Observation of VLF Emissions at Syowa Station in 1970–1971
II. Spectral Structure of Quasi-Periodic VLF Emissions

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昭和基地における VLF エミッション観測（1970—1971）
Ⅱ．準周期的 VLF エミッションのスペクトル構造

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要旨：1970年2月から1971年2月まで南極昭和基地で VLF 帯自然電波の観測が各種の装置によって行なわれた．この論文では 5 kHz より低い周波数帯でみられる VLF エミッションの中で，その強度が約 20 秒～60 秒の周期で変動する準周期的 VLF エミッション（QP エミッション）と呼ばれる現象を取り扱う．

自動反転型のテープレコーダによって連続録音された VLF 帯自然電波の磁気テープ記録を周波数分析することにより，VLF エミッションのダイナミック・スペクトルが作成され，QP エミッションのスペクトル構造が詳しく調べられた．さらに，これらのスペクトル記録を地磁気脈動記録と比較することによって，（1）地磁気脈動と同じ周期をもち，しかも脈動と同時に始まる QP エミッションがしばしば発生する，（2）磁気圏全体の圧縮に対応すると思われる磁場変動に伴って QP エミッションが発生することが多い，（3）地磁気活動度の最も低い日の午後から夕方にかけての時間帯で，地磁気脈動を伴わない QP エミッションが発生する，の点が明らかになった．

1. Introduction

VLF emissions modulated with fairly regular periods longer than the two-hop whistler group delay have been called the quasi-periodic (QP) VLF emissions (HELLIWELL, 1965). Such VLF emissions are generally observed in the daytime at high and middle latitudes (CARSON *et al.*, 1965; KITAMURA *et al.*, 1969; KOKUBUN, 1971). The period of the quasi-periodic VLF emissions ranges from 10 s to 2 min, but QP emissions with periods from 20 to 30 s are most often observed at high latitudes (EGELAND, 1965; KITAMURA *et al.*, 1969). KITAMURA *et al.* (1969) found that quasi-periodic VLF emissions are classified into two types on the basis of spectral structure and associated geomagnetic micropulsation (GP) activity, i. e., the first type is a quasi-periodic VLF emission associated with geomagnetic pulsations (GP-associated QP's) and the second type is an emission without any corresponding geomagnetic pulsations or with a period different from that of correspond-

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ing geomagnetic pulsations (QP's not associated with GP activity). They have shown that the spectrum of GP-associated QP's is characterized by a diffuse structure and the upper frequency limit of the emission band often fluctuates, synchronously with a change in the signal strength, whereas the spectrum of QP's not associated with GP activity comprises regularly spaced rising frequency segments.

This paper is a preliminary report concerning the quasi-periodic VLF emissions observed at Syowa Station (corrected geomagnetic lat. −66.7°, long. 72.5°; L= 6.4) in Antarctica. The characteristics of the two types of QP emissions, which were classified by KITAMURA *et al.* (1969), are examind statistically first. Then, the spectral structure is discussed in detail through the spectral analysis of the continuous magnetic tape records of VLF emissions. The relationship between the occurrence of QP emissions and the worldwide geomagnetic change also is investigated.

2. Instrumentation

A block diagram of the instruments for the observation of VLF emissions in the frequency range 0.2–5 kHz is shown in Fig. 1 (For the technical detail of the instruments, see HAYASHI, 1972). The VLF signals detected by a loop antenna with an effective area of 400 m^2 were amplified by means of a low-noise preamplifier and a main amplifier, whose gains are about 68 and 98 dB, respectively, and the output signals were recorded with several equipments. In these records, the magnetic tape records and the records of VLF emission signal strengths in 5 filtered frequency bands (0.5, 0.7, 1.0, 1.5 and 2.0 kHz) are mainly utilized for the present analysis.

The tape recorder was continuously operated from February 1970 to February 1971 except the period when QP emissions were not observed. The total recording time during this period was about 5,200 hours. From these magnetic tape records, frequency-time spectra of VLF emissions in the frequency range 0.2–5 kHz were produced on 35 mm film by means of a Rayspan spectrum analyzer.

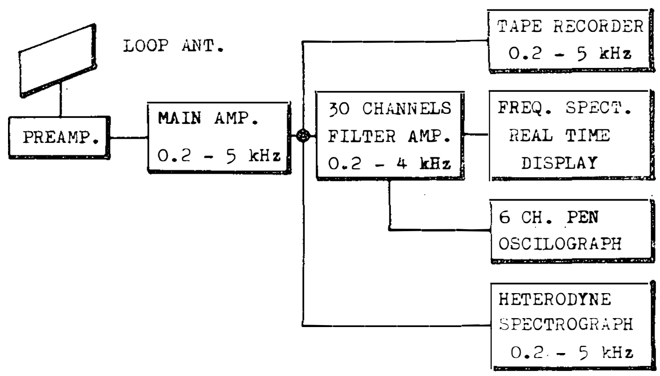

Fig. 1. A block diagram of the observation system for VLF emissions in the frequency range 0.2–5 kHz.

On the other hand, geomagnetic micropulsations were detected by a three-component induction magnetometer, and the output signals were recorded by a PWM data recorder and a scratchfilm recorder. The X- and Y-components of pulsations and the VLF emission signal strengths were also simultaneously recorded by a 6 channel pen recorder to investigate the correlation between quasi-periodic VLF emissions and geomagnetic pulsations.

3. Diurnal Variations of Occurrence and Period of Quasi-Periodic (QP) VLF Emissions

The diurnal variation of quasi-periodic VLF emission occurrence at Syowa Station from February 16, 1970 to February 16, 1971 is shown in Fig. 2. Most QP emissions were observed on the dayside with a maximum occurrence around noon. This tendency is in agreement with the diurnal variation of polar chorus emission occurrence reported by UNGSTRUP and JACKEROTT (1963) and HAYASHI and KOKUBUN (1971). However, if the statistics of the occurrence is taken for each type of QP emissions, i. e., GP-associated QP's (type 1) and QP's not associated with GP activity (type 2), the diurnal variation pattern is a little different from that shown in Fig. 2. Fig. 3 illustrates the percentage of the occurrence of the second type QP's against the occurrence of the first type QP's as a function of geomagnetic local time. It is noticeable that the percentage of occurrence of the second type QP emissions increases greatly after 1400 GLT. That is, GP-associated QP's are most frequently observed from the morning to the afternoon, whereas the appearance of QP's not associated with GP activity is dominant in the evening hours.

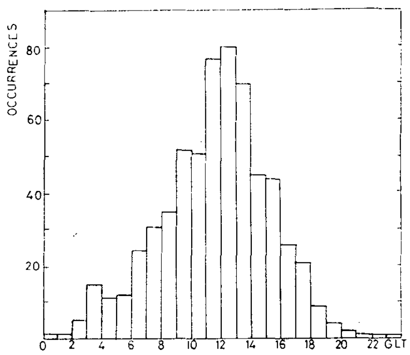

Fig. 2. Diurnal variation of occurrence of quasi-periodic VLF emissions observed from February 16, 1970 to February 16, 1971 at Syowa Station. When QP emissions are observed in a one-hour interval, that time interval is counted as an event.

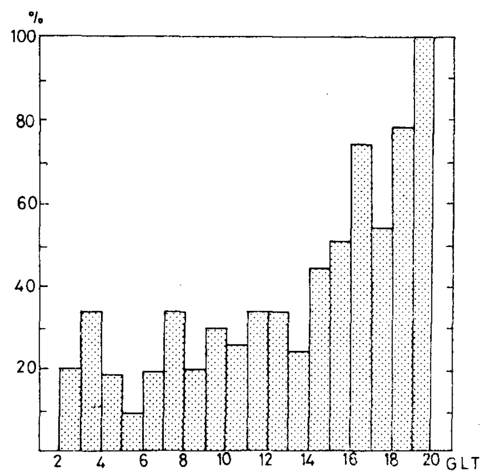

Fig. 3. Percentage of occurrence of QP's not associated with GP activity against occurrence of GP-associated QP's as a function of geomagnetic local time.

The frequency range of the observed QP emissions was about 0.3–1.5 kHz, which is the same as that of polar chorus emissions observed at Syowa Station. Fig. 4 indicates the occurrence that QP emissions in the frequency range higher than 1.5 kHz was seldom. The periods of most QP emissions range from 20 to 60 s. The diurnal variations for the periods are illustrated in Figs. 5 and 6 for each type of QP's. It may be evident that the period tends to increase gradually from the morning to the evening. This tendency is more markedly observed for the GP-

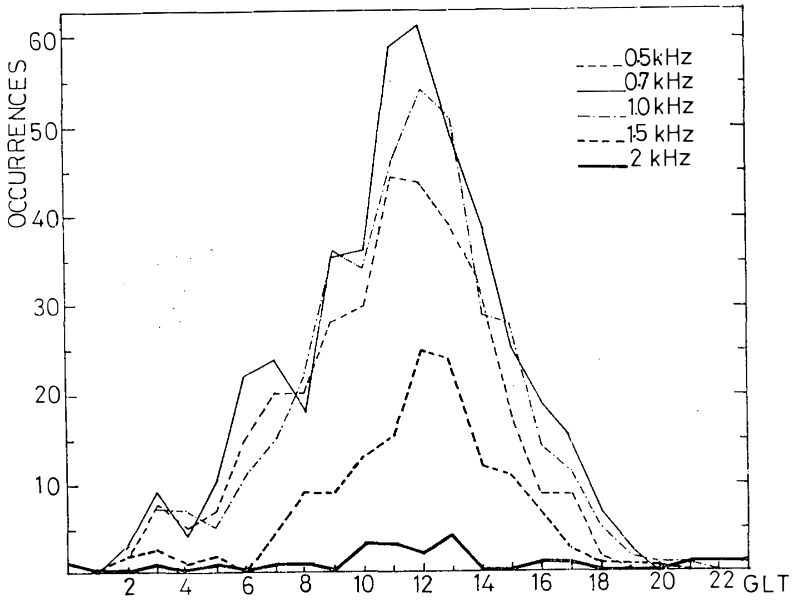

Fig. 4. Diurnal variation of occurrence of QP emissions observed from February 16, 1970 to February 16, 1971 at Syowa Station. The statistics of the occurrence was taken for each frequency band centered at 0.5, 0.7, 1.0, 1.5 and 2.0 kHz.

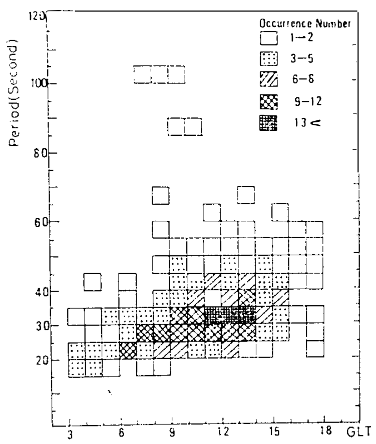

Fig. 5. Diurnal variation of period of GP-associated QP's observed from February 16, 1970 to February 16, 1971 at Syowa Station.

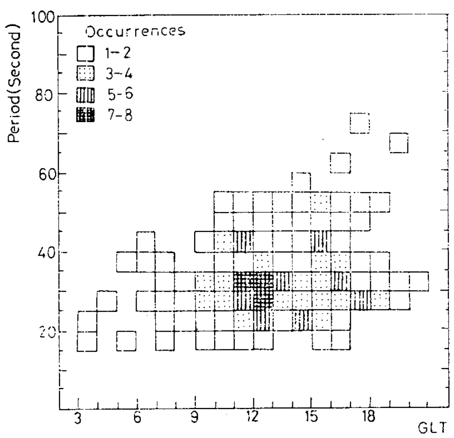

Fig. 6. Diurnal variation of period of QP's not associated with GP activity, which were observed from February 16, 1970 to February 16, 1971 at Syowa Station.

associated QP's in Fig. 5.

As for the dependence of the occurrence on magnetic activity, it is concluded that QP emissions were generally observed at Syowa Station in the recovery phase of a magnetic storm. The Kp-dependence of the occurrence is shown in Fig. 7. It is found that GP-associated QP's have a maximum occurrence in the period of low magnetic activity of $2_0 \leqq Kp \leqq 3-$, while the appearance of QP's not associated with GP's is dominant when the magnetic activity is the most quiet, i. e., $1_0 \leqq Kp \leqq 2-$.

4. Spectral Structure of Quasi-Periodic (QP) VLF Emissions

Durations of the QP events observed at Syowa Station were in the range from a few minutes to several hours. The spectral structure of QP emissions considerably varies in these durations. Examples of the dynamic spectra of QP's from the onset to the end of the events, whose durations were about 1-4 hours, are illustrated in Appendix I.

