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ROCKET OBSERVATIONS OF MODULATIONS OF THE LOW ENERGY ELECTRON FLUX IN THE AURORAL IONOSPHERE

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Abstract: An instrument has been developed for observing the high frequency modulations or fluctuations (upto several megahertzs) of the auroral electron flux. The instrument utilizes an on-board processing hardware for calculating auto-correlation functions of particle flux measured by any type of particle detector which output a series of pulses. Two rocket observations by using the instrument were carried out as a part of low energy auroral electron experiments on board the S-310JA-11 and -12 rockets which were launched into the Antarctic auroral ionosphere. The instrument is capable of measuring the flux modulations in three frequency ranges, *i.e.* 1.5–100 Hz, 0.1–8 kHz and 0.1–4 MHz, respectively. Results from one rocket experiment launched under relatively quiet conditions indicate that the auroral electrons are almost uniform in the high frequency range. Results from another rocket experiment (JA-12) conducted under highly active aurora conditions show low frequency modulations of electron flux associated with a strong electron precipitation.

1. Introduction

Interaction between plasma waves and particles (wave-particle interaction) in the auroral ionosphere has been extensively investigated both theoretically and experimentally. A variety of phenomena have been observed to show that the wave-particle interaction is one of the most interesting processes occurred on auroral field lines. In general, researches of these phenomena have been conducted based on observations of plasma waves and particle's distribution functions. However, at the very vicinity of the plasma wave source region, it can be expected that particle fluxes are modulated by a strong wave field generated by the wave-particle interaction. There are several characteristic frequencies in the space plasma such as upper hybrid resonance, plasma frequency, cyclotron frequencies for ions and electrons, and lower hybrid resonance. These frequencies give a rough estimate what could be expected in modulations of particle fluxes. There have been several attempts to detect these modulations as direct evidence of the wave-particle interaction. GOUGH and URBAN (1983) observed notable modulations of the auroral electrons near twice the electron cyclotron frequency in their rocket experiment. At geosynchronous orbit the GEOS satellite observed the gyro-phase bunching effect in low energy ions, which was suggested to be a result of the wave-particle interaction between thermal ions and electromagnetic ion cyclotron waves. Also strong ion cyclotron waves predicted to be associated with the ionospheric ion heating at the 90° pitch-angle may give rise to modulations in the heated ions.

We have developed an instrument for detecting the high frequency modulations of particle fluxes by utilizing the autocorrelation function (ACF) technique. The instrument can detect the modulation upto 4 MHz. In the following sections, we describe the technique, rocket instrument, and rocket observations in the auroral ionosphere.

2. Detection of the High Frequency Modulations of Particle Fluxes

In order to measure the high frequency modulations of particle fluxes in space, there are two methods both are theoretically equivalent: one is a direct Fourier analysis of a time series of the particle flux data, another is the ACF technique. It is common in the space environment to measure a particle flux by using an electrostatic energy analyzer equipped with a combination of a type of electron multiplier and pulse counting electronics. This technique has a great advantage both in sensitivity and energy resolution over other techniques. An output from the analyzer is the number of pulses counted during the predetermined time period (gate time), and this is proportional to a particle flux into the analyzer. In order to observe the low frequency flux modulation, a series of these counts can be used as an input to the Fourier analysis if the average counts of pulses per gate time is much larger than one. Then the gate time give a minimum sampling interval, which, in turn, determines a maximum frequency observable by this technique. In order to observe higher frequencies, the gate time must be smaller accordingly. As descreasing the gate time, however, average counts per gate time also decrease proportionally. This makes difficult to obtain a power spectrum by this technique in the higher frequency range. In order to measure the high frequency flux modulation, SPIGER *et al.* (1974) tried to use an analog spectrum analyzer connected directly to the output from an electrostatic energy analyzer with a large geometrical factor. But the method gives a lot of spurious peaks in power spectrum due to waveforms of input pulses in addition to the true spectrum due to modulations of the particle flux.

