A MULTI-SATELLITE STUDY OF MAGNETIC PULSATIONS ASSOCIATED WITH A STORM SUDDEN COMMENCEMENT (SSC) AS OBSERVED AT SYNCHRONOUS ORBIT

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***Abstract*:** Oscillation characteristics of ultra-low frequency (ULF) hydromagnetic waves at synchronous orbit in response to a storm sudden commencement (SSC) are studied on the basis of the magnetic field observed on March 23, 1975, simultaneously by the three synchronous satellites, SMS-1, SMS-2 and ATS-6, 20 degrees apart from one another in longitude. The oscillations exhibited damped-type, quasi-sinusoidal oscillations. They were purely transverse and azimuthally polarized, indicating a toroidal mode oscillation. The characteristics of the pure toroidal mode oscillation were emphasized with a drastic change of the oscillation component of the magnetic field perturbation from the radial (V) to the azimuthal (D) direction in association with the SSC. The oscillations appeared as a harmonic structure in the frequency. The dominant harmonics were odd ones, *i.e.* 1st, 3rd, etc. Furthermore, the frequencies of the harmonics observed at each satellite showed a clear local time dependence. In conclusion, the present study verifies that the ULF waves in association with the SSC on March 23, 1975 in the afternoon-side of the magnetosphere behaved as a clear standing oscillation of toroidal mode of the field line resonance excited by the SSC.

1. Introduction

The damped-type, quasi-sinusoidal magnetic pulsations are excited by storm sudden commencements (SSC) and sudden impulses (SI). Since the study of WILSON and SUGIURA (1961), the ground pulsations have been examined extensively by many researchers. Especially, SAITO and MATSUSHITA (1967) have investigated a lot of ULF wave data accompanying SSC and SI observed on the ground. Their results have been reviewed by SAITO (1969). According to their works the pulsations were named Psc and classified into four groups: Psc 1 (T=0.2–5 s), Psc 2, 3 (5–30 s), Psc 4 (30–150 s) and Psc 5 (150–600 s). The theoretical interpretation for excitation of such ULF waves has been proposed by CHEN and HASEGAWA (1974), who predicted that surface waves can be excited at a density gradient by impulsive forces.

The analytical study of such ULF waves has been extended by LANZEROTTI *et al.* (1973, 1975) and FUKUNISHI (1979). Their studies were motivated by the theoretical work of CHEN and HASEGAWA. Their analyses were based mainly on a power spectral method. The spectra of the Psc's in the H- and D-components of the magnetic field showed quite different characteristics. The difference suggests that the oscillations in the magnetosphere can take place in a different way in the azimuthal and radial directions.

Therefore, the oscillation behavior of the magnetic field in the magnetosphere in response to SSC and SI should be clarified in more detail. Such studies have received little attention. KAUFMANN and WALKER (1974) and NOPPER *et al.* (1982) have examined SSC excited waves in the magnetosphere. KAUFMANN and WALKER reported the magnetic oscillations observed by Explorer 12 at $L=8$ in the deep magnetosphere. NOPPER *et al.* studied the data observed at the ground and simultaneously observed by multi-satellites at the geostationary orbit. The results obtained by them were similar in that the waves in the magnetosphere are exhibited rather in the azimuthal component of the magnetic field. Our companion paper (SAKURAI *et al.*, 1984) revealed similar properties on Psc oscillations observed by the synchronous orbit satellite, ATS-6. In the paper it has been clarified that most of Psc's oscillate with a purely azimuthal component and the lower frequency component, Psc 5 exhibits a clear dawn-dusk asymmetry. Furthermore, the Psc is verified to show two or more spectral peaks indicating a harmonic relation to each other. These facts indicate that Psc exhibits a standing oscillation of troidal mode of field line resonance excited by SSC.

The present paper attempts to clarify more detailed characteristics of field line resonant oscillations of Psc in the magnetosphere in response to SSC, laying particular emphasis on the interrelation of Psc oscillations simultaneously observed by the three synchronous satellites, SMS-1, SMS-2 and ATS-6. A drastic change of oscillation component of the magnetic field took place in association with SSC, which is described in Section 4. The oscillation characteristics of Psc are discussed in detail in connection with a resonant oscillation of field line in the magnetosphere in the last section.