Typical examples of the frequency-time spectra of GP-associated QP's and QP's not associated with GP activity are shown in Figs. 8-11 and Figs. 12-15, respectively. The simultaneous records of geomagnetic pulsations and VLF emission signal strengths in the frequency bands centered at 0.5, 0.7 and 1.0 kHz are illustrated also in these figures. The spectrum of GP-associated QP's generally has a diffuse structure, and the quasi-periodic variations of the emission strengths are often accompanied by a synchronous fluctuation of the upper frequency limit of emissions (Figs. 8 a, b and 9). These spectral features have been already pointed out by KITAMURA *et al.* (1969). However, a rise of the emission frequency during a quasi-period is sometimes observed (Figs. 10 and 11). This spectral structure is similar to the spectrum of QP's not associated with GP activity, but the emissions are well synchronized by the geomagnetic pulsations so that the time interval be-

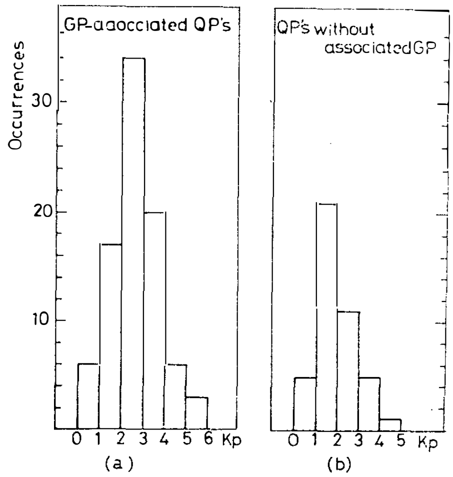

Fig. 7. Kp dependence of occurrence of (a) GP-associated QP's and (b) QP's not associated with GP activity.

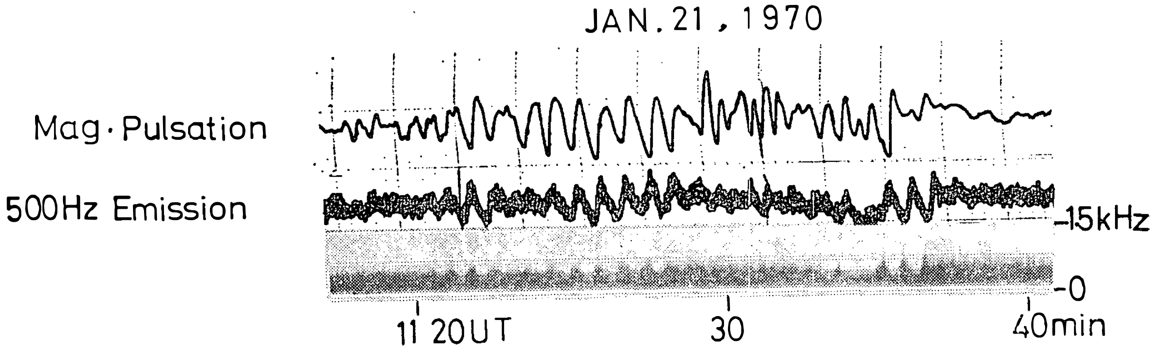

Fig. 8(a). Example of a GP-associated QP emission with a period of about 50 seconds. A distinct one-to-one correspondence can be seen between QP emission and geomagnetic pulsation.

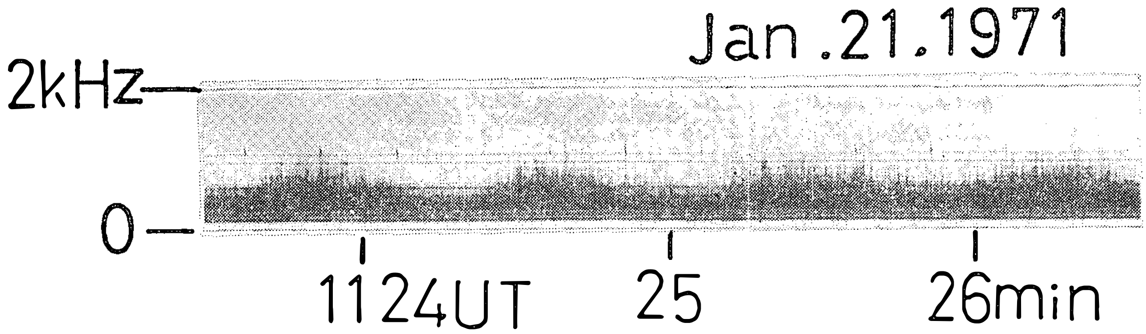

Fig. 8(b). Fine structure of a frequency-time spectrum of the QP emission which is shown in Fig. 8(a). It is found that the spectrum of the emission has a diffuse structure and the quasi-periodic variation of the emission intensity is accompanied by a synchronous modulation of the upper frequency limit of the emission.

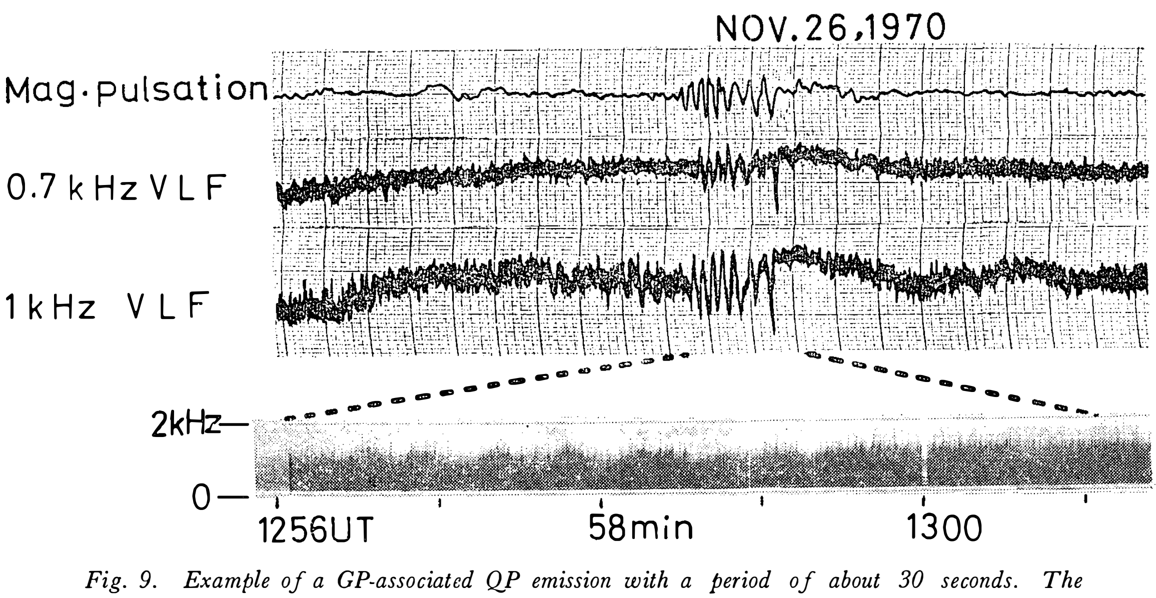

Fig. 9. Example of a GP-associated QP emission with a period of about 30 seconds. The simultaneous onset and cessation of QP emission and geomagnetic pulsation are noticed in the time interval 1256–1300 UT.

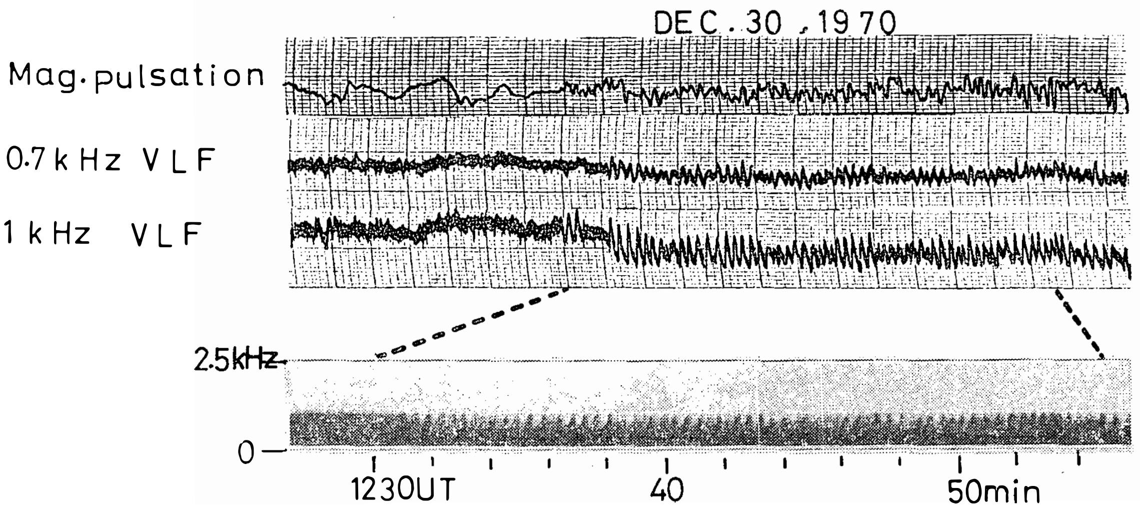

Fig. 10. Example of a GP-associated QP emission with a period of about 24 seconds. The QP modulation of VLF emission began at 1228 UT simultaneously with the onset of geomagnetic pulsation, but the VLF emission activity had been already enhanced before 1228 UT.

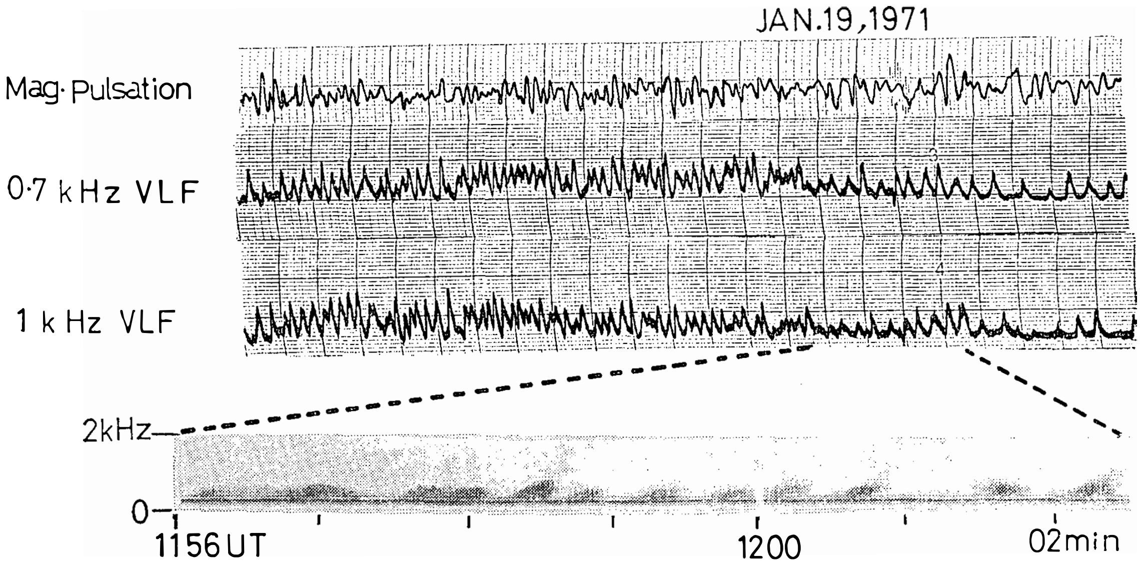

Fig. 11. Example of a GP-associated QP event. The time interval between segments is fairly irregular, ranging from 20 to 60 seconds.

tween rising segments is fairly irregular in contrast with that of QP's not associated with GP's. The simultaneous onset and cessation of QP's and GP's were often observed, suggesting a close relation between the generation mechanisms of both the phenomena. Figs. 9 and 10 are typical examples of such events.

On the other hand, the spectrum of QP's not associated with GP activity consists of regularly spaced risers (Figs. 12–15). The spectral structure of risers is diffuse (Fig. 15 b) or it is a superposition of diffused noises and discrete emissions

(Fig. 12 b). The time interval between discrete emissions is about 2–4 seconds, and this period is comparable to the two-hop whistler group delay time.

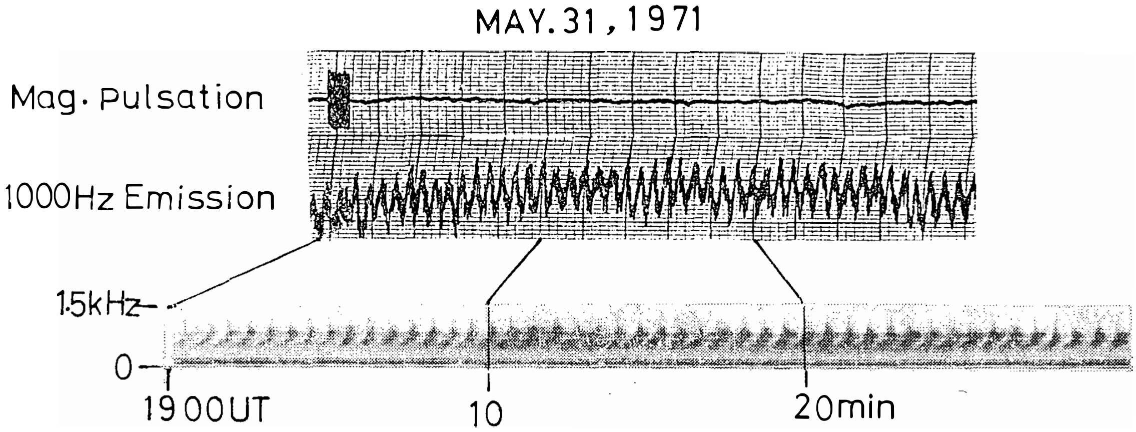

Fig. 12(a). Example of a QP event without any corresponding geomagnetic pulsation. The period of the QP emission is about 40 seconds.

