positive ion collisions is small in the frequency range above 500 Hz (SWIFT, 1962; HELLIWELL, 1965).

Geophysical phenomena, SWF, SCNA, SPA, *etc.*, associated with the solar flare, are produced by enhanced ionization in the lower ionosphere caused by

X-ray radiation from the solar flare. VLF chorus intensity decrease, associated with the solar flare shown here, may also be explained by an increase in ionospheric ionization due to the solar flare.

6. Discussions

6.1. Generation mechanism of polar chorus

As to the generation mechanism of VLF emissions, single particle radiation theories and various plasma instability theories have been proposed (see reviews by BRICE, 1964 ; KIMURA, 1967). Among them proton cyclotron (KIMURA, 1961 ; GENDRIN, 1965) and electron cyclotron (TRAKHTENGERTS, 1963 ; BELL and BUNEMAN, 1964) instabilities in the magnetosphere are thought to be most promising. On the other hand, a quasi linear interaction between energetic electrons and whistler mode waves has been discussed in connection with particle distribution in the radiation belt (TRAKHTENGERTS, 1965, 1966 ; ANDRONOV and TRAKHTENGERTS, 1964 ; KENNEL and PETSCHEK, 1966).

For the excitation of a whistler mode wave through electron instability it is necessary for energetic electrons to have a pitch angle anisotropy in the direction perpendicular to the ambient magnetic field. The growth of a whistler mode wave is determined by the pitch angle anisotropy and by the fraction of particles that are resonant, and part of the kinetic energy of resonant particle in the direction perpendicular to the magnetic field is converted into wave energy. As the whistler mode wave grows resonant particles tend to be lost into the ionosphere due to a decrease in pitch angle, and this diffusion in pitch angle in turn tends to maintain a pitch angle anisotropy of trapped particles that is favourable for wave growth. It is possible for a quasi steady generation of VLF waves to be maintained in the magnetosphere by this mechanism, if some sort of continuous supply of energetic particles or acceleration process exists.

On the other hand, wave amplification in the proton and whistler mode wave interaction originates in the parallel velocity component of energetic protons to the ambient magnetic field. Then, favourable conditions for a quasi steady generation of VLF waves may not be expected in case of proton cyclotron instability.

Polar chorus is a quasi steady daytime phenomenon, the duration of which ranges from a few tens of minutes to sometimes a few hours. Such a quasi steady nature of polar chorus may be explained by an electron instability process in the magnetosphere, mentioned above. If this is the case, electron precipitation should be essentially correlated with polar chorus. Some evidences, showing that precipitatin of electrons from the magnetosphere correlates with VLF chorus observed at the ground station and also at the satellite levels have been reported by many investigators, including OLIVEN and GURNETT (1968), MOROZUMI (1967) and HARTZ and BRICE (1967).

OLIVEN and GURNETT (1968) have found that precipitation of electrons is always accompanied by a group of VLF chorus near the 1000 km levels. The occurrence pattern of VLF emissions in magnetic local time-latitude system, derived from the Injun 3 data, is statistically similar to that obtained from the ground observation data (TAYLOR and GURNETT, 1968). Such a VLF chorus occurrence zone, derived from both ground and satellite observations, agrees fairly well with the precipitation zone of comparatively high energy electrons obtained by HARTZ and BRICE (1967).

VLF chorus variations have often been noted to be associated with CNA variations in the auroral zone (MOROZUMI, 1967). Examinations of the correlation records at Byrd, Antarctica, published by MOROZUMI and HELLIWELL (1966) and MOROZUMI (1967), showed that some of the correlated variations in VLF chorus and CNA are associated with sudden impulses discussed in the last section.

In connection with the electron cyclotron instability in the magnetosphere, a recent satellite observation of the electron pitch angle distribution is also very interesting. According to the energetic electron observation with Explorer 33 (HASKELL, 1968) a favourable condition for the excitation of electron cyclotron instability, being that the pitch angle distribution of energetic electrons ($E \geqq 40$ keV) is anisotropic in the direction perpendicular to the ambient magnetic field, is found to exist near the trapping boundary region in the daytime magnetosphere.