2. Data Acquisition and Analysis Procedure

The magnetic field data dealt with in the present study are those of SSC which occurred on March 23, 1975 and were simultaneously observed by the three satellites, SMS-1, -2 and ATS-6. These satellites are synchronous orbit satellites, located at 75, 115 and 96 degrees in the west longitude, respectively. SMS-1 and -2 are the synchronous meteorological satellites, carrying on board the magnetometer with biaxial fluxgate sensors. The instrumentation of SMS-1 and -2 and their data availability have been described in detail by GRUBB (1975) and briefly by ARTHUR (1979). The sensitivity of the magnetometer is basically 0.2 nT and the time resolution is 3.06 s.

The data are provided with the magnetic tape and basically expressed with three components, HP, HE and HN, respectively. The HP-axis is parallel to the earth's rotation axis, HE is radially earthward and HN is azimuthally westward. The magnetic field in this earth's rotation axis coordinate system is transformed into the dipole coordinates, *i.e.*, V, D and H coordinates. The H-axis is parallel to the dipole axis and positive northward, D is defined by $\boldsymbol{D}=\boldsymbol{H}^*\boldsymbol{R}$, where $\boldsymbol{R}$ is the radius vector from the center of the earth to the satellite and V is outward, parallel to the magnetic equatorial plane.

The magnetic field data obtained by ATS-6 were measured with the UCLA fluxgate magnetometer. Detailed descriptions of the instrumentation have been given by

BARRY and SNARE (1966), MCPHERRON (1974) and MCPHERRON *et al.* (1975). The data are plotted on the microfilm with a sampling period of 5 s, and are given in the dipole coordinate system. The spectral power used in the present analysis is calculated with the maximum entropy method.

3. General Characteristics of Magnetic Field Variations of SSC and Psc

A storm sudden commencement and associated damped-type magnetic pulsations (Psc) were observed at 2208 UT on March 23, 1975, simultaneously by the three synchronous satellites, SMS-1, ATS-6 and SMS-2. These satellites were separated with 20 degrees in longitude at 75°W, 96°W and 115°W in order of SMS-1, ATS-6 and SMS-2, respectively. The corresponding satellite local time was 1708, 1548 and 1428, which means that these satellites were located in the afternoon sector.