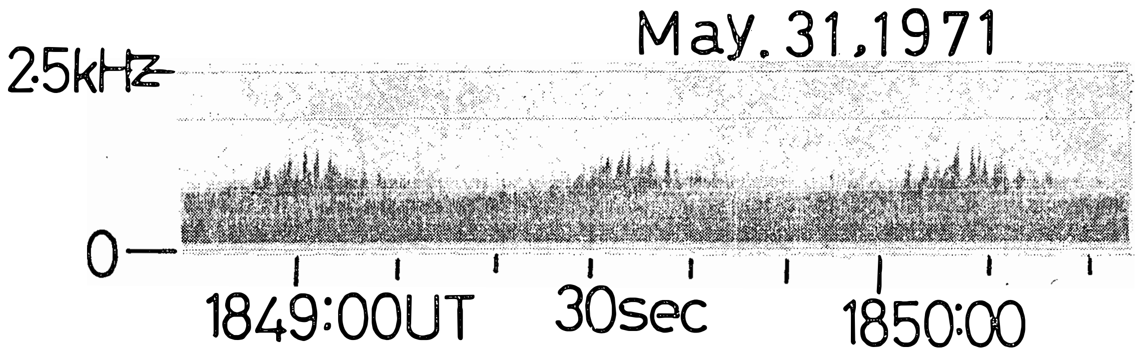

Fig. 12(b). Fine structure of a frequency-time spectrum of the QP emission which is shown in Fig. 12(a). A rising segment comprises superposition of diffuse noise and discrete emissions.

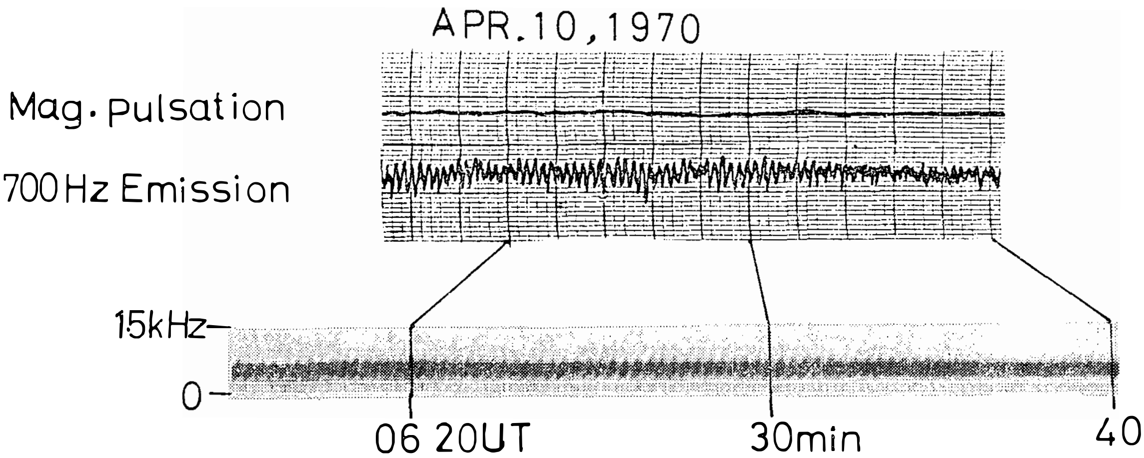

Fig. 13. Example of a QP event without any corresponding geomagnetic pulsation. The period of the QP emission is about 20 seconds.

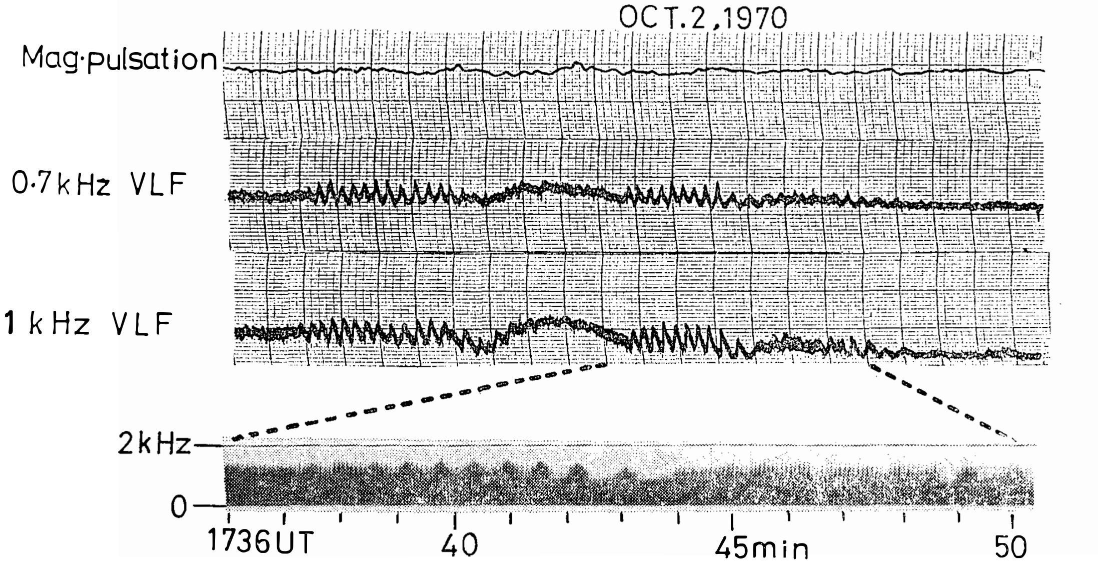

Fig. 14. Example of a QP event without any corresponding geomagnetic pulsation. It is found that the periodic emissions with a period of 5 seconds are quasi-periodically modulated with a period of about 36 seconds, resulting in the risers. The variation in the slope of the risers also can be seen in this spectrum.

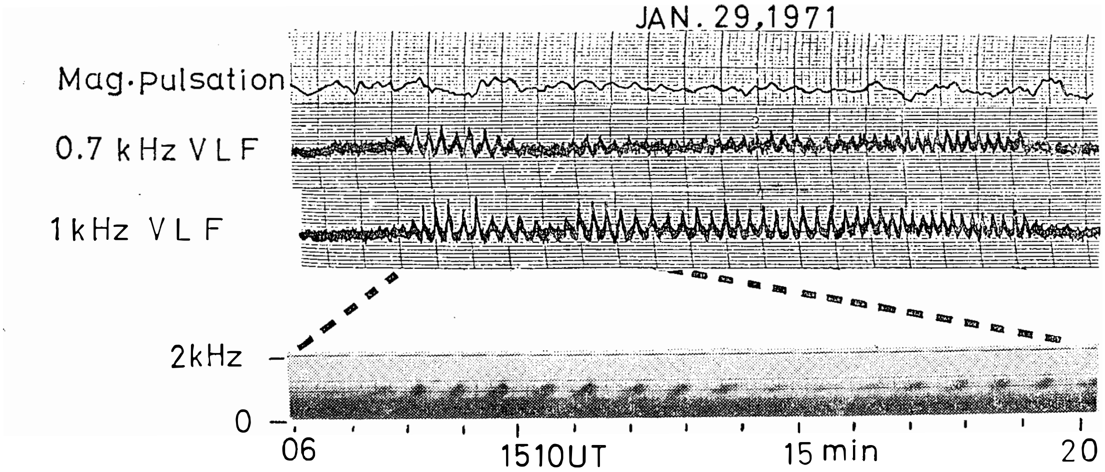

Fig. 15(a). Example of a QP event with a period different from that of accompanying geomagnetic pulsation. The period of QP emission is about 52 seconds.

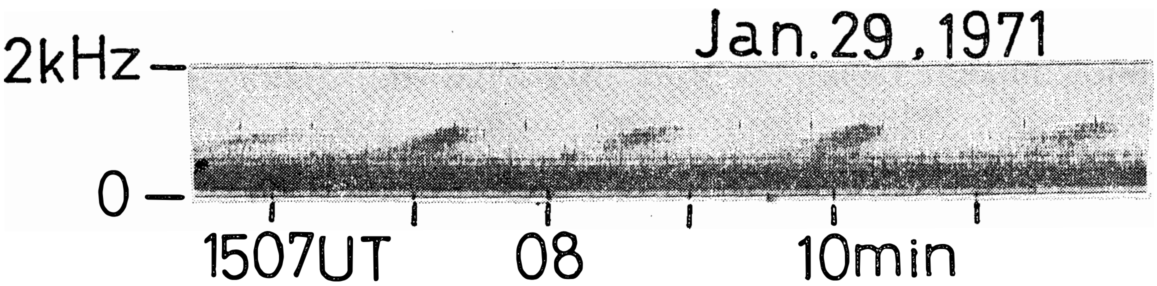

Fig. 15(b). Fine structure of a frequency-time spectrum of the QP emission which is shown in Fig. 15 (a). The rising segments consist of diffuse noises.

5. Occurrences of Quasi-Periodic (QP) VLF Emissions Associated with a Worldwide Geomagnetic Change

When the amplitude of geomagnetic pulsations associated with QP emissions is large at Syowa Station, the corresponding geomagnetic pulsations are observed at middle and low latitudes also. Fig. 16 is an example showing a good correlation between the QP emissions observed at Syowa Station in the auroral zone and the geomagnetic pulsations at San Juan (geomagnetic lat. 29.9°, long. 3.2°) at low latitude. The GP-QP association is most distinct in the time intervals 1134-1143 UT and 1210-1220 UT. Fig. 17 is another example of the GP-associated QP's. The GP-QP association is remarkable between 1255 and 1300 UT.

In addition to the VLF emission modulation related to the rapid geomagnetic pulsations of 20-60 seconds in period, the fluctuation of the VLF emission intensity associated with the slowly varying geomagnetic H component was often observed. Fig. 18 shows that the intensity of both the background emissions and the QP emissions increased, in association with the worldwide increase in the geomagnetic H component, which can be considered to result from compression of the magnetosphere. Such a relationship can be seen in Fig. 16 also. It may be evident that the background emission intensity rises when the H component increases, and vice versa. The increase in the polar chorus emission intensity accompanied by a sudden compression of the magnetosphere such as ssc's and positive si's has been already

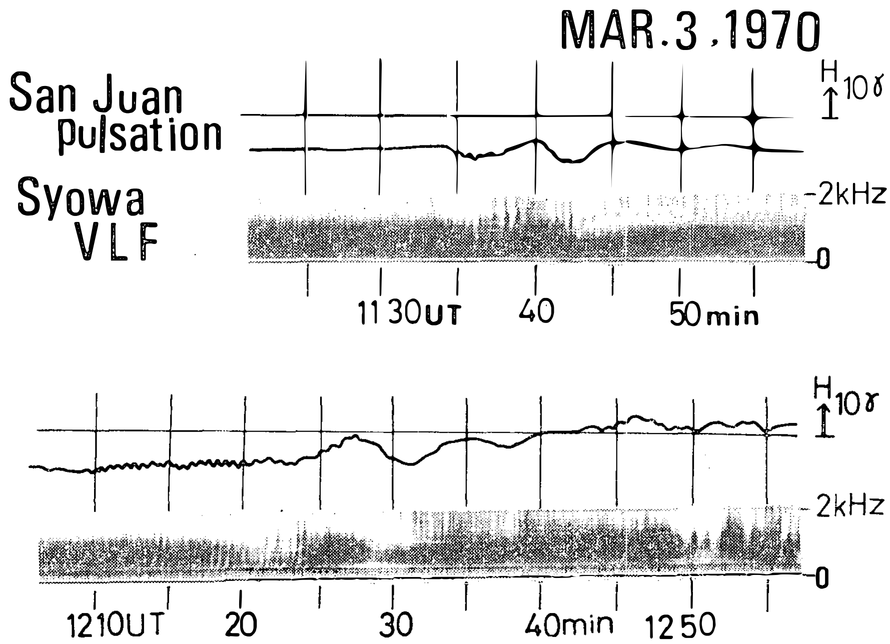

Fig. 16. Example of a close correlation between the QP emission observed at Syowa Station in the auroral zone and the geomagnetic pulsation at San Juan at low latitude.