The present result of sudden impulse effects on polar chorus also seems to support the possibility of electron cyclotron generation near the equatorial plane in the magnetosphere. Since the sudden impulse is interpreted as a manifestation of magnetospheric compression or expansion resulting from changes in the state of the solar wind, a sudden compression at the time of a positive sudden impulse would tend to create an enhanced anisotropy in pitch angle distribution of trapped electrons in the direction perpendicular to the magnetic field through the betatron acceleration mechanism. Then the enhanced anistropy produces an enhancement in wave energy and precipitation of electrons from the magnetosphere through the cyclotron instability process. The fact that positive sudden impulses in magnetic field are associated with polar chorus enhancements may be explained by the above process. Decreases in chorus intensity at times of negative sudden impulses would be due to a reduced pitch angle anisotropy through deceleration associated with a decrease in magnetic field.

The center frequency change of polar chorus at times of sudden impulses seems to be related to the resonant point change in the cyclotron instability process due to a change of gyrofrequency in the interaction rigion. This change may be deduced from a change in linear growth rate in the processs of the instability.

The following ralations hold, provided that the first adiabatic invariant is conserved in the initial stage of the sudden impulse, and the Fermi acceleration is relatively less than betatron acceleration,

$$\mu=\frac{\frac{1}{2}m\beta_{\perp}{}^{2}{}_{0}c^{2}}{B_0}=\frac{\frac{1}{2}m\beta_{\perp}{}^{2}c^{2}}{B}=\text{const.}$$

$$\beta_0 \cos \alpha_0=\beta \cos \alpha=\text{const.}$$

Here

$\beta=v/c$, v : particle velocity, c : light velocity.

$\beta_{\perp}=\beta \sin \alpha$, α : pitch angle.

$B=B_0(1+\varepsilon)$, ε : compression ratio of magnetic field.

then

$$\sin \alpha_0=\frac{\sin \alpha}{\sqrt{1+\varepsilon \cos^2 \alpha}}$$

$$\beta_0{}^2=\frac{1+\varepsilon \cos^2\alpha}{1+\varepsilon}\beta^2.$$

Therefore, if the initial distribution function is given by

$$F=A\beta_0{}^{-2n}\sin^{\lambda} \alpha_0,$$

then the distribution function after a compression is obtained as

$$F=A\left(\frac{1+\varepsilon\cos^2\alpha}{1+\varepsilon}\right)^{-n}\beta^{-2n}\frac{\sin^{\lambda} \alpha}{(1+\varepsilon \sin^2\alpha)^{\lambda/2}}. \tag{1}$$

The linear growth rate for electron cyclotron instability is derived by KENNEL and PETSCHEK (1966) as follows,

$$\gamma=2\pi^2|\Omega_e|^2\left(1-\frac{\omega}{|\Omega_e|}\right)^3\frac{c}{n\omega}\left(a-\frac{1}{|\Omega_e|/\omega-1}\right)\int_{\beta\perp\min}^{\beta\perp\max}\beta_{\perp}d\beta_{\perp}F(\beta_{\perp},\ \beta_{\parallel}=\beta_R) \tag{2}$$

where

$$a=\int_{\beta\perp\min}^{\beta\perp\max}d\beta_{\perp}\beta_{\perp}\tan \alpha\frac{\partial F}{\partial\alpha}\bigg/2\int_{\beta\perp\min}^{\beta\perp\max}d\beta_{\perp}\beta_{\perp}F\bigg|_{\beta_{\parallel}=\beta_R} \tag{3}$$

$$\beta_R=\left\{1-\left[1-\left(1+\frac{|\Omega_e|^2}{\omega^2n^2}\right)\left(1-\frac{|\Omega_e|^2}{\omega^2}(1-\beta_{\perp}{}^2)\right)\right]^{1/2}\right\}\bigg/n\left(1+\frac{|\Omega_e|^2}{\omega^2n^2}\right)$$

β_R : resonance velocity of electron (LIEMOHN, 1967),

$n^2=\dfrac{\omega_p{}^2}{\omega(|\Omega_e|-\omega)}$ n : refractive index for whistler mode wave

$\Omega_e=\dfrac{eB}{mc}$: electron gyrofrequency

$\omega_p{}^2=\dfrac{4\pi e^2n_e}{m}$: plasma ferquency

$\beta_{\perp\max}$ and $\beta_{\perp\min}$ represent the maximum and minimum limits of electron velocity respectively.