GOUGH (1980) developed another technique based on ACFs of particle flux. In early 1970 s statistical characteristics of laser light were investigated by using the photon-correlation technique (JAKEMAN, 1969). In these experiments, several experimental methods were employed to calculate correlation functions from outputs of photo-multiplier which produces a train of pulses proportional to the input intensity of light. Utilization of a time-to-amplitude converter combined with a pulse height analyzer is a most simple method from the hardware point of view (DAVIDSON, 1969). In this method, a separation time of two successive pulses from photo-multiplier is measured to give a histogram of the occurrence probability of a particular separation time event. The separation time is measured as the number of time steps each has a fixed time width. This time width determines the minimum time resolution. An ACF of photon flux irradiating the photo-multiplier can be calculated from the histogram by using the iterative approximation technique (DAVIDSON, 1969). The method is quite useful for detecting high frequency modulations of the pulse train because of a simple hardware, and can be applied directly to measurements of ACFs of particle fluxes. Statistical property of pulses from the particle detector is different from those of laser light. Without modulations, the pulses have a Poission distribution which is determined only by the counting rate (MANDEL, 1959), while those from the laser light has, typically, a Gaussian-Lorenzian property. Note that the method is applicable when the average count of pulses per single time step is much smaller than one. Figure 1 shows a schematic diagram of this method. We employed a counter clocked by a crystal oscillator instead of the time-to-amplitude converter. An input pulse starts or stops the counter alternatively which give a separation time between two pulses. The output from the counter is used to update the histogram of the separation time stored in the random access memory.

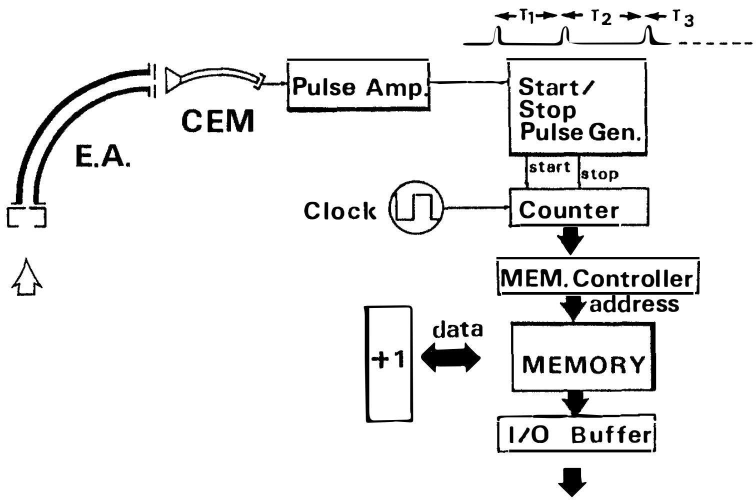

Fig. 1. Block diagram of the pulse separation method.

When the counting rate of pulses from the detector becomes comparable to the frequency range of modulations observed, the above method can not be used (KELLY, 1971). Although ACF of a pulse train can be calculated in real time manner by following its definition, it needs a too complex circuitry to be appropriate as a space-born instrument, particulary, when dealing with the fast sampling time. There are several ways to simplify the real-time calculation of ACF. By reducing the number of bit which representing the input signal, a digital correlator would be greatly simplified. The most simple, and equivalently, fastest hardware can be designed by using the "One bit - One bit correlator" technique. In this technique input signals are treated as "1" or "0" according to their amplitude, thus ACFs are calculated by using AND gates and counters instead of multipliers and adders for the "Multi bit - Multi bit correlator". Note, however, that this approximation introduces distortions in calculating ACF. A good compromise between simplicity of hardware and an amount of distortions introduced to ACF can be achieved by employing the "One bit - Multi bit correlator", which consists of AND gates and adders as shown in Fig. 2 (KELLY, 1971).