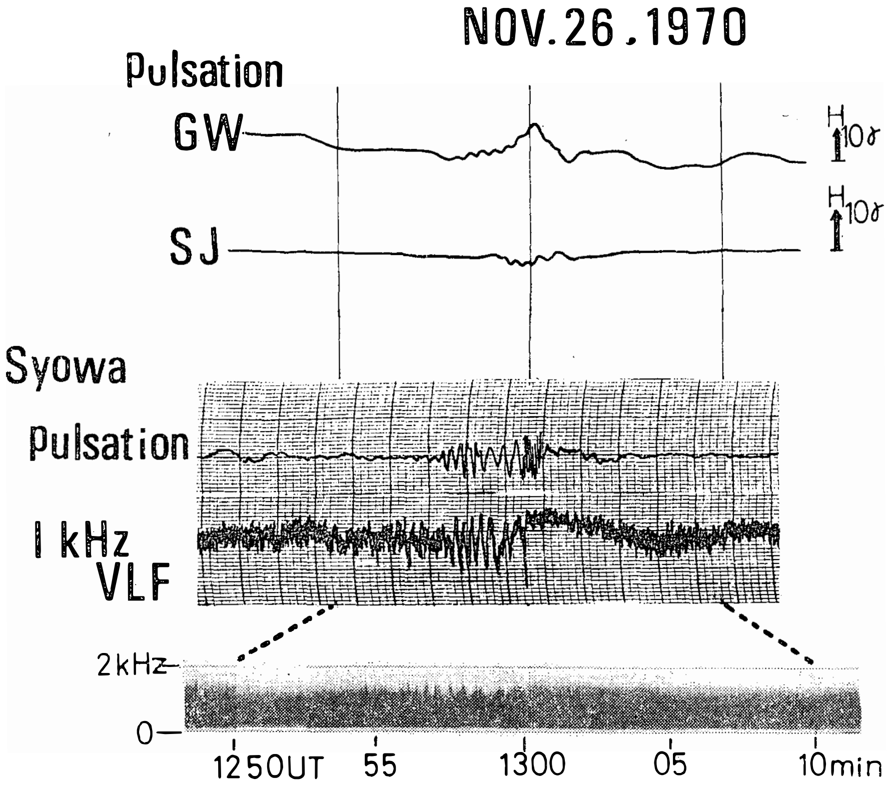

Fig. 17. Example of a QP emission correlated with geomagnetic pulsations which were observed at Syowa Station and Great Whale River in the auroral zone and also at San Juan at low latitude.

reported by MOROZUMI (1965) and HAYASHI *et al.* (1968). Fig. 19 shows that the sudden enhancement of the QP emission intensity occurred after a positive si at 1507 UT, whereas the emission intensity rapidly decreased after negative si's at 1440 UT and 1545 UT. An example of the occurrence of the QP emissions just after ssc is given in Fig. 20.

6. Discussion

The quasi-periodic VLF emissions with the same period as that of the geomagnetic pulsations were observed on moderately quiet days at Syowa Station in the auroral zone. The simultaneous onset and cessation of the QP emissions and the geomagnetic pulsations were often observed (Figs. 9 and 10). Moreover, it is shown in Section 5 that the intensities of the QP's and the bockground VLF emissions rise after ssc's and si's and also during the gradual worldwide increase in the geomagnetic H component, all of which are thought to be generated by compression of the magnetosphere. Therefore, it will be possible that the QP emissions are generated by modulation of VLF emission source due to compressional Alfvén

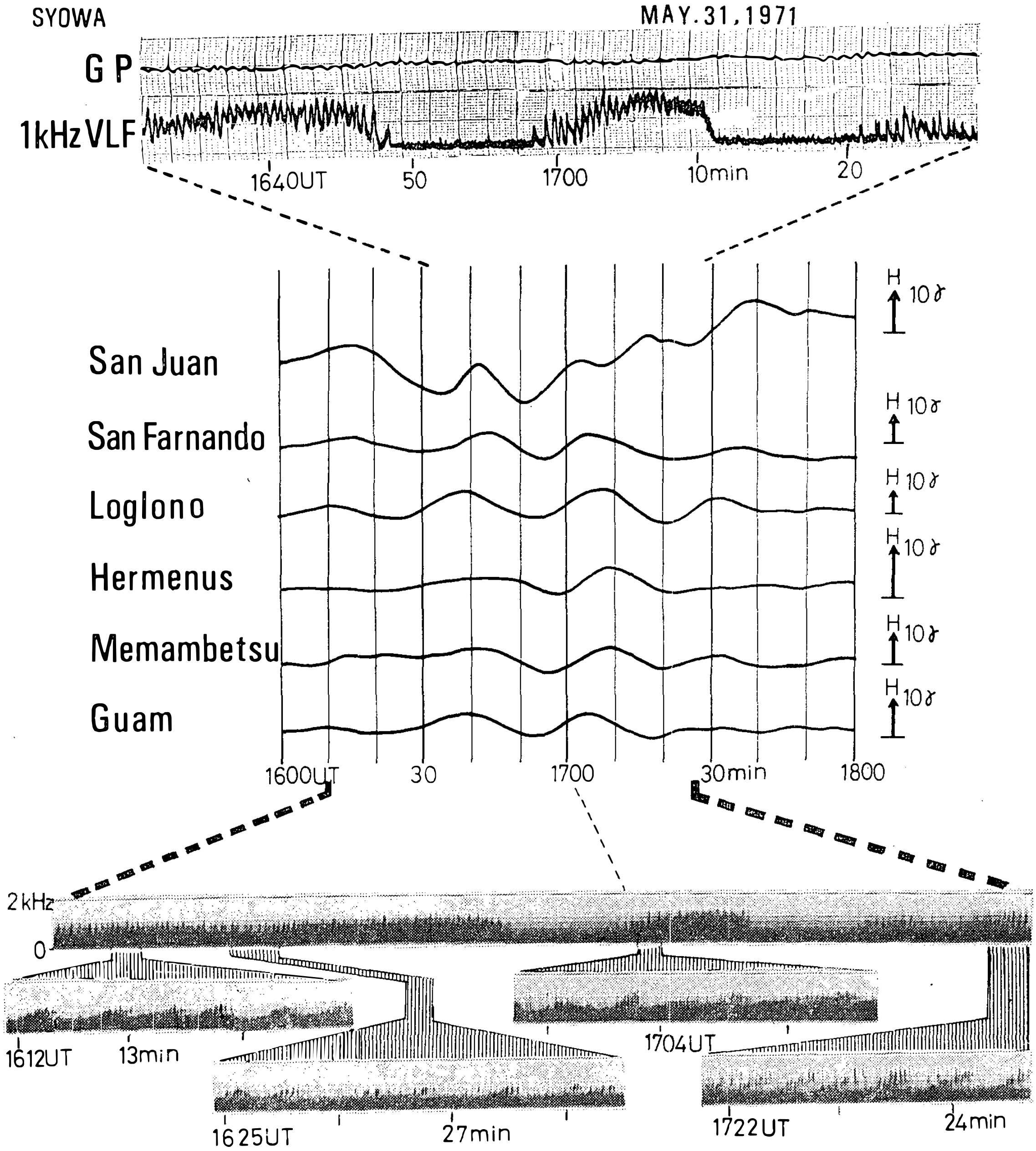

Fig. 18. Enhancement of the intensity of both the background emission and the QP emission, corresponding to the worldwide increase in the geomagnetic H component.

mode (R mode) waves. The same idea has already been suggested by KOKUBUN (1971) and HAYASHI (1972).

On the other hand, the QP's not associated with geomagnetic pulsation activity were observed on most quiet days at Syowa Station. The occurrences of emissions of this type are dominant in the evening region. The L value of Syowa Station is 6.4 so that the geomagnetic field lines connected to the station are considered to enter into the plasmasphere bulge in this local-time region on quiet days. The

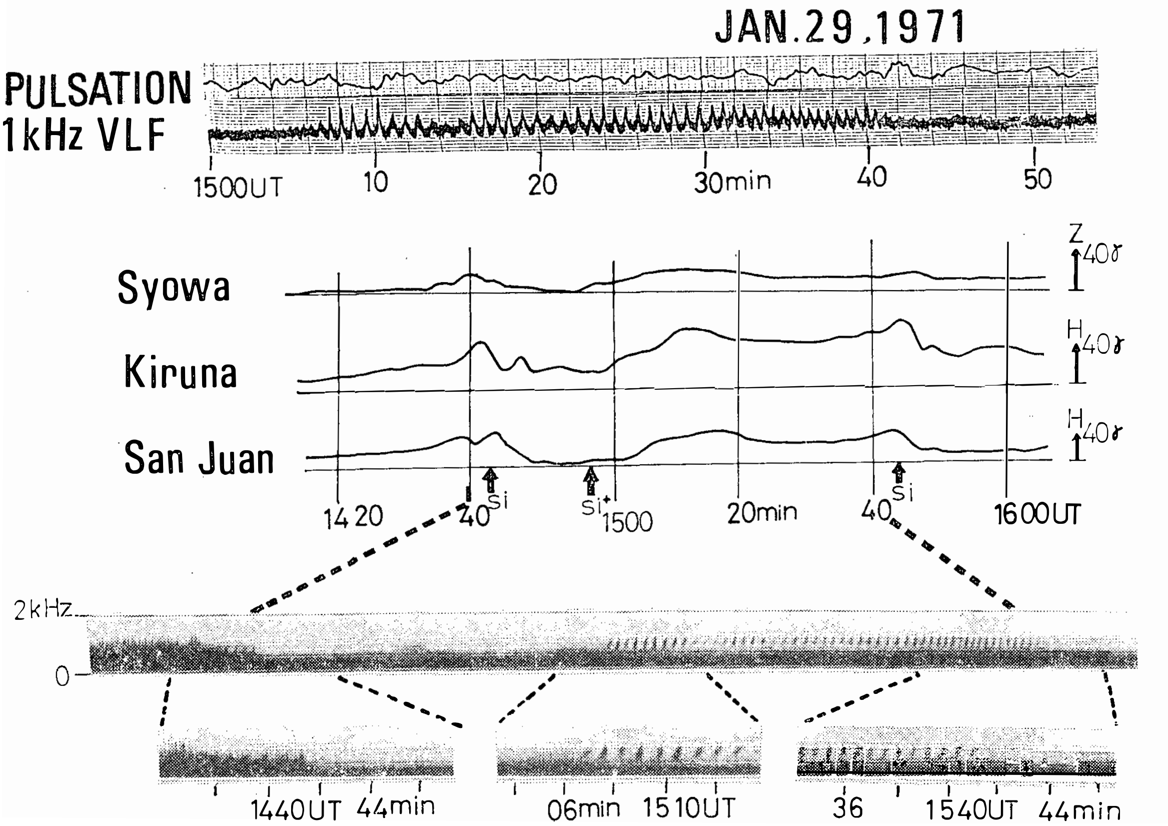

Fig. 19. Example of the appearance and the disappearance of QP emissions just after the positive and negative si's.

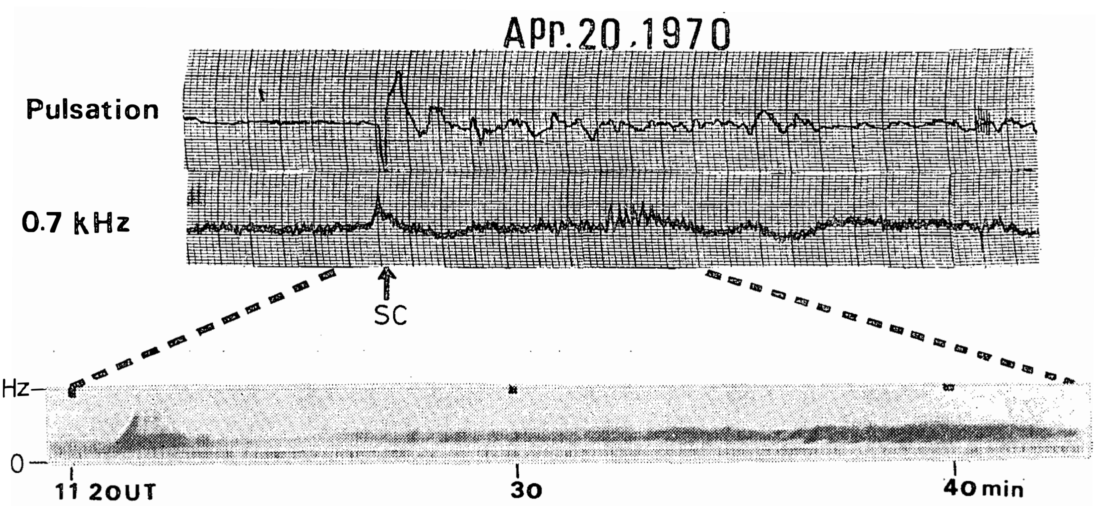

Fig. 20. Example of the occurrence of the QP emission just after ssc at 1122 UT.

spectral structure comprises regularly spaced risers, the structure being well similar to that of QP emissions observed at middle latitudes (CARSON *et al.*, 1965). Therefore, QP's of this type may be generated inside the plasmapause. However, the explanation for the periodicity of the emissions is still unknown. A study on this subject is in progress.

Acknowledgements

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References

CARSON, W. B., J. A. KOCH, J. H. POPE and R. M. GALLET (1965): Long-period very low frequency emission pulsations. J. Geophys. Res., **70**, 4293–4303.

EGELAND, A., G. GUSTAFFSON, S. OLSEN, J. AARONS and W. BARRON(1965): Auroral zone emissions centered at 700 cycles per second. J. Geophys. Res., **70**, 1079–1082.

HAYASHI, K. (1972):VLF • ELF emissions in high latitudes, especially their generation and modulation in the magnetosphere. Ph. D. Thesis, Univ. of Tokyo, December.

HAYASHI, K. and S. KOKUBUN (1971): VLF emissions during post breakup phase of polar substorm. Rep. Ionos. Space Res. Japan, **25**, 369–382.

HAYASHI, K., S. KOKUBUN and T. OGUTI (1968): Polar chorus emission and worldwide geomagnetic variation. Rep. Ionos. Space Res. Japan, **22**, 149–160.

HELLIWELL, R. A. (1965): Whistlers and related ionospheric phenomena. Stanford University Press, Stanford California.

KITAMURA, T., J. A. JACOBS T. WATANABE and R. B. FLINT, Jr. (1969): An investigation of quasi-periodic VLF emissions. J. Geophys. Res., **74**, 5652–5664.

KOKUBUN, S. (1971): Association between quasi-periodic VLF emission and micropulsation. Rep. Ionos. Space Res. Japan, **25**, 383–388.