Then, the distribution function (1) is substituted in formulae (2) and (3). The linear growth rate was numerically calculated as a function of the compression ratio, taking into account the changes in Ω_e and $\omega_p{}^2$ as

$$\Omega_e = \frac{eB_0}{mc}(1+\varepsilon)\ ; \quad \omega_p{}^2 = \frac{4\pi e^2 n_{e0}}{m}(1+\varepsilon)\ .$$

A result for the case of $n=2.5$, $\lambda=3$ is shown in Fig. 19, where it is seen that the frequency of the maximum growth rate increase nearly proportional to the magnetic compression rate.

In the daytime magnetosphere, sudden impulses are generally observed approximately twice the magnitude of that observed at the surface of the earth (NISHIDA and CAHILL, 1964). Therefore, if the frequency change in polar chorus is entirely due to a change in gyrofrequency, then from an empirical relation obtained in Section 4 the magnitude of the magnetic field in the source rigion of polar chorus is estimated to be about 120 γ during a period free from any sudden compression or expansion. The average field configuration of the magnetosphere has recently been deduced from the satellite data of Imp. 1, 2 and 3, by FAIRFIELD (1968). According to this model, the field strengh 120 γ corresponds to $L=6.2$ at the equatorial plane of the magnetosphere and a latitude 66.5°.

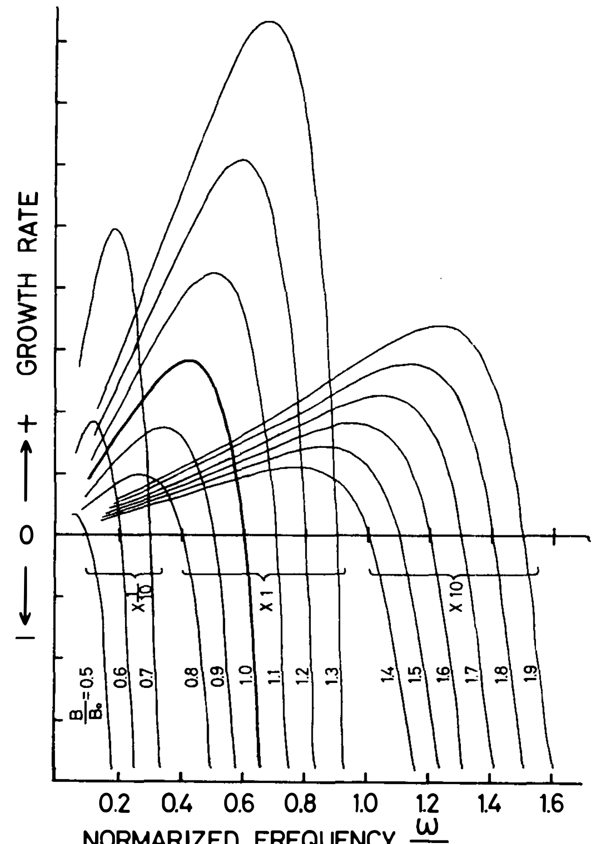

Fig. 19. The effect of variation in magnetic field intensity on linear growth rate of electron instability under the conservation of the first adiabatic invariant. The ordinate is in arbitrary units and the abcissa in frequency normalized to the electron cyclotron frequency.

These values agree fairly well with the latitude of maximum chorus occurrence (UNGSTRUP, 1967 ; TAYLOR and BURNETT, 1968).