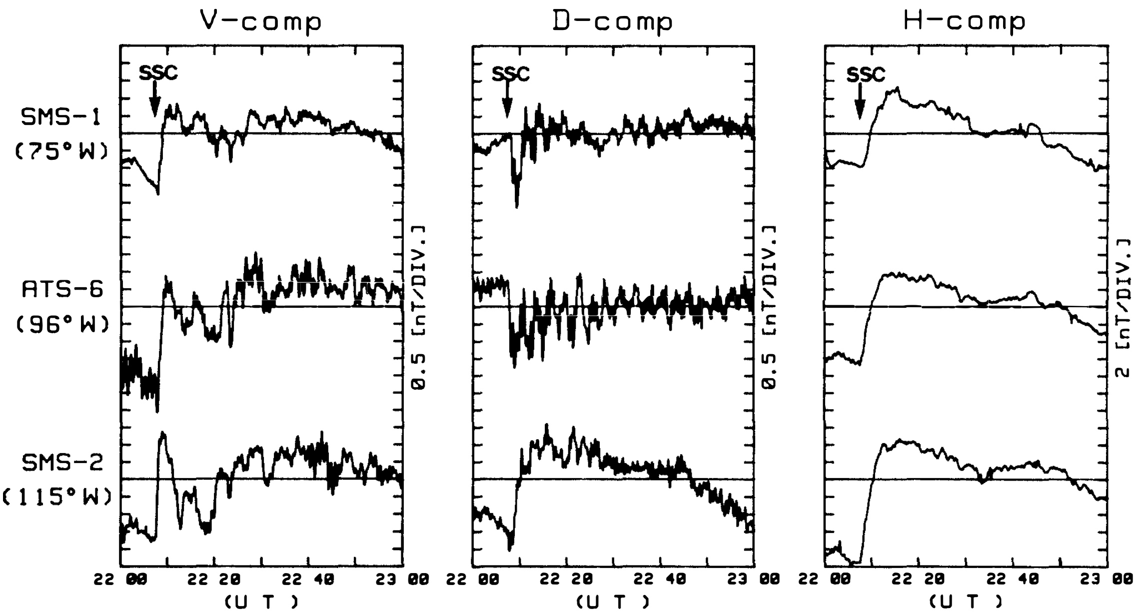

Fig. 1. Simultaneous observation of Psc oscillations which occurred in association with SSC at 2208 UT on March 23, 1975 by three synchronous satellites, SMS-1, -2 and ATS-6. The three magnetic field components (V, D, H) of the Psc are illustrated from the left to the right columns. The Psc oscillations are dominantly seen in the azimuthal (D) component.

The observed SSC and associated Psc oscillations are shown in Fig. 1. The simultaneous sudden increment in the *H*-component of the magnetic field shows that the magnetic field was compressed suddenly in association with the SSC. The magnitudes of this increment at each satellite 9, 10 and 14 nT, which slightly increased in both magnitude and steepness toward the noon. This fact implies that the compression of the magnetic field took place severely toward the noon. However, no compressional oscillations clearly occurred in association with the SSC.

The Psc oscillations were exhibited clearly in the azimuthal component of the magnetic field at each location of the satellite. Among them the clearest damped-type oscillations of the Psc's were observed by ATS-6. All Psc oscillations were superimposed on the clear deflections of the ambient magnetic field. The ambient DC field, however, deflected toward the different directions, *i.e.*, westward at SMS-1 and ATS-6, and eastward at SMS-2, respectively. SMS-1 and ATS-6 were located in the late afternoon, while SMS-2 rather close to the noon. The magnitude of the deflection depicted was largest at SMS-2, since it was located closest to the noon among the three satellites. The deflections of the DC field in the azimuthal component of the magnetic field may reflect a sudden increase of field-aligned current density associated with the SSC. The current flowing above the satellite indicates the sense from the ionosphere toward the magnetosphere in the forenoon side and the reversal sense in the late afternoon side. The field-aligned current tends to decrease gradually and to die away concurrently with the disappearance of the Psc oscillations. Furthermore, the Psc oscillations were largest at the ATS-6 location, suggesting that the oscillations took place preferably at this location of local time.

The radial (V) component of the magnetic field showed the intermediate variation between the H- and D-components of the magnetic field. The DC field of the V-component magnetic field increased about 3.7, 3.0 and 2.5 nT in the order of ATS-6, SMS-2 and SMS-1, showing the most significant increment at the ATS-6 location. The increment of the V-component means that the magnetic field at each satellite location was compressed similarly by the SSC.