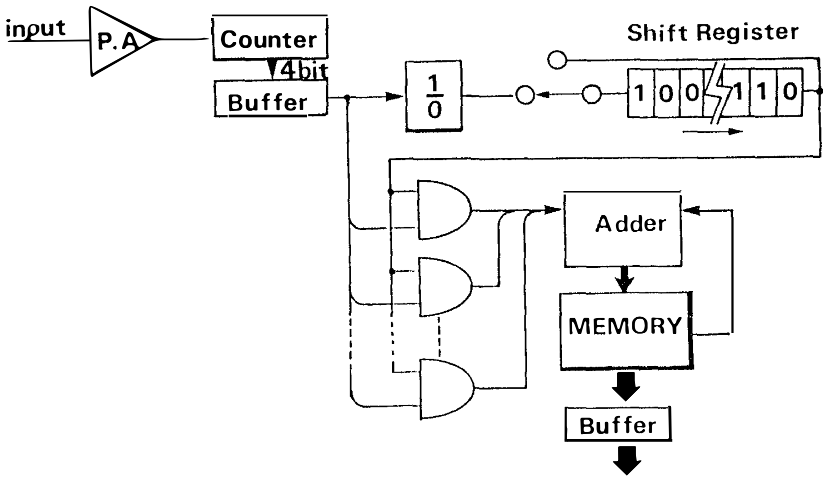

Fig. 2. Block diagram of the One bit – Multi bit correlator.

3. Rocket Experiments

A high frequency flux modulation detector employing the techniques described above was built as a part of the auroral particle experiments on board rockets launched in Antarctica. Details of the auroral particle experiment are discussed by YAMAGISHI *et al.* (1988a). As shown in Fig. 3, a Particle Flux Modulation Detector (PFMD) package processes signals from one of three channel electron multipliers (CEMs) attached to a quadri-spherical electrostatic energy analyzer. Three CEMs detect electron fluxes from three different directions each apart by 60 degrees. The CEM connected to the PFMD is looking at perpendicular direction to the rocket spin axis. The PFMD consists of three parts: a pulse separation detector (PSD) for measuring the highest frequency range of flux modulations (<4 MHz), a One bit – Multi bit correlator (OMC) for detecting flux modulations in the medium frequency range (<8 kHz), and three counters with the fast gate time of 5 ms for detecting the low

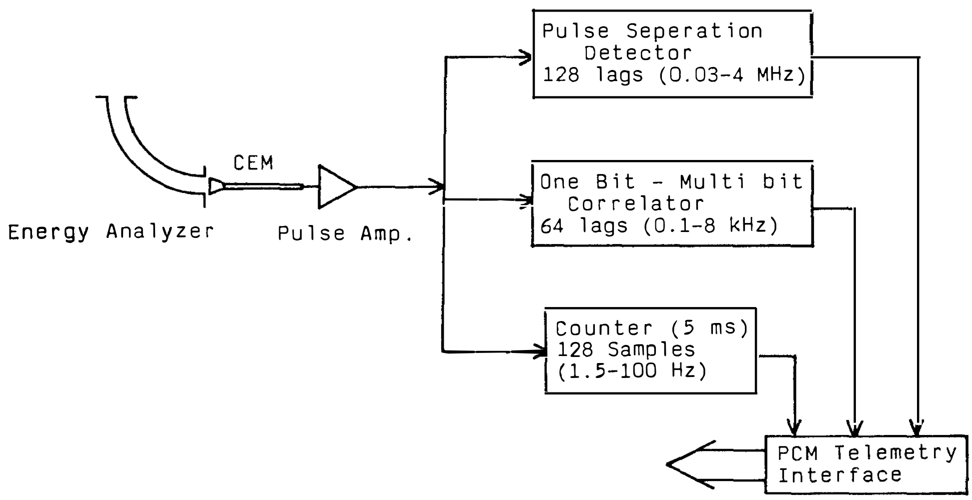

Fig. 3. Functional block diagram of the rocket-borne particle flux modulation detector package (PFMD).

frequency flux modulation (<100 Hz), each of counters accepts signals from one of three CEMs so that the lowest frequency range is observed at all three directions. The energy analyzer has four modes of operation repeated every 2.5 s. One of them is the energy scan mode in which energy steps from 16 keV down to 50 eV. In other three modes, the analyzer observes one of three fixed energies for 0.6 s, *i.e.*, 8 keV, 2.6 keV, and 500 eV, respectively. The data from the PFMD is only meaningful during the last three modes of operation.