MOROZUMI, H. M. (1965): Enhancement of VLF chorus and ULF at the time of SC. Rep. Ionos. Space Res. Japan, **15**, 371–374.

UNGSTRUP, E. and L. M. JACKEROTT (1963): Observation of chorus bellow 1500 cycles per second at Godhaven, Greenland from July 1957 to December 1961. J. Geophys. Res., **68**, 2141–2146.

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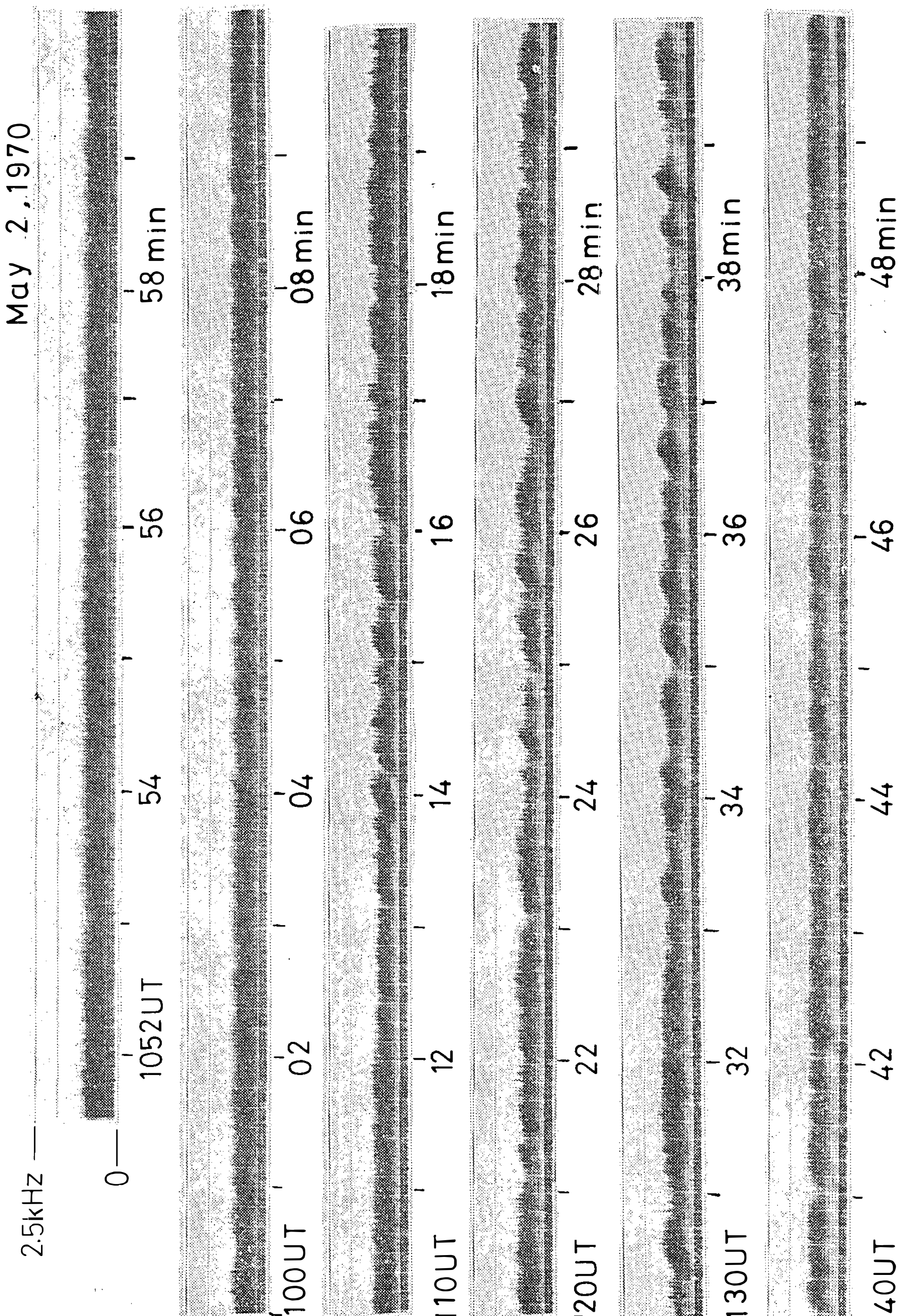
Appendix I

The frequency-time spectra of QP emissions are continuously shown from the onset to the end of the event. The events on May 2, 1970 and January 19, 1971 are examples of the GP-associated QP emissions, whereas the events on April 1–2, 1970 and May 31, 1971 are examples of the QP emissions not associated with geomagnetic pulsations. In the event on April 1, 1970, a sudden enhancement of background VLF emissions after 0852 UT was induced by a positive si.


May 2, 1970
2.5kHz
0
1052UT
54
56
58 min
1100UT
02
04
06
08 min
1110UT
12
14
16
18 min
1120UT
22
24
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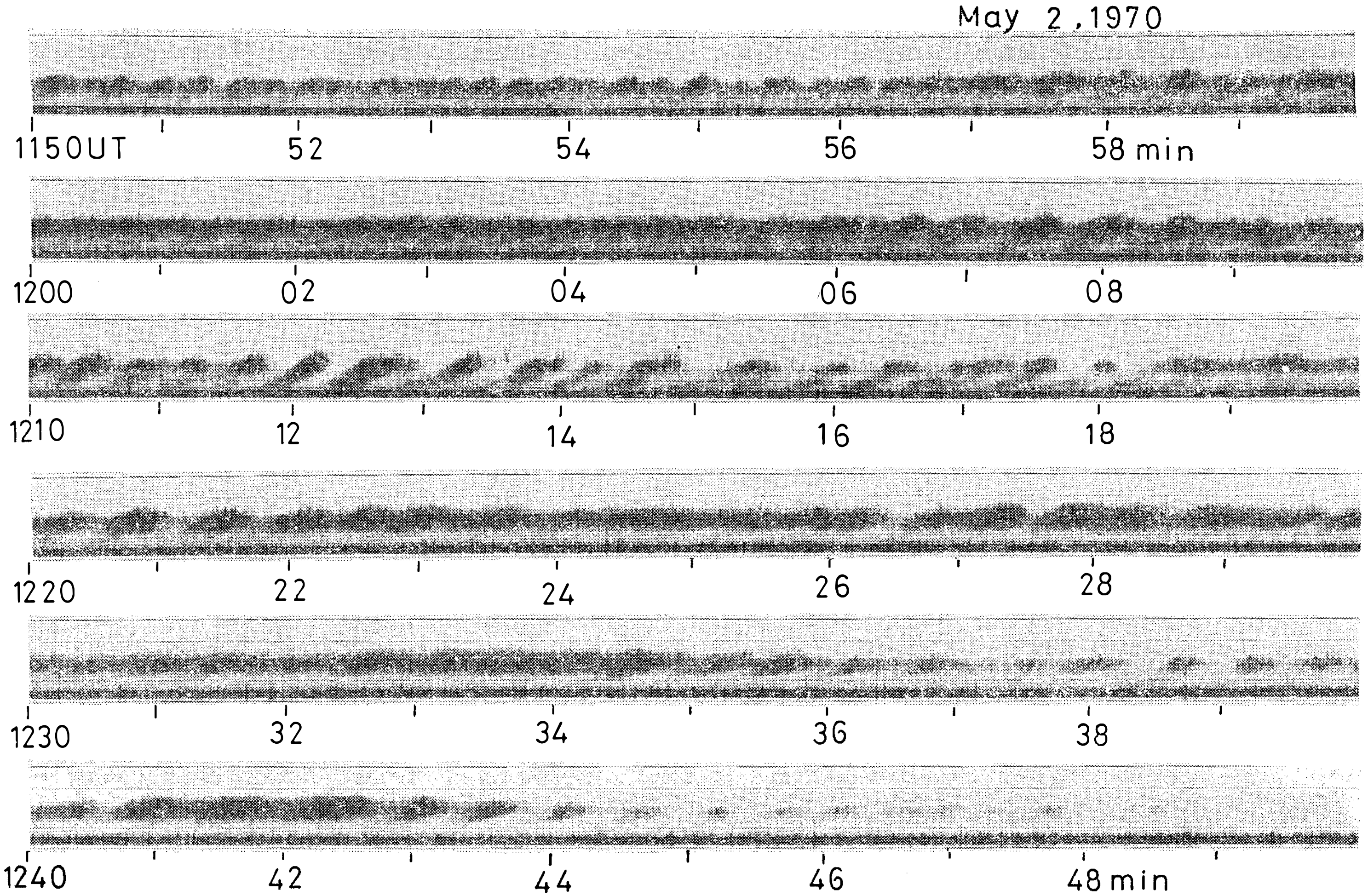
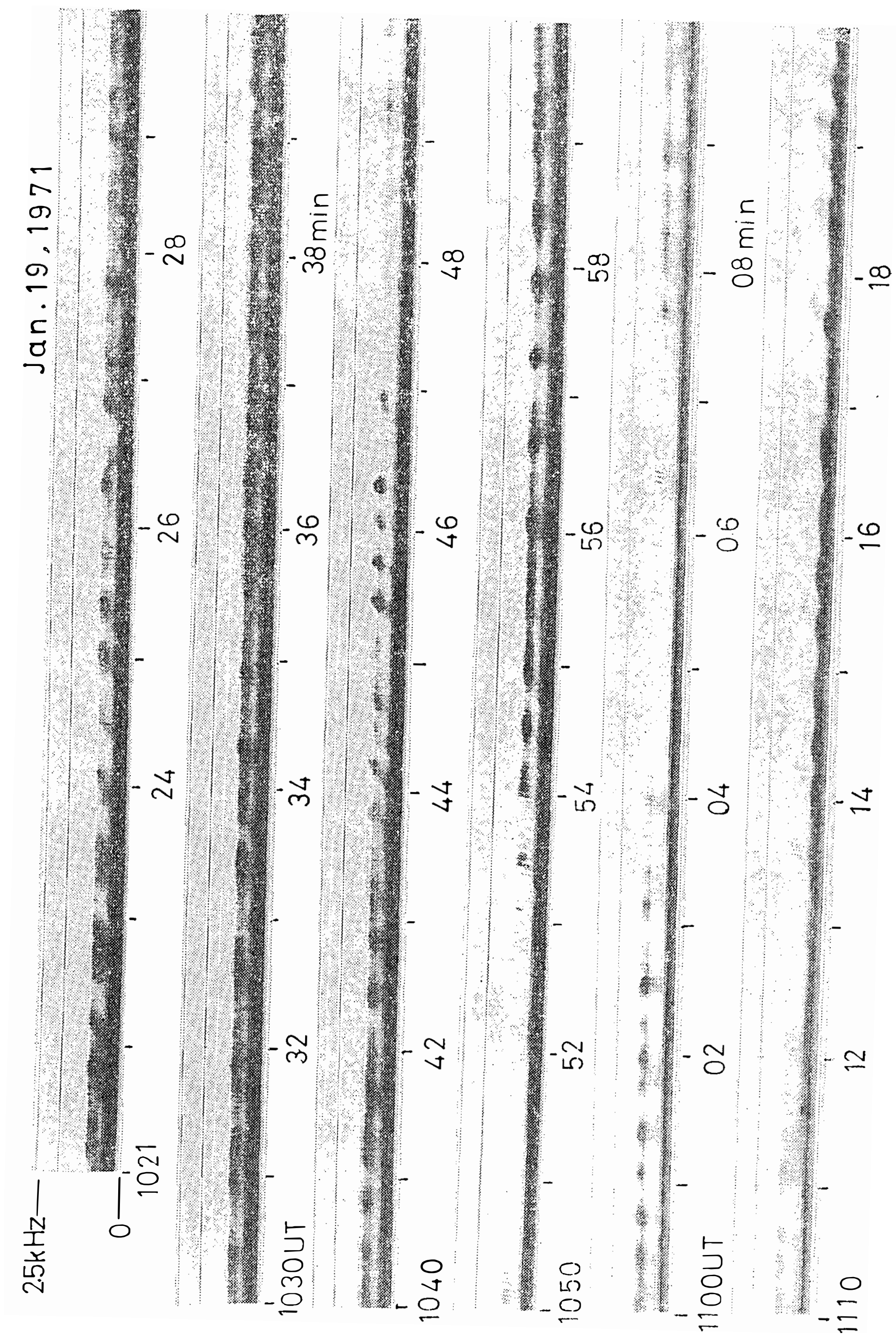
32
34
36
38 min
1140UT
42
44
46
48 min


May 2 ,1970
1150UT 52 54 56 58 min
1200 02 04 06 08
1210 12 14 16 18
1220 22 24 26 28
1230 32 34 36 38
1240 42 44 46 48 min