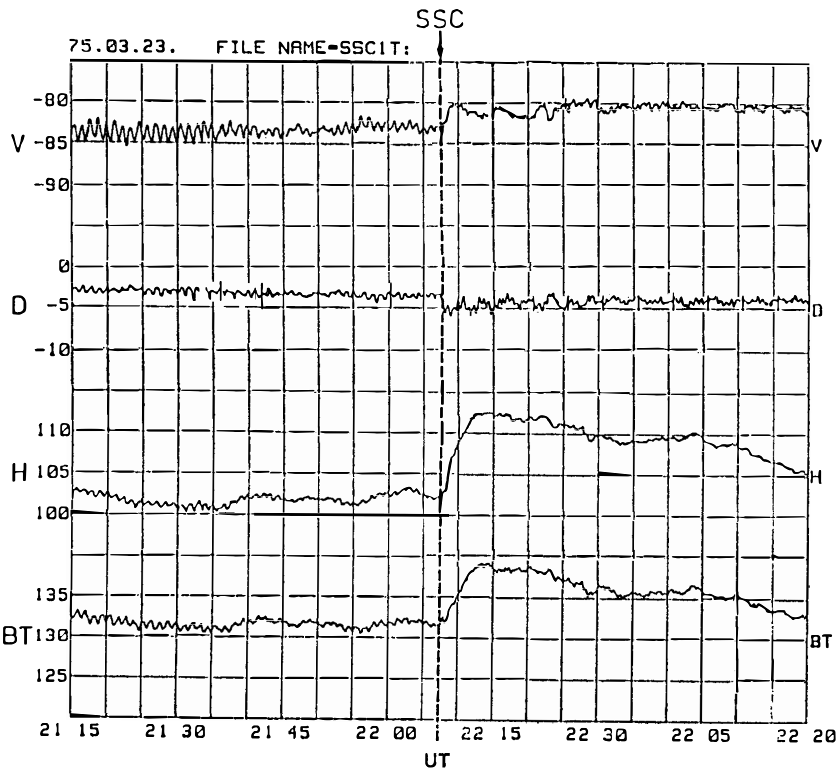

Fig. 2. The Psc oscillations observed by ATS-6, including Pc 4 period-range magnetic pulsations during one hour before the SSC. Before the SSC the V-component oscillations predominated, but after the SSC the oscillations changed to the D-component.

It is seen from the simultaneous observation of the magnetic field variations associated with SSC at the three satellites, that the compressional effect on the magnetic field appeared most clearly at the SMS-2 location, *i.e.*, closest to the noon, but the most predominant Psc oscillations occurred at ATS-6 of intermediate location.

4. Drastic Change of Oscillation Mode in Association with SSC

The Psc's oscillated similarly at SMS-1, ATS-6 and SMS-2. One of the most striking features of this Psc event is seen in Fig. 2, appearing with a drastic change of field variation from the *V*- to *D*-component in association with the SSC. The three components (*V*, *D*, *H*) and the total magnitude of the magnetic field observed by ATS-6 during the interval from 2115 to 2220 UT containing the SSC are illustrated in the top to the bottom panels of the figure. During two hours before the SSC the magnetic pulsations in the Pc 4 frequency range continued to oscillate clearly and dominantly in the *V*-component. However, in association with the SSC the *V*-component (radial) oscillations changed to the *D*-component (azimuthal) oscillations, which appeared as Psc oscillations. They contained the period range from Pc 4 to Pc 5.

In order to clarify more precisely this drastic change from the *V*- to *D*-component field variations, the magnetic field data are filtered with three band-pass filters corresponding to the period ranges from Pc 3 to Pc 5, which are illustrated respectively