It is thought that sudden impulses propagate to the earth's surface as Alfven mode waves, the propagation velocity of which is typically 10^3 km/s in the magnetosphere. On the other hand, a typical value for a whistler mode wave in the magnetosphere is in the order of 10^4 km/s. Then, a time difference of about 30 seconds or more between the polar chorus variation and the corresponding magnetic variation is consistent with the conclusion that the outer magnetosphere is the source region of polar chorus.

The present result thus suggests that polar chorus originates in a cyclotron resonant process of energetic electrons near the equatorial plane in the daytime magnetosphere, at $L=6\sim10$.

6.2. Seasonal variation of polar chorus

As previously mentioned, polar chorus is observed more often in summer than in winter. For example, the average power density of VLF emissions at 750 Hz observed at Byrd Station in summer is about five times as large as that in winter (HELLIWELL, 1965). On the other hand the VLF emission occurrence in the topside ionosphere has been found to be not strongly dependent on the season (TAYLOR and GURNETT, 1968). This difference suggests that the summertime predominance of polar chorus occurrence at the ground is mainly controled by propagation conditions of the whistler mode wave in the ionospheric region below about 1000 km. The ionospheric absorption of VLF waves in daylight conditions is several db larger than that in night conditions at 1 kHz (HELLIWELL, 1965). Therefore, the summertime predominance should be attributed to other propagation than absorption.

As has been shown in whistler studies, whistlers that are observed at the ground are believed to travel in field alined ducts (SMITH, 1961). Without ducts of enhanced ionization, whistler energy is guided only to a limited extent along the magnetic field and cannot reach the ground (KIMURA, 1966). The OGO-1 observation has recently yielded evidences for ducted and non-ducted modes of whistlers in the magnetosphere near $L\simeq3$ (SMITH and ANGERAMI, 1968).

In the case of VLF emissions ducted propagations can be expected according to the characteristics of periodic emissions. Ion effects on whistler mode waves are, however, necessarily taken into account in the explanation of polar chorus characteristics, because the frequency of polar chorus is nearly equal to the proton gyrofrequency at 500 km altitude. In this connection, the VLF emissions spectra recorded simultaneously at the conjugate stations, Great Whale and Byrd Station in June, 1962 (HELLIWELL, 1965) are very interesting (Fig. 20). Fig. 20 shows that the periodic emission above 1 kHz is present at both stations, but polar chorus below 1 kHz is present only at Great Whale, which is located in the sunlit polar region. The periodic emissions have been interpreted as propagating in field alined ducts between the north and south polar regions. The absence of polar chorus suggests that ducting conditions do not hold for

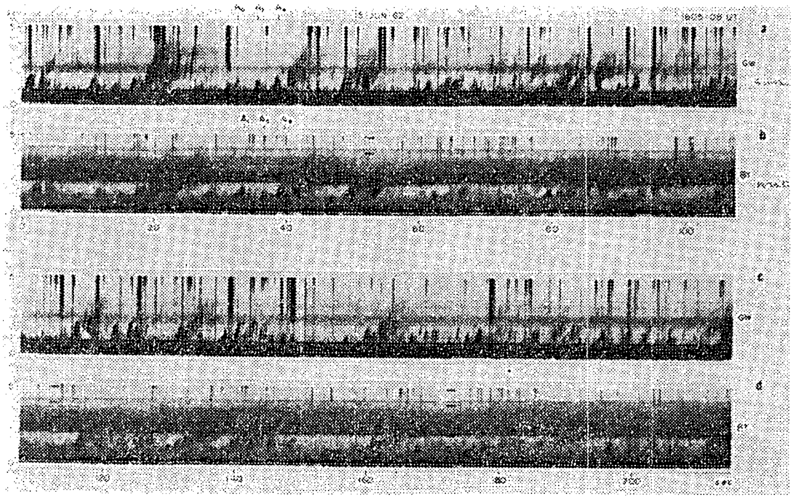

Fig. 20. VLF emission spectra recorded at the conjugate stations, Great Whale and Byrd Station in June 1962. Polar chorus band at 500 Hz is relatively strong at GW and virtually absent at BY (after HELLIWELL).

waves below 1 kHz near the southern end of the propagation path. Such a non-conjugacy of polar chorus may be related to the $L=0$ cutoff frequency (STIX, 1962) in the multicomponent ionospheric plasma.