Two rockets equipped with the identical experiment package were launched from Syowa Station, Antarctica on May 29, 1987 (S-310JA-11: JA-11 hereafter) and on July 12, 1987 (S-310JA-12: JA-12), respectively. Details of the geophysical conditions are discussed by YAMAGISHI *et al.* (1988b). In short the JA-11 was launched into a quiet aurora arc, and the JA-12 carried out the experiment in a bright aurora arc which was deforming quickly. The PFMD package on the JA-11 started to send back the data on 105 s after the launch when high voltage to the CEMs was turned on and continued the data transmission throughout the rest of the rocket flight. However, on the JA-12, one CEM which fed pulses to the PFMD failed soon after the high voltage was turned on. Therefore we discuss the data from the JA-11 only for the high and medium frequency ranges, and data from two rockets for the lowest frequency range.

4. Data Analysis

4.1. *JA-11 results*

Figure 4 shows an example of the PSD (left diagrams) and OMC (middle diagrams) data and their power spectra. The right diagrams show the raw count data sampled every 5 ms, and its power spectrum. The data were obtained around the height of 200 km on the ascending of the JA-11. As for the PSD data (left diagrams), upper panel shows both the raw data (thick line) and the normalized ACF calculated from the data (broken line). The ordinate is the number of events in a logarithmic scale for the thick line and the normalized ACF value in a linear scale for the broken line. The abscissa is the pulse separation time, or equivalently, the lag time in the number of time steps. Single time step corresponds to 0.125 μs. The lower panel is a cosine Fourier transform of the ACF, where the ordinate is the logarithm of normalized power (Hz^{-1}). As shown in the upper panel, the first two or three time steps of the PSD data suffered from the hardware timing problem. The next ten or so time steps show an enhancement by about factor of four compared to the rest of the data. This enhancement has been shown by laboratory experiments to be due to the ion feed-back (after-pulse) effect occurring inside CEM (ADAMS and MANLEY, 1966). In data analysis this effect must be removed appropriately. In order to cancel the effect, however, we need to investigate nature of the ion feed-back effect in more detail. Meanwhile the first part of the ACF is simply ignored in the following analysis. Figure 5 shows a summary of the PSD data in which intensities of flux modulation are plotted at six frequency points along with the count rate as a function of time after launch. Each point of spectra has a 677 kHz band width. The figure indicates that the power spectrum of the PSD data on the JA-11 typically shows a flat distribution