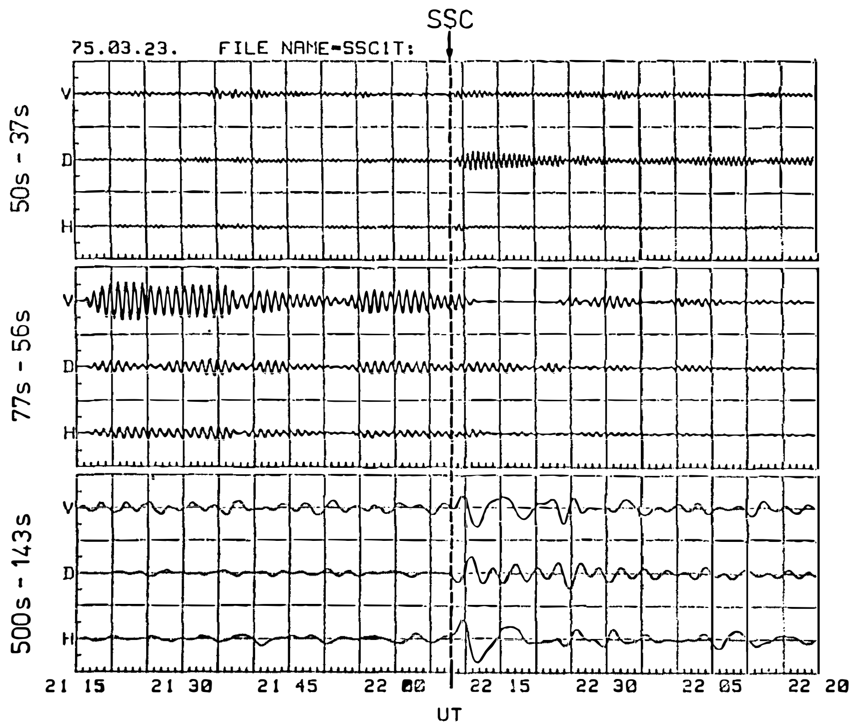

Fig. 3. The Psc oscillations filtered out with three band-pass filters. The period ranges of each band are 37–50 s, 56–77 s and 143–500 s, which correspond to Pc 3, Pc 4 and Pc 5 magnetic pulsations, respectively. The pre-SSC oscillations predominated in the Pc 4 and changed to the periods of Pc 3 and Pc 5 after the SSC.

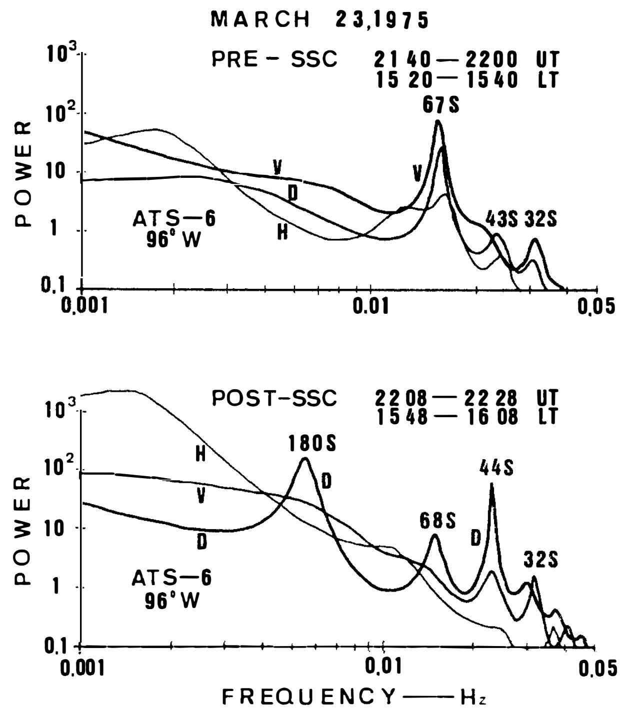

Fig. 4. The oscillation characteristics shown in Fig. 3 are clearly recognized also in the power spectra of the pre- and post-SSC. In the pre-SSC the power peak at 67 s appears in all components of the field, while after the SSC it does mainly at 44 s and 180 s only in the D-component of the field.

in the top, the middle and the bottom panels of Fig. 3. As seen in the figure, the dominant oscillations differed before and after the SSC. Before the SSC the Pc 4 magnetic pulsations dominated the *V*-component magnetic field for two hours and changed to the *D*-component field in the period range of Pc 4 in association with the SSC.

The changes of the period and the dominant component of the oscillations can be well recognized in the power spectra calculated for the interval of twenty minutes before and after the SSC. These are designated as pre- and post-SSC, respectively, and are presented in Fig. 4. The spectrum for the pre-SSC interval shows three spectral peaks. The most dominant power occurred at the period of 67 s. The corresponding spectral peak is seen in both the *V*- and *D*-components. The spectral power in the *V*-component exceeded that in the *D*-component. On the other hand, the spectrum for the post-SSC interval shows different characteristics. The significant difference appears as exhibiting more spectral peaks in the *D*-component, which are seen at the periods of 180, 68, 44 and 32 s, respectively. The most dominant power appeared at the longest period, 180 s. The subsidiary spectral peak took place at the period of 44 s. The peak power of the *D*-component exceeded that of the *V*-component. This is contrary to the characteristics seen in the spectrum of the pre-SSC. Therefore, these facts show that the Psc oscillations occurred more preferentially with the *D*-component oscillations and with more numerous spectral peaks than the pre-SSC pulsations.