Jan.19,1971
25kHz
0
1021
24
26
28
1030UT
32
34
36
38min
1040
42
44
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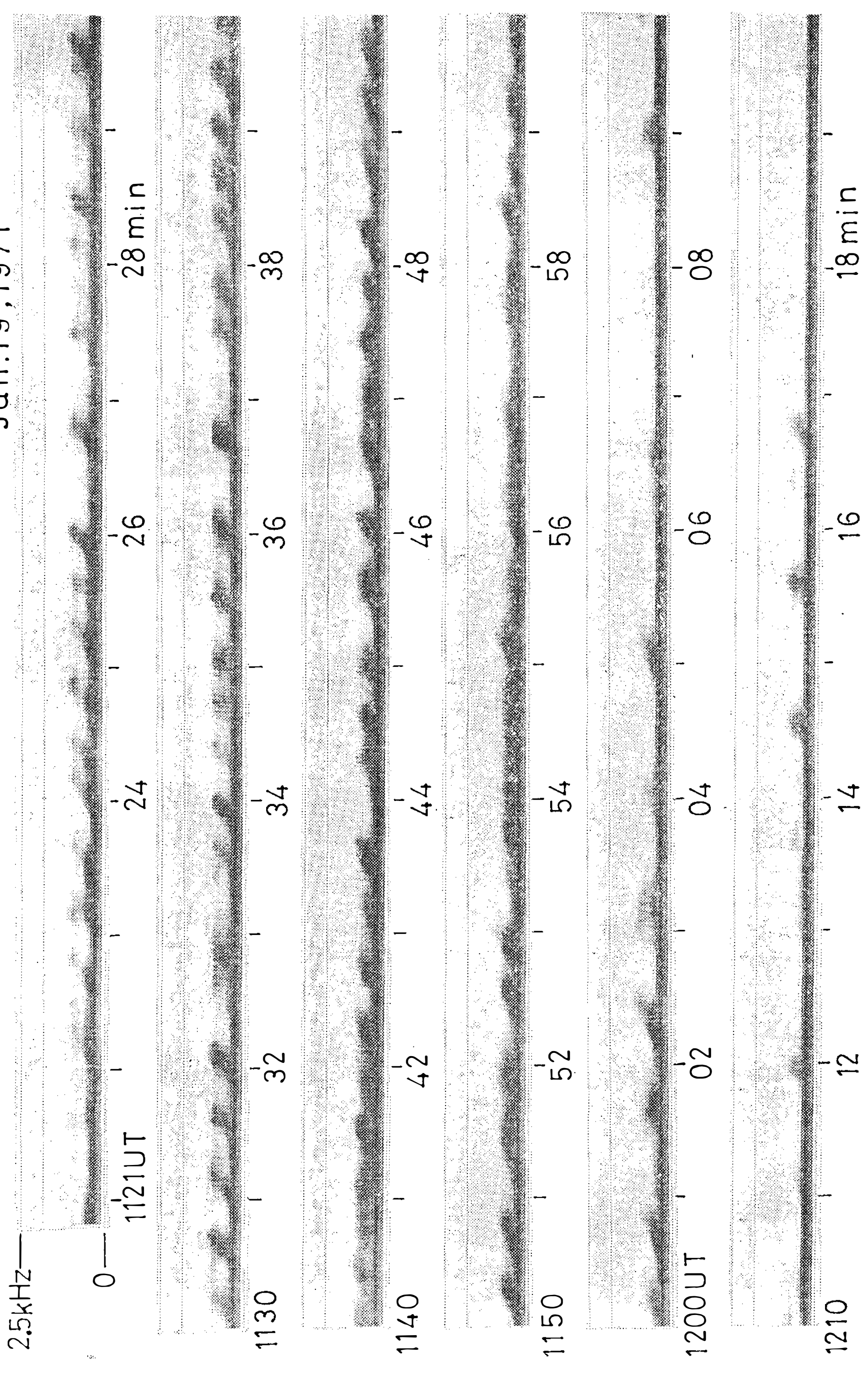
Jan.19,1971
2.5kHz
0
1121UT
24
26
28 min
1130
32
34
36
38
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42
44
46
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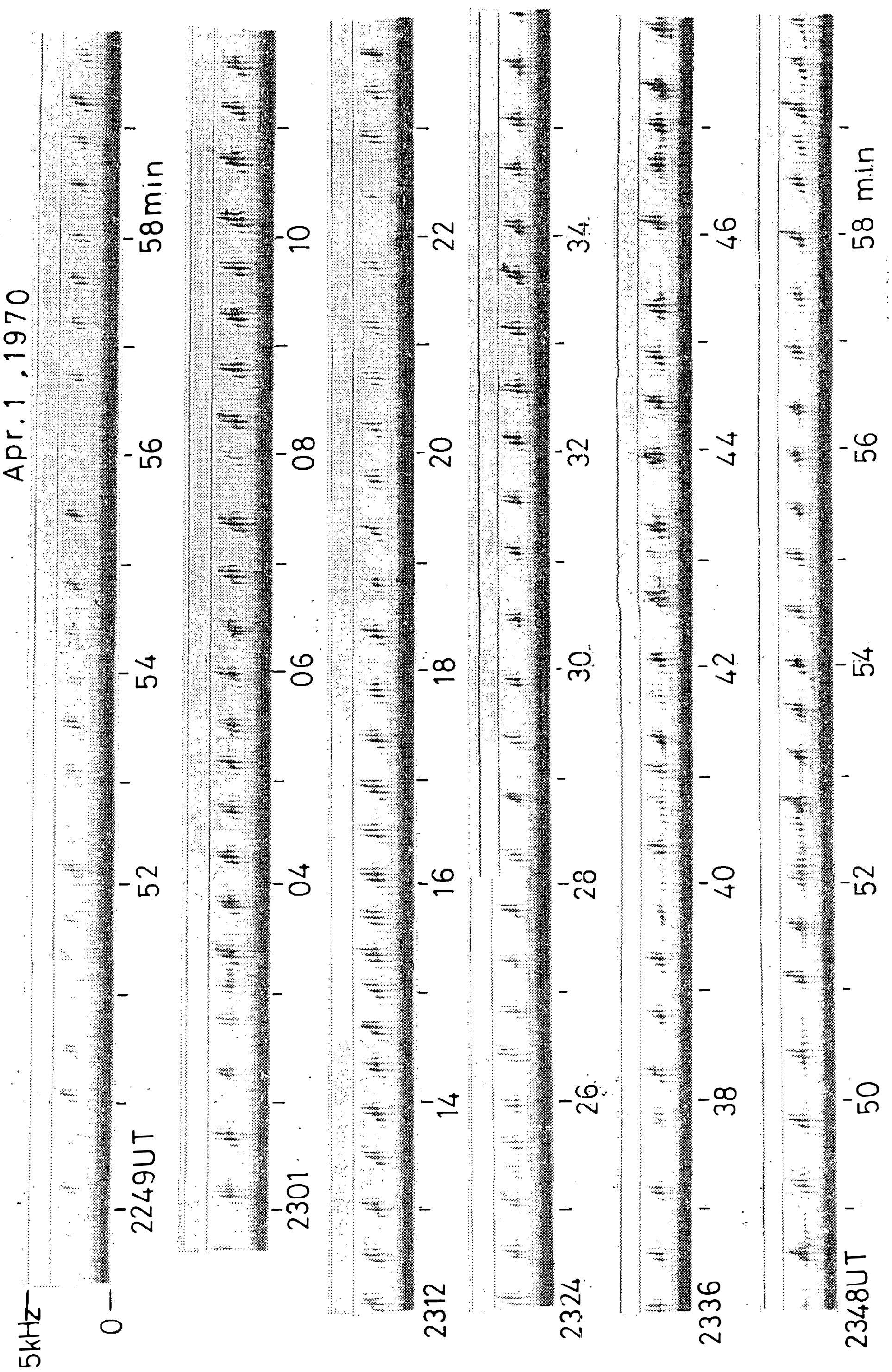
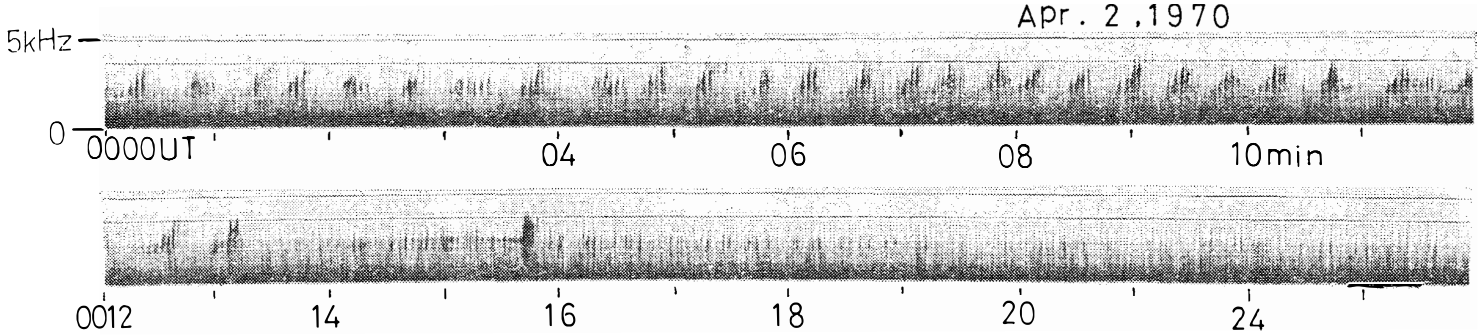
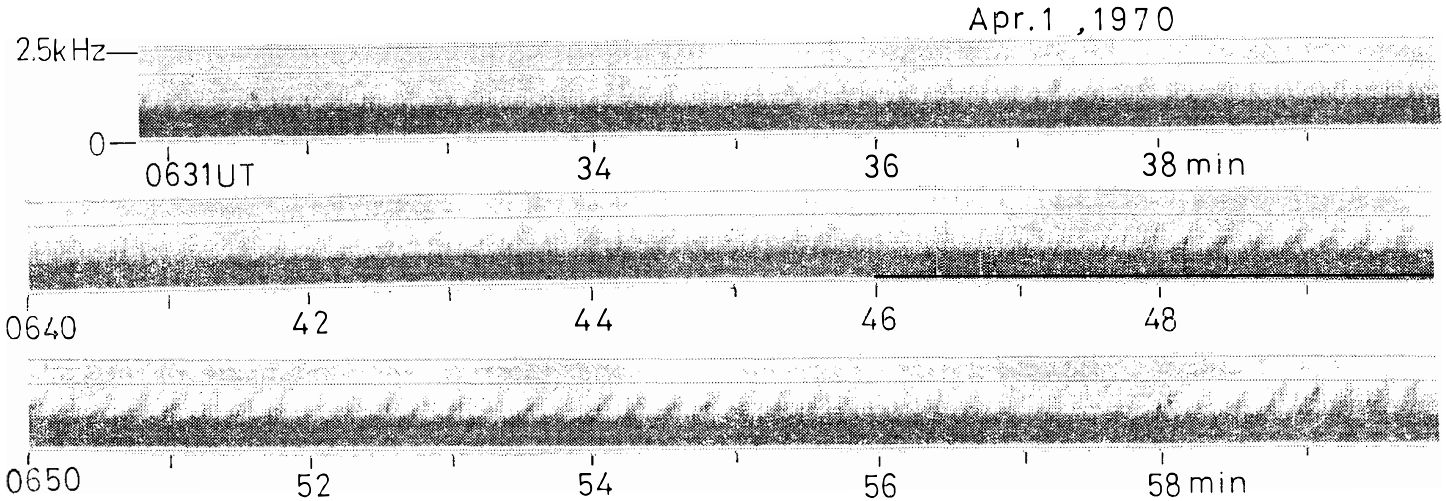
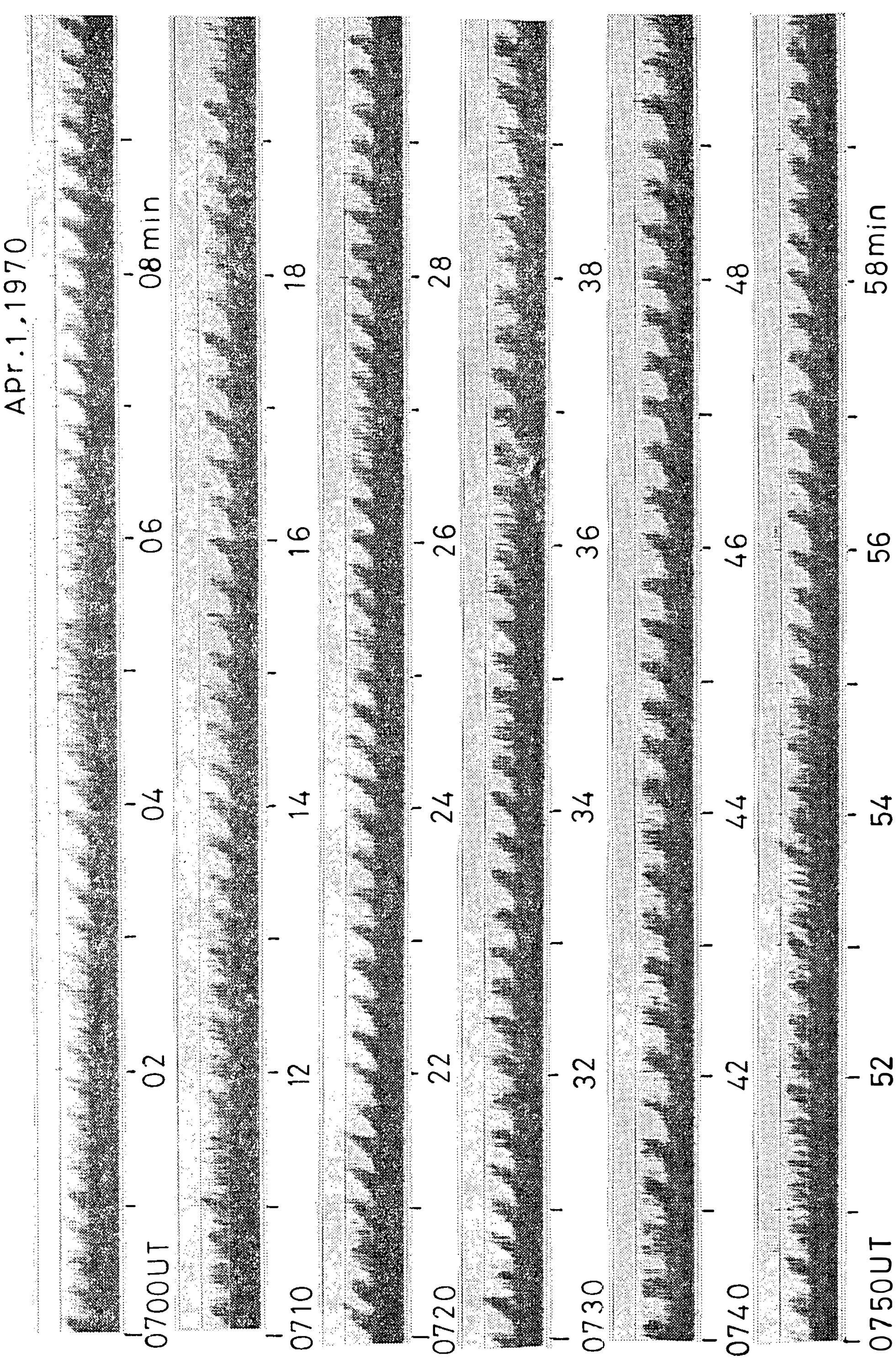
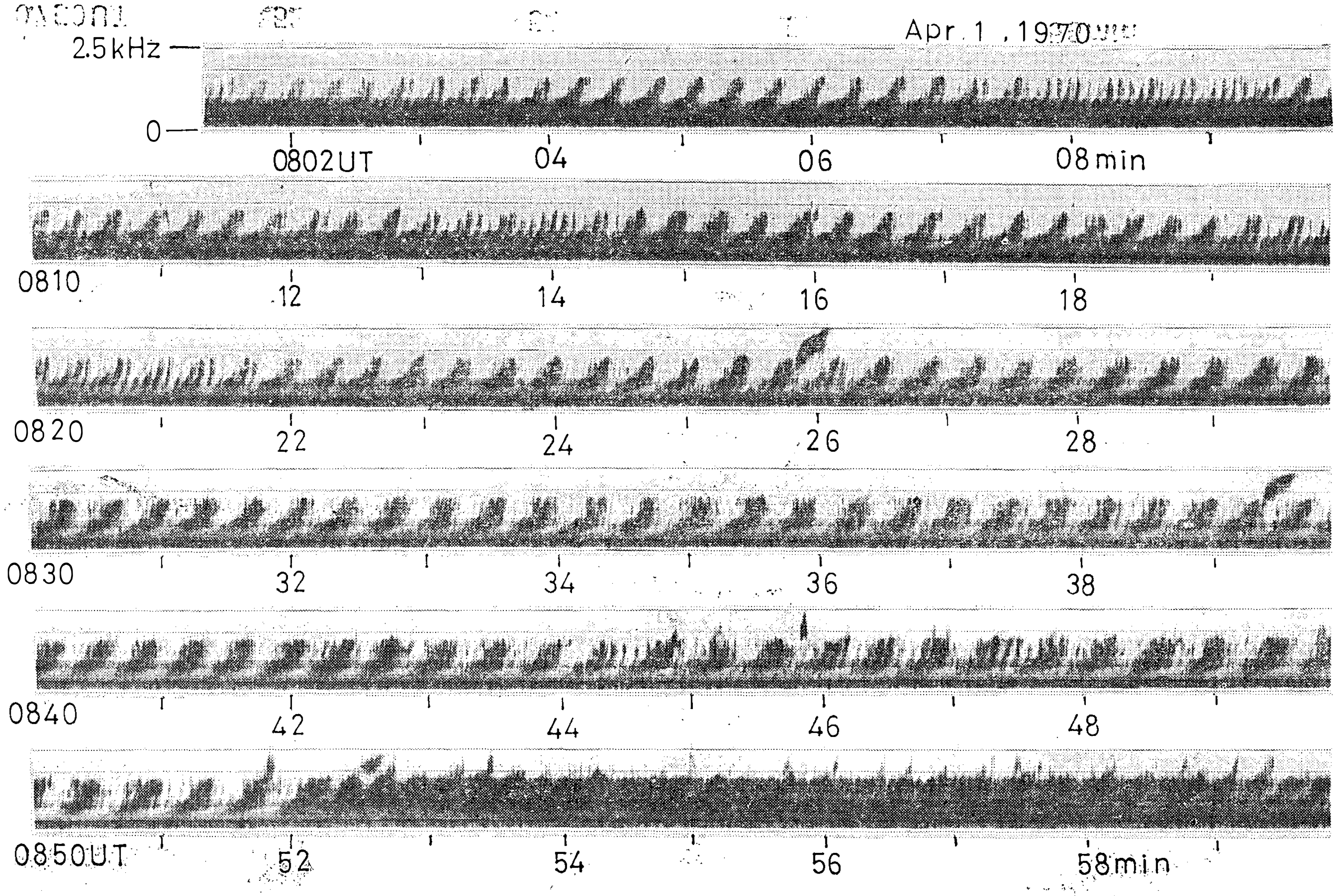
1150
52
54
56
58
1200UT
02
04
06
08
1210
12
14
16
18 min