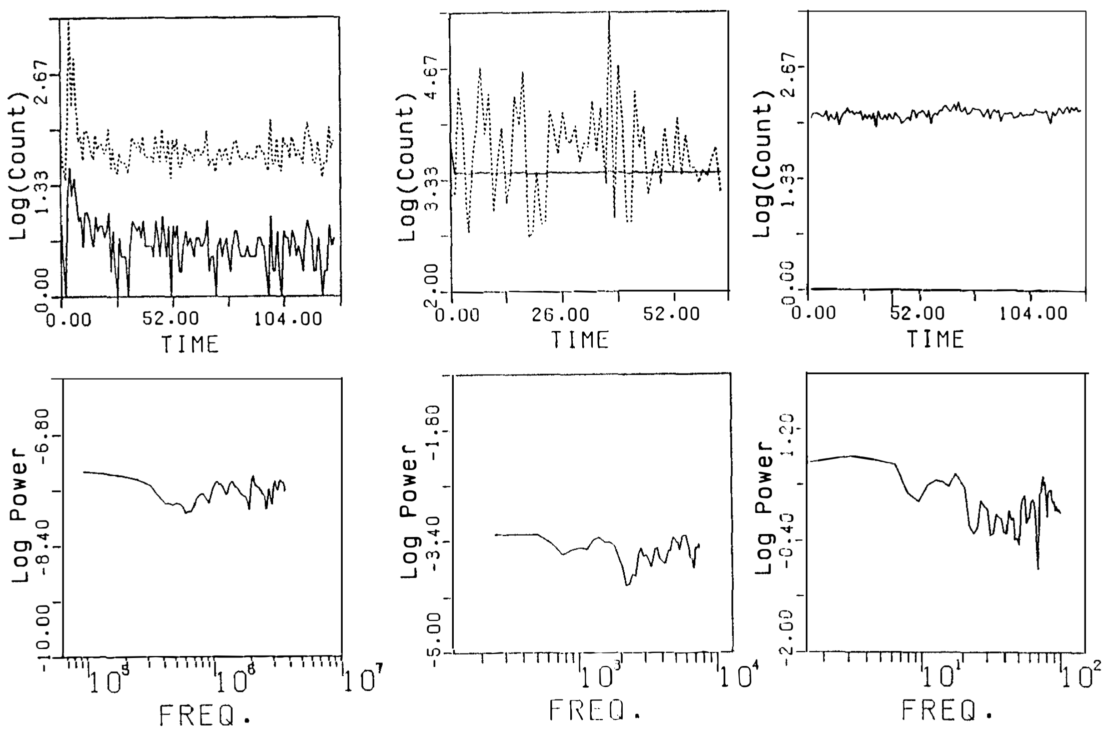

Fig. 4. Three examples of the observed data (upper panels) and their power spectra (lower panels) obtained by the high (left), medium (middle), and low (right) frequency modulation detectors of PFMD. In the left and middle upper panels, thick lines are the raw data plotted in a logarithmic scale, and the broken lines are the normalized ACFs plotted in a linear scale ranging from −1.0 to +1.0 (scale is not shown). The right upper panel plots the logarithmic counts per 5 ms for 0.6 s. The three lower panels are power spectra of the data shown above. Abscissas are the frequency in Hz.

which characterizes a Poisson distribution, and that the power itself is anti-correlated with the counting rate. This is due to an increase of statistical error with decreasing the counting rate.

As for the middle diagrams of Fig. 4, the ordinate is a logarithmic value of the raw ACF obtained by the OMC (thick line) and the normalized ACF in a linear scale (broken line). The lower panel show the power spectrum obtained by applying the cosine Fourier transform to the ACF. Results of the spectral analysis of the OMC data also show that no major flux modulation was observed during the JA-11 flight. The right diagrams of Fig. 4 show an example of the Fourier analysis of a time series of counting rates obtained by the CEM looking at 30° from the rocket spin axis of the JA-11. In the JA-11 experiment, no major flux modulation was observed in this frequency range as well as in other two frequency ranges.

4.2. *JA-12 results*

In the JA-12 rocket experiment, when the rocket passed through the intense precipitation region, low frequency flux modulations were observed. Unfortunately, the PSD and OMC did not send back the data because of the CEM failure. Figure 6 shows several examples of the low frequency modulations of the electron flux obtained by the JA-12. The left diagrams show the raw data and a power spectrum of the 8 keV