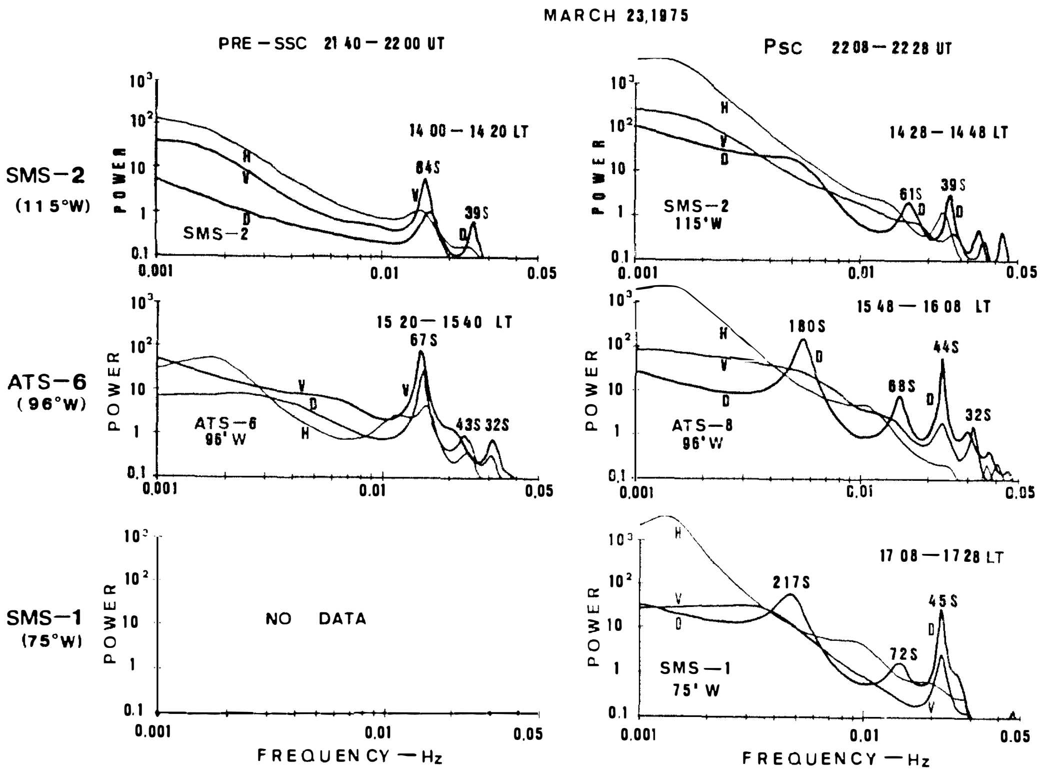

Fig. 5. The drastic change of oscillation mode in association with the SSC is clearly recognized in the power spectra at each satellite location. Before the SSC the period of the spectral peak in the Pc 4 becomes longer with advance of local time. Similar characteristics of the Psc periods are clearly seen at each satellite.

The clear change of the oscillation properties, *i.e.*, dominant field component in the oscillations and number of spectral peaks in the power spectrum, during the pre- and post-SSC are also seen similarly at the other satellite, SMS-1 and SMS-2. The pre- and post-SSC power spectra for each satellite are illustrated in the left and the right columns of Fig. 5. From the top to the bottom of the figure the spectrum of each satellite is also given in order of location from near noon to the late afternoon. In the case of SMS-1, the pre-SSC magnetic field data are not available.

Comparing the periods of spectral peaks seen at each satellite, it is found that the periods became longer with advance of local time. The most dominant spectral peak of the Psc appeared at 39 s at SMS-2 located closest to the noon. The corresponding period of the Psc at ATS-6 and SMS-1 occurred at 44 and 45 s, respectively. Other two spectral peaks also occurred at the three satellites. The periods corresponding to these spectral peaks became longer when the satellite was located in the late afternoon.