The propagation of electromagnetic waves in the ionosphere in the same order as ion gyrofrequencies has been discussed by GURNETT *et al.* (1965) in connection with ion cyclotron whistlers. It is shown that downgoing extraordinary mode waves below the proton gyrofrequency are not always able to reach the ground through the ionosphere without mode coupling at the crossover frequency (SMITH and BRICE, 1964). GURNETT and BURNS (1968) have recently shown that ELF and VLF noises with a sharp cutoff near the proton gyrofrequency are often observed from the satellite in the ionosphere. This cutoff is a manifestation of the two ion cutoff effects on downgoing extraordinary waves from a higher altitude source. The minimum transmission frequency through the ionosphere is determined by the altitude at which the proton concentration becomes so small that polarization reversal at the crossover frequency no longer occurs.

Since the altitude of the base of the protonosphere is a function of ionospheric temperature and is higher in the daytime than at night (BARRINGTON *et al.*, 1965), the minimum transmission frequency is lower in the daytime than at night. The summer peak of polar chorus occurrence may be interpreted in terms of the difference in minimum transmission frequency of downgoing extraordinary waves. This is due to the temperature difference between the sunlit and the dark polar ionosphere, if the frequency of polar chorus generated in the outer magnetosphere does not vary with season. The diurnal varation of polar chorus frequency, as shown in Section 2, is also explained by a change in minimum transmission frequency due to diurnal variation of ionospheric temperature. If this interpretation is correct, spectra of polar chorus may vary with season. This point deserves a detailed investigation.

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APPENDIX

Instrumentation

A block diagram of the VLF system at Syowa Station in 1966 is shown in Fig. 21. The system was designed for survey of natural VLF noises in the frequency range between 50 Hz and 50 kHz.

Two loop antennas were constructed at a distance of about 250 m from the station (Fig. 22). The effective area and inductance of the antenna are 400 m^2 and 180 μ H, respectively. Low-noise preamplifiers with a gain about 60 db and an input impedance 1 ohm, were installed in a wooden box at the foot of the antenna pole. The frequency response of the antenna and amplifier system is illustrated in Fig. 23 as in the case without filter.

The recording device consists of a magnetic tape recorder, a hiss recorder, a frequency sweep analyzer in the band below 1 kHz, and a six channel narrow

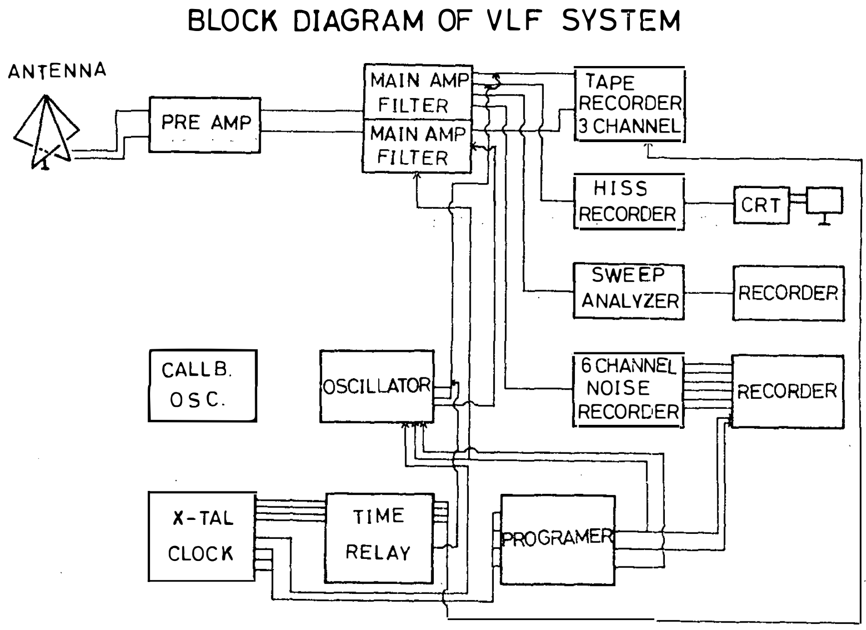

Fig. 21. A block diagram of the VLF observation system at Syowa Station.