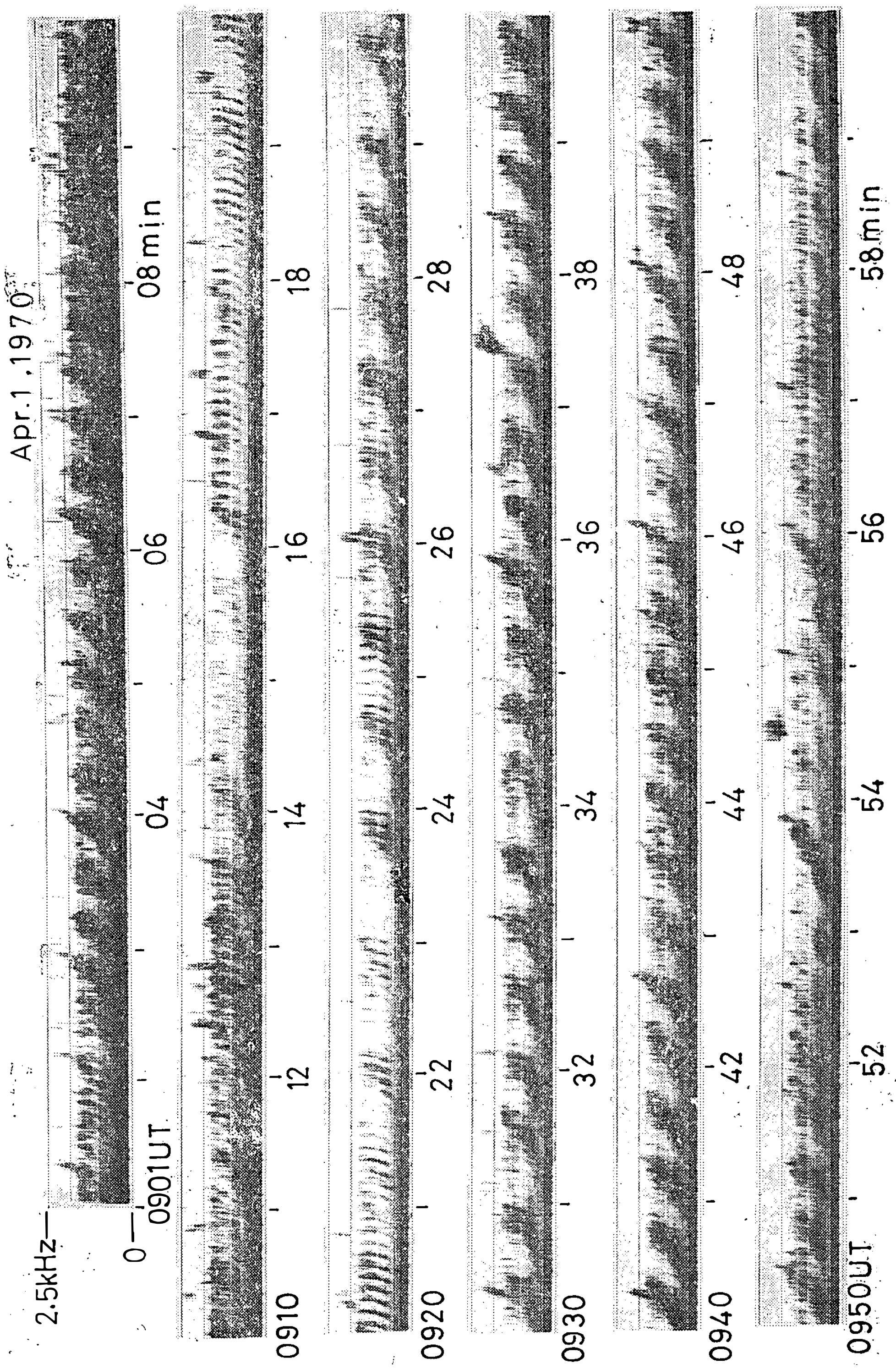

Apr. 1, 1970
5kHz
0
2249UT
52
54
56
58min
2301
04
06
08
10
2312
14
16
18
20
22
2324
26
28
30
32
34
2336
38
40
42
44
46
2348UT
50
52
54
56
58 min

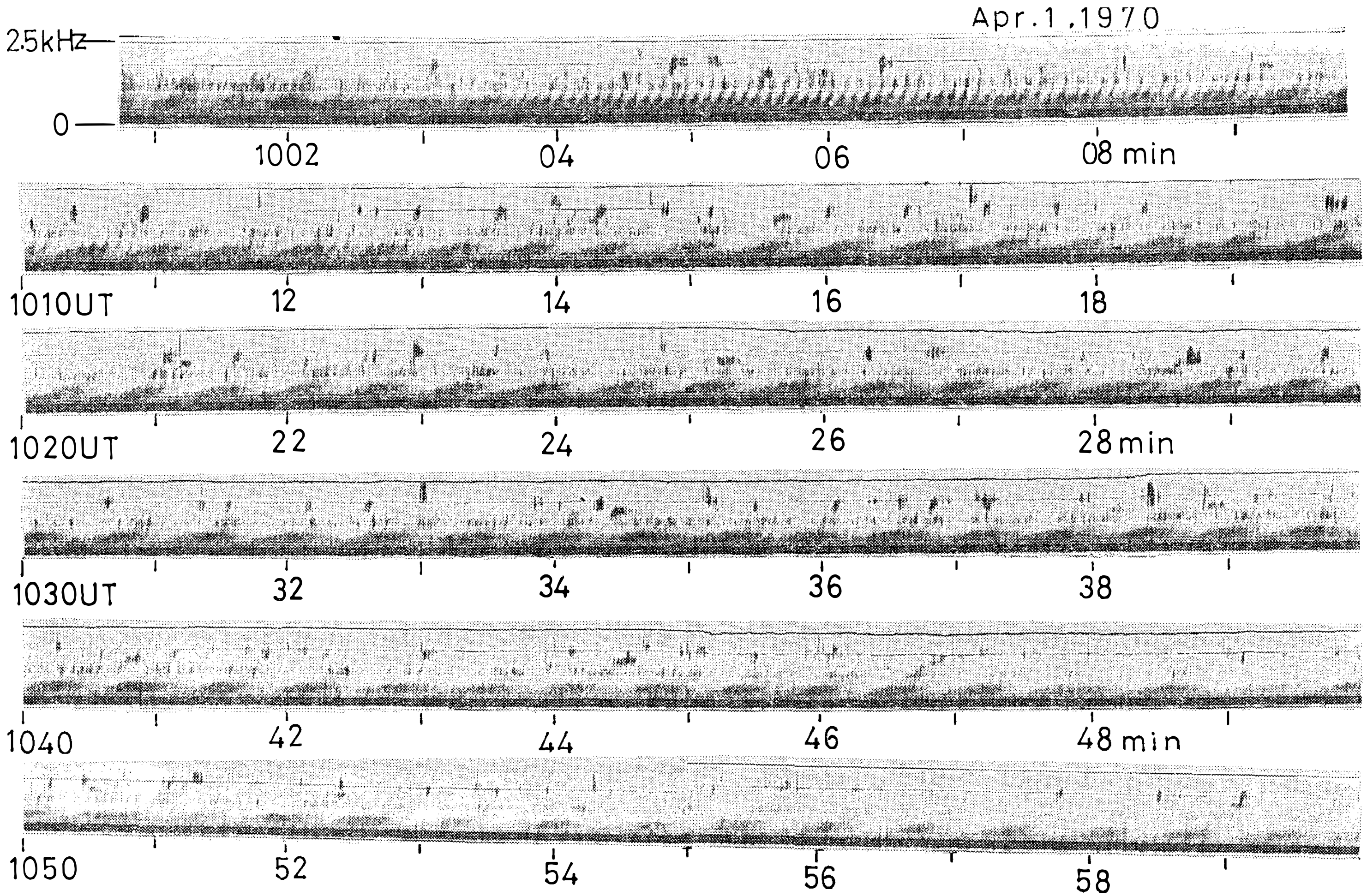

Apr. 2 ,1970
5kHz
0
0000UT
04
06
08
10min
0012
14
16
18
20
24


Apr.1 ,1970
2.5kHz
0
0631UT
34
36
38 min
0640
42
44
46
48
0650
52
54
56
58 min


APr.1,1970
0700UT 02 04 06 08min
0710 12 14 16 18
0720 22 24 26 28
0730 32 34 36 38
0740 42 44 46 48
0750UT 52 54 56 58min