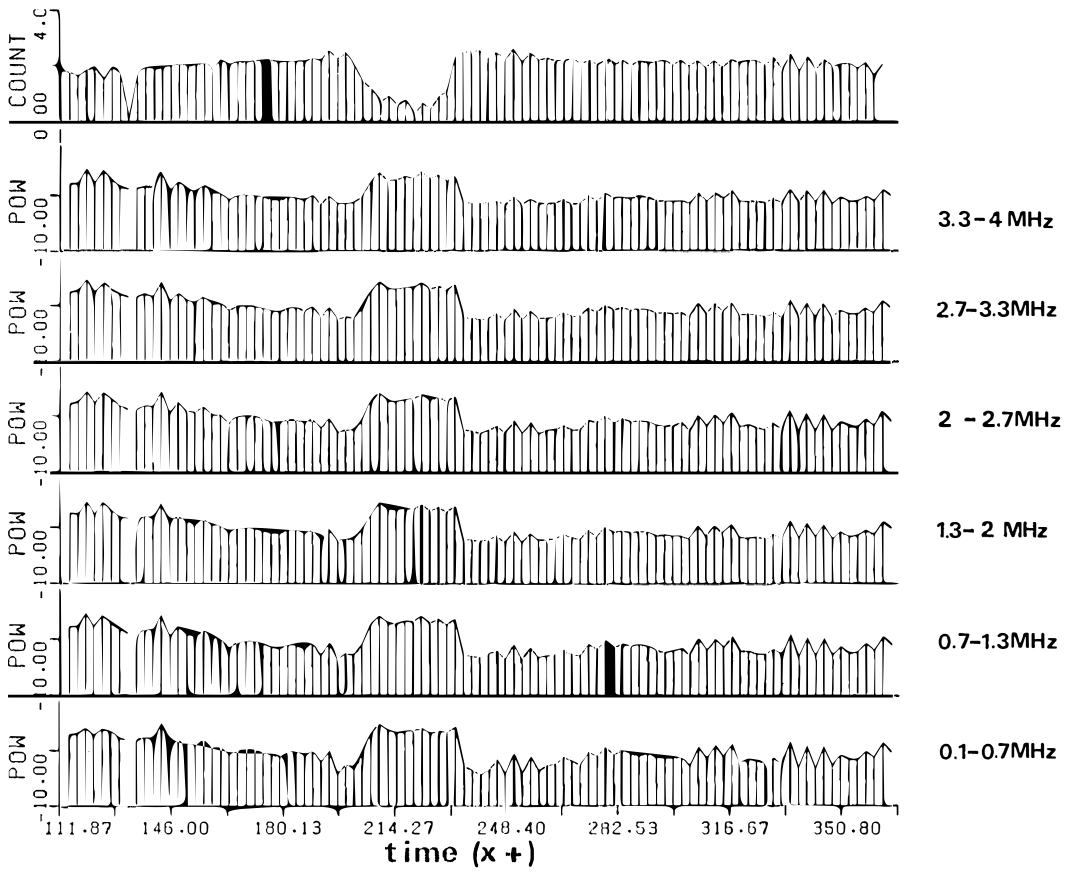

Fig. 5. Six point power spectra of the PSD data (JA-11) are plotted as a function of time after launch. Ordinates of the lower six panels are the normalized power in a logarithmic scale. The top panel plots the counts per 5 ms in a logarithmic scale.

electron flux observed at X+350.7 s. The power spectrum shows a clear peak near 10 Hz. The CEM was looking at the upward direction at that time. The modulation depth at 10 Hz was about 10% of the average flux. Small peak in the power spectrum of the 2.6 keV electrum flux (not shown) was also observed at this frequency, but it is not clear as in the figure. The middle diagrams of Fig. 6 show another example observed at X+363.5 s at the 8 keV energy. The power spectrum indicates the modulation with a more noise-like feature than the spectrum in the left diagrams. The right diagrams show an example observed by the CEM looking downward at the 500 eV energy. The data was taken at X+346.8 s. In this example, the peak frequency (7 Hz) was lower than the previous two examples. Note that, when these low frequency modulations were observed in the data from one CEM, another CEM which was simultaneously observing at the different pitch-angle did not detect modulations. This was true for all three cases shown in the figure.

During the data aquisition period of 0.6 s, the rocket spinned almost 130° due to the 0.57 Hz rocket spin frequency. Pitch-angle of the electron flux observed by the CEM looking at 30° from the spin axis changed within a range from 15° to 70° at maximum. Therefore a part of the flux modulation shown in the figure may be due to the change in pitch-angle. However the 10 Hz modulations correspond to the