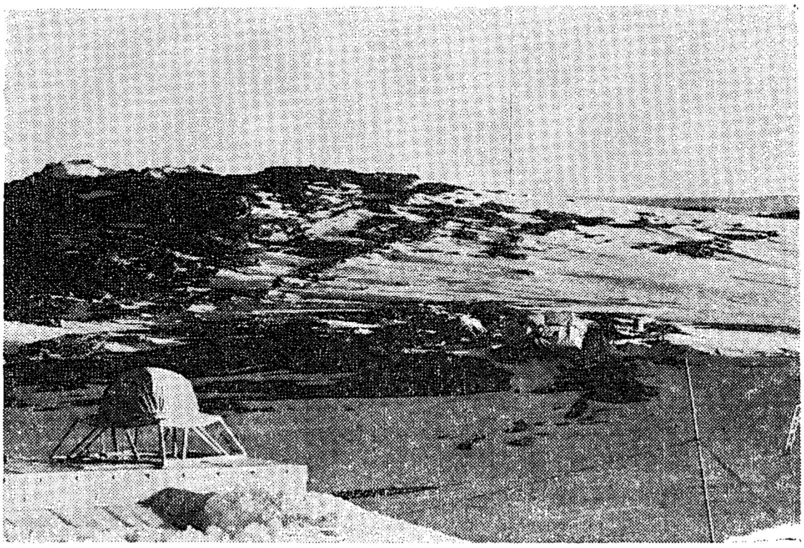

Fig. 22. VLF antenna viewed from the station. The dome on the left is the all sky camera.

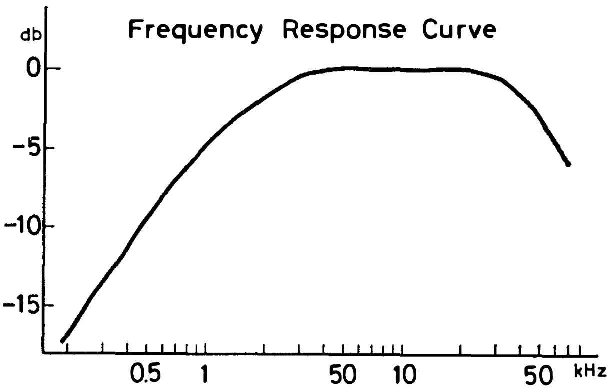

Fig. 23. The frequency response of the VLF system.

band VLF noise recorder. The characteristics of these recorders are summarized in Table 1. The 16 mm film recording and the paper chart recording were continuously operated from April to December, 1966. Magnetic tape recording of VLF signals from both the N–S and E–W antennas was usually operated in the frequency range between 300 Hz and 12 kHz on an hourly routine basis. The recording duration is 2 minutes 30 seconds, from 49 m 45 s every hour. The recording program and time marker for these devices were controlled by signals from a crystal clock with a stability 10^{-7}. Continuous magnetic tape recording was occasionally made during periods of distinct chorus or hiss events.

Table 1. Characteristics of recording devices.

Multichannel VLF noise recorder	Center frequency	Band width	Time constant		Chart speed
	kHz	Hz	Discharge	Charge	
	0.75	75	50 ms	10 s	60 mm/hr
	1.00	100	50	5	
	2.00	200	50	5	
	4.00	400	50	5	
	12.00	1200	50	10	
	1 - 10 kHz	9 kHz	50	10	
	30 - 50 kHz	20 kHz	50	10	50 mm/hr
Frequency sweep analyzer	Frequency range	Filter band width	Sweep time		
	50 - 1000 Hz	10 Hz	10 min		40 mm/10 min
					Film speed
Hiss analyzer	300 Hz - 8 or 24 kHz	45 Hz	1 s		60 mm/hr

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