Apr. 1 , 1970
2.5kHz
0
0802UT
04
06
08min
0810
12
14
16
18
0820
22
24
26
28
0830
32
34
36
38
0840
42
44
46
48
0850UT
52
54
56
58min


Apr.1,1970
2.5kHz
0
0901UT
04
06
08 min
0910
12
14
16
18
0920
22
24
26
28
0930
32
34
36
38
0940
42
44
46
48
0950UT
52
54
56
58min


Apr.1,1970
25kHz
0
1002
04
06
08 min
1010UT
12
14
16
18
1020UT
22
24
26
28min
1030UT
32
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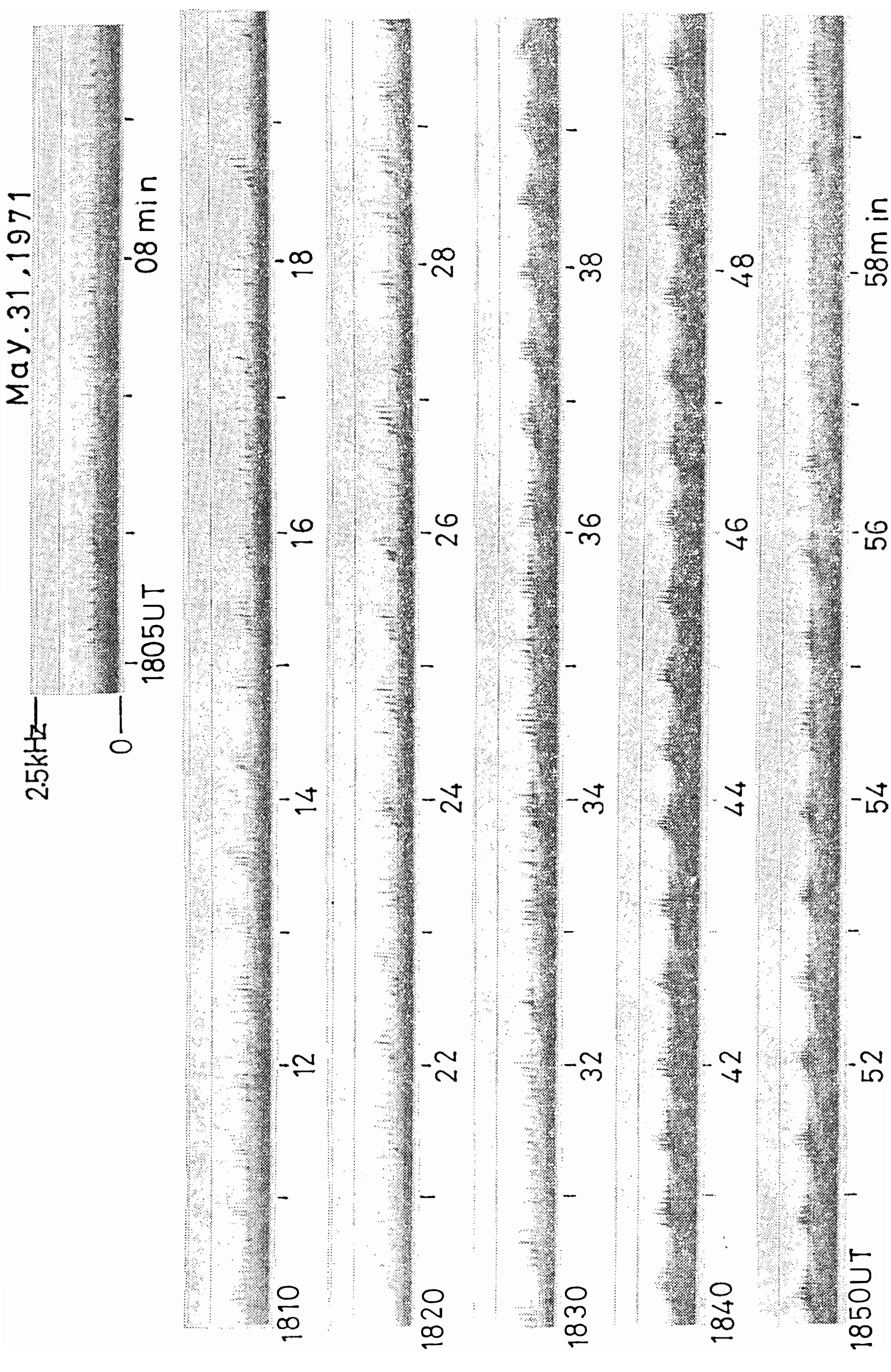
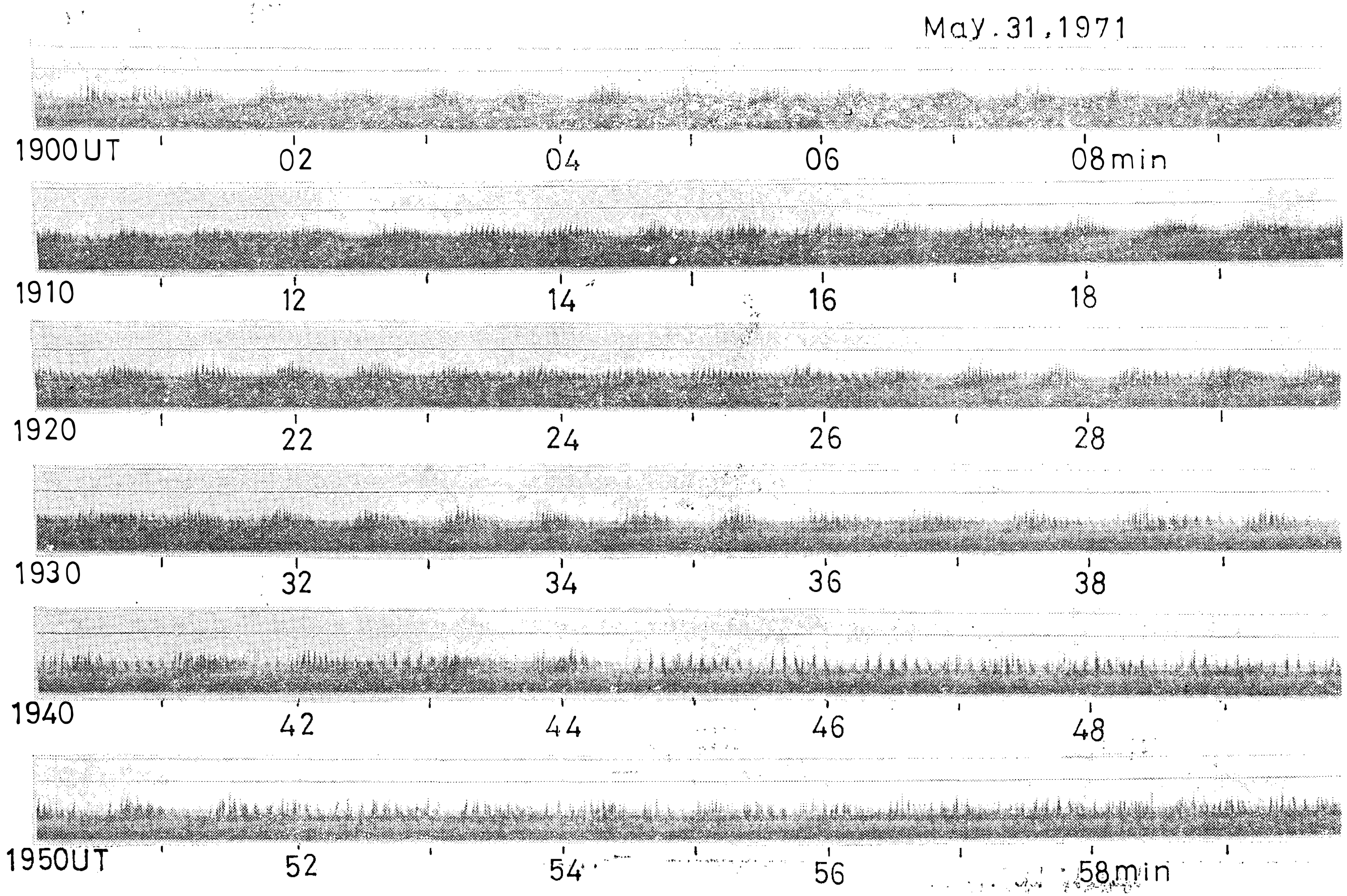
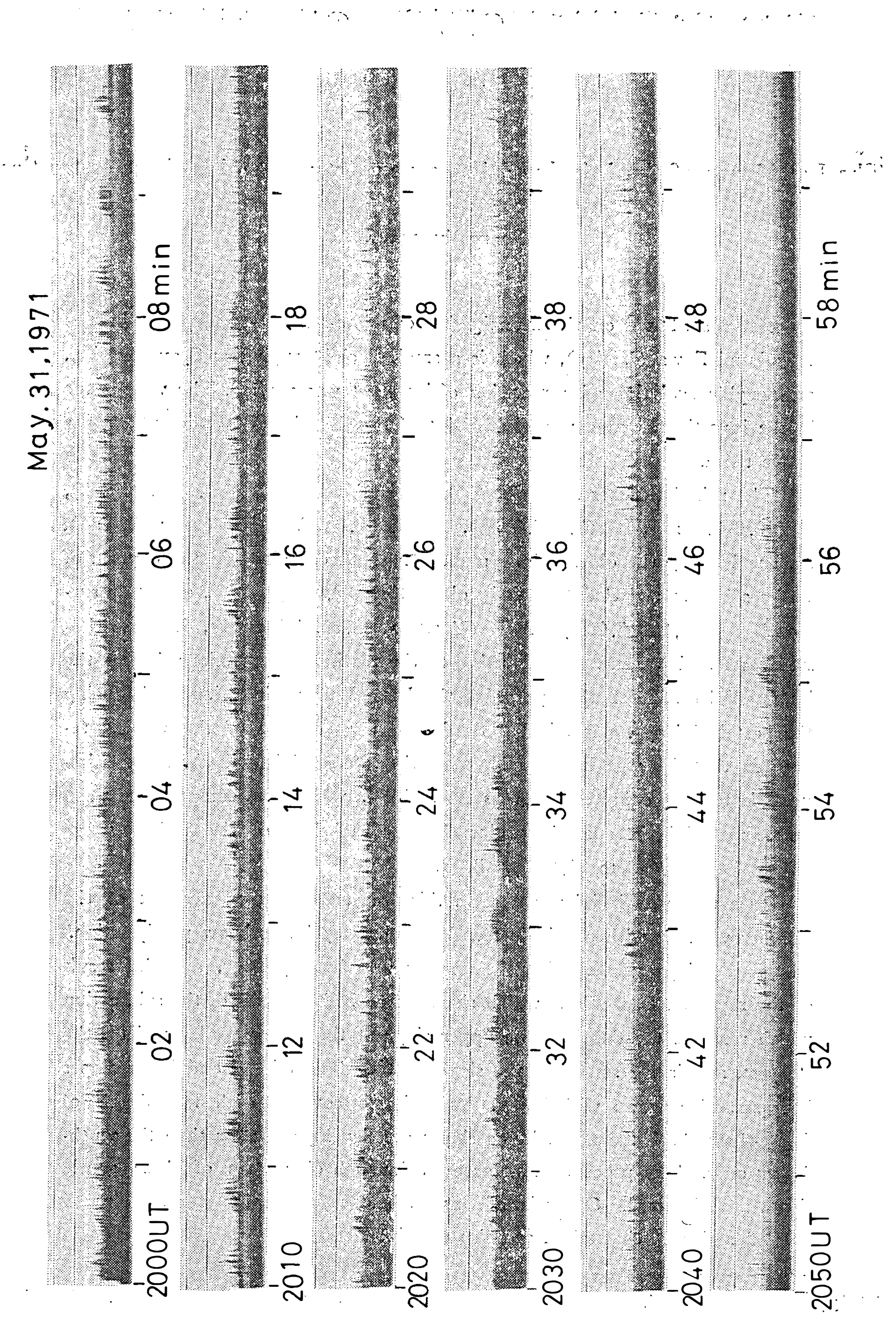
46
48 min
1050
52
54
56
58


May.31,1971
2.5kHz
0
1805UT
08 min
1810
12
14
16
18
1820
22
24
26
28
1830
32
34
36
38
1840
42
44
46
48
1850UT
52
54
56
58min


May.31,1971
1900UT
02
04
06
08min
1910
12
14
16
18
1920
22
24
26
28
1930
32
34
36
38
1940
42
44
46
48
1950UT
52
54
56
58min


May. 31, 1971
2000UT
02
04
06
08 min
2010
12
14
16
18
2020
22
24
26
28
2030
32
34
36
38
2040
42
44
46
48
2050UT
52
54
56
58 min