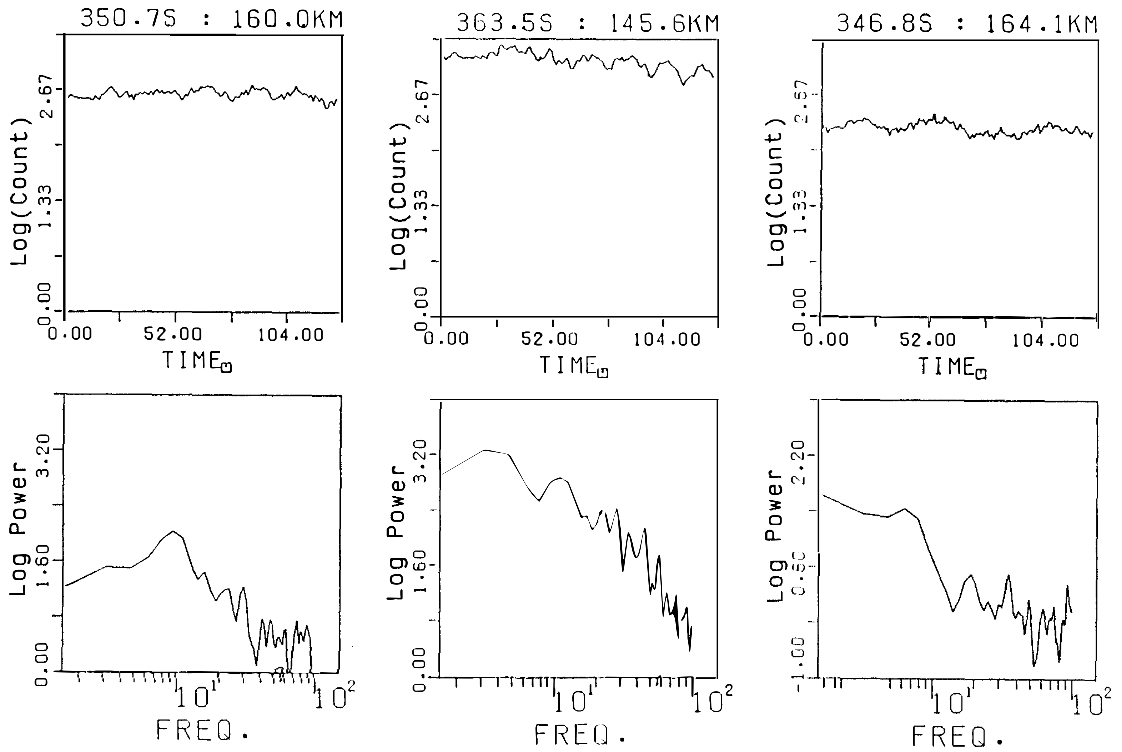

Fig. 6. Three examples of low frequency modulations of electron flux observed by the JA-12. See the legend of Fig. 4.

less than 10° change in pitch-angle, if the modulation was due to a non-uniform pitch-angle distribution of electrons. This seems too small to account for the amount of the flux modulation shown in the figure.

5. Summary

An instrument was developed for observing the particle flux modulation up to several megahertzs. The instrument consists of three parts, each utilizes different techniques to detect the flux modulation in one of three frequency ranges. For the highest range of frequency, the pulse separation method was used to calculate ACFs, for the medium frequency range, we use the One bit – Multi bit correlator, and for the lowest frequency range, the raw count data were transmitted for the Fourier analysis on the ground. The instrument was on board two rockets launched into the auroral ionosphere in Antarctica. One rocket (JA-11) penetrated a relatively quiet auroral arc. The electron flux showed no major modulation in all frequency ranges. There was no strong plasma wave activity observed by plasma wave instruments on board the same rocket. Another rocket (JA-12) made observations in a bright auroral arc. Results show some low frequency modulations of the electron flux associated with intense precipitations of electrons. Unfortunately, only the lowest frequency range of the flux modulation was obtained in the JA-12 experiment. It is interesting that, when one of these low frequency modulations was observed at X+331.5 s, the magnetic field experiment detected a strong perturbation which suggests a presence

of field-aligned currents (TOHYAMA *et al.*, 1988). However further investigation is necessary to clarify what process is responsible for these low frequency modulations of electrons.

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