Figure 6 shows the periods corresponding to these spectral peaks seen in the power spectrum at each satellite location against local time. The corresponding periods of the spectral peaks for the pre- and post-SSC are given by the different symbols, *i.e.*, small and big ones, respectively. The periods for each satellite, SMS-2, ATS-6 and SMS-1, are indicated by solid circle, solid star and circle with open star at the corresponding local time of the satellite location, respectively. The periods of the

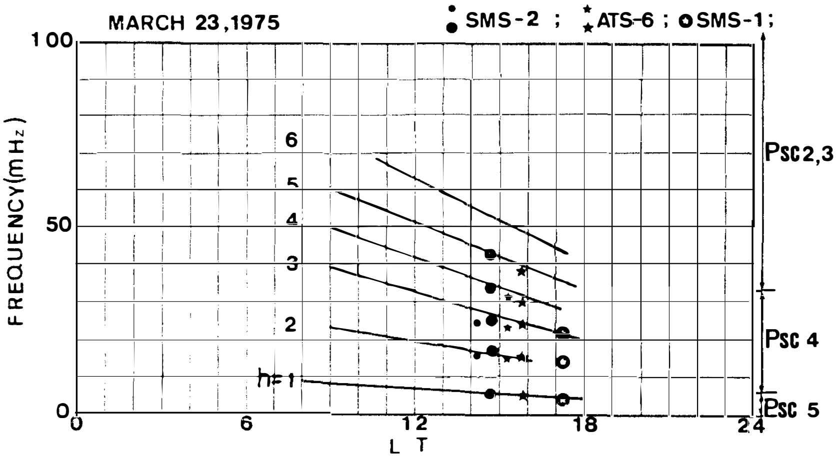

Fig. 6. Harmonic spectral structures are clearly seen in the power spectra of each Psc. The frequency of the harmonics indicates a clear local time variation. The big and small symbols represent the spectral peak period in the power spectra of the pre- and post-SSC pulsations. The solid lines show the harmonic trends of the D-component of magnetic pulsations observed by ATS-6 on August 22, 1974.

spectral peaks at each satellite indicate a harmonic relation with each other, as is evident in the figure. The solid lines superimposed on this figure indicate the spectral trends with a harmonic relation with each other. They are given by the dynamic spectrum of the ATS-6 magnetic data during the moderately active magnetic condition of August 22, 1974. These spectral trends showing harmonics are generally seen in the dynamic spectra of the magnetic field data observed at the synchronous orbit during the daylight hours (TAKAHASHI and MCPHERRON, 1982; TONEGAWA *et al.*, 1983). As seen in the figure, the period of each spectral peak during the Psc event appears with a clear harmonic relation and shows a clear local time dependence at each satellite location. The dominant spectral power appeared at the 1st and 3rd harmonics in each Psc spectrum, which is also consistent with the general characteristics of the harmonics seen in the dynamic spectra of magnetic pulsations observed during the daylight hours at the synchronous orbit.

5. Discussion and Conclusions

The Psc event which occurred on March 23, 1975 has been examined on the basis of magnetic field data simultaneously observed by the three synchronous satellites, SMS-1, -2 and ATS-6, which were located in the afternoon sector with a separation of about one hour in longitude. The latitudinal separation among the three satellites was very small, with only about 3 degrees from 8 to 11 degrees. The satellites were located above the magnetic equator in the northern hemisphere.

The Psc oscillations observed by the satellites indicate similar characteristics as follows:

(1) The Psc oscillations exhibited damped-type quasi-sinusoidal oscillations.

(2) The Psc oscillated predominantly in the azimuthal (D) component of the magnetic field, indicating a pure toroidal mode of field line resonant oscillations.

(3) The initial perturbation of the Psc appeared with a dawn-dusk asymmetry, *i.e.*, eastward deflection in the dawn side and westward deflection in the dusk side.

(4) The initial perturbation of the Psc was superimposed on the DC-field shift to the same direction.

(5) The DC-field shift in association with SSC showed a clear dawn-dusk asymmetry and decreased to the background as the Psc died away.

These characteristics of the Psc are also consistent with the previous studies on Psc in the magnetosphere (KAUFMANN and WALKER, 1974; NOPPER *et al*., 1982; SAKURAI *et al.*, 1984). KAUFMANN and WALKER reported that the long period oscillation of Psc 5 was observed by Explorer 12 at $L=8$ in the magnetosphere as azimuthally polarized oscillation. NOPPER *et al.* showed that the similar signature on oscillation of Psc was also observed at the synchronous orbit simultaneously by multi-satellites, GOES-1, GOES-2, ATS-6 and GEOS-1. The Psc oscillations with the similar period were simultaneously observed in the H-component on the ground near $L=5$. They suggested that an azimuthally polarized resonant field line oscillation was excited near $L=5$. The D-component oscillations were seen far more globally on the ground, which may correspond to radially polarized oscillations in the magnetosphere due to the fast mode signal propagating throughout the magnetosphere.

The present study of the Psc on March 23, 1975 demonstrates that the Psc behaved as a purely azimuthal oscillation even when the satellites were located in the afternoon sector. It indicates that the resonant oscillation of field line due to the SSC occurs at the synchronous orbit even at this local time. Contrast to our result on the Psc, recent studies by NAGANO and ARAKI (1984) and KUWASHIMA *et al.* (1984) showed that Psc's occurring in the afternoon side at the synchronous orbit accompany compressional oscillations. The discrepancy between our results and those of NAGANO and ARAKI, and KUWASHIMA *et al*., may be attributed at least to the following effects, *i.e.*, strength of SSC and asymmetrical characteristics of occurrence signatures about ULF waves in the dawn and dusk sectors of the magnetosphere (HUGHES *et al.*, 1978; KOKUBUN, 1980). According to their studies, the magnetic pulsations in the afternoon sector observed at the synchronous orbit appear generally with compressional characters in oscillation mode. The compressional ULF waves in the period range of Pc 4 and Pc 5 were also observed in association with the particle flux variations of energetic electrons and protons, which were clearly demonstrated at the synchronous satellite, ATS-6 (BAKER *et al*., 1978; BELIAN *et al*., 1978; HIGBIE *et al.*, 1978; SU *et al.*, 1977, 1979; TONEGAWA, 1982). They may be attributed to wave-particle interaction

The reversal deflection of the initial perturbation of the Psc in the dawn and dusk sectors suggests that the magnetic field was stretched tailward in the dawn and dusk sectors due to the compression of the magnetosphere by the SSC. In other words, this may be interpreted as the reversal currents flowing along the magnetic field above the satellite at the synchronous orbit in each sector, *i.e.*, flowing from the ionosphere into the magnetosphere in the dawn sector and from the magnetosphere to the ionosphere in the dusk sector, as discussed in Section 3.

Another important characteristic of the Psc oscillations studied in the present paper is a drastic change in the oscillation mode in association with the SSC. The V-component oscillations designated with the radial polarization in the period of Pc 4 prevailed for about two hours before the SSC and changed to the purely azimuthal oscillations in association with the SSC. This drastic change in oscillation mode was recognized simultaneously at the three satellites covering a wide longitudinal extent in the afternoon sector.

Furthermore, the present study was intended to reveal another interrelationship of Psc observed at different longitudes of the synchronous orbit. The dynamic spectra exhibited several peaks, especially in the azimuthal component of the magnetic field, showing a similar harmonic relation with each other. The odd mode harmonics, such as the 1st and 3rd, were predominant in the Psc oscillations at each satellite. The periods of these predominant oscillations of the Psc obeyed a clear local time dependence, which appeared similarly to those obtained by a single satellite (SAKURAI *et al.*, 1984).

In conclusion, the present study clarified that in the case of the SSC which occurred on March 23, 1975, the Psc oscillations in the afternoon side of the magnetosphere behaved as a clear standing oscillation of toroidal mode of field line resonance excited by the SSC. The pure toroidal oscillation of the Psc can be recognized with a drastic change of the perturbed field from the V- to the D-component in association with the SSC. The Psc at each satellite location appeared simultaneously with a peculiar local time dependence of a harmonic structure in frequency.

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