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Wave Characteristics of Magnetic Pi2 Pulsations in the Magnetosphere and on the Ground

by

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Abstract

The Pi2 wave characteristics are studied by using ULF data simultaneously obtained at the geosynchronous satellite, ATS 6, and at the conjugate ground-based stations (Syowa Station in Antarctica and Reykjavik in Iceland). It is experimentally clarified that the major axis of the Pi2 wave polarization is rotated through 90° in a propagation from the magnetosphere to the ground through the ionosphere. The evidence indicates that Pi2 is caused by the fundamental-mode of the hydromagnetic torsional oscillation of the localized field lines anchored on the nightside auroral ovals. The amplitude behavior of Pi2 also supports the standing oscillation of the field lines as a cause of Pi2.

1. Introduction

A magnetic *Pi*2 pulsation (*Pi*2) is observed almost simultaneously with an onset of the magnetospheric substorm expansion over the whole dark hemisphere on the ground and in the magnetosphere. A generation mechanism of *Pi*2 is considered to be closely associated with the magnetospheric substorm expansion. In this meaning, *Pi*2 is one of the important manifestations of the magnetospheric substorm. In the previous two papers (Kuwashima, 1978 and 1981), wave characteristics of *Pi*2 have been studied on the basis of data obtained at ground-based stations.

In the paper 1 (Kuwashima, 1978), spectral and polarization characteristics of *Pi*2 were studied by using ULF data obtained at Syowa-chain stations, which were Mawson ($L=8.9$), Mizuho Station ($L=7.5$), Syowa Station ($L=6.1$), Sanae ($L=4.0$) and Hermanus ($L=1.8$). In the study, the close relationship of the *Pi*2 period to the auroral breakup position was clarified. Namely, the *Pi*2 period increases with increase of the geomagnetic latitude where the associated auroral breakup started. The *Pi*2 period behavior has been clarified to be interpreted by the fundamental-mode of the hydromagnetic torsional oscillation of the field lines localized on the northern and southern nightside auroral ovals. The polarization behaviors of *Pi*2 near the auroral electrojet also support the hydromagnetic resonant oscillation of the field lines as a cause of *Pi*2.

In the paper 2 (Kawashima, 1981), conjugate relationships of *Pi*2 were studied by using ULF data obtained at Syowa Station in Antarctica and Reykjavik in Iceland. These two stations are the best conjugate-pair among many stations in the polar region. In the study, it was clarified that the *Pi*2 wave was observed simultaneously with similar waveforms at the conjugate-pair. An important finding in the conjugate study is the following characteristic *Pi*2 wave-phase relationship as that the *Pi*2 wave shows an in-phase oscillation in the *H*-component, while an anti-phase oscillation in the *D*-component at the conjugate-pair. The *Pi*2 wave-phase relationship has been interpreted as a result from the odd-mode hydromagnetic torsional oscillation of the localized field lines (Sugiura and Wilson, 1964).

As aboved-mentioned, wave characteristics of *Pi*2 have been clarified by using the data obtained at the station-network situated over a wide latitudinal range from the auroral region through low-latitudes along the same geomagnetic meridian and the data obtained at the conjugate-pair stations in the auroral region. However, a generation mechanism of *Pi*2 has not been clarified yet, sufficiently. This is due primarily to the lack of concurrent observations of *Pi*2 on the ground and in the magnetosphere. In the present paper (the paper 3), wave characteristics of *Pi*2 are studied by using ULF data obtained at the geosynchronous satellite, ATS 6, as well as those obtained at the conjugate ground-based stations.

ATS 6 was placed in geosynchronous orbit at 96°W longitude on May 31, 1974. It remained at this location until May 20, 1975, at which time it was moved to a new location at 35°E longitude. It arrived at this new location on June 24, 1975. In the course of this movement, ATS 6 passed near the conjugate area of Syowa and Reykjavik on June 14–18, 1975 as illustrated in Fig. 1. Conjugate relationship of *Pi*2 will be studied on the basis of data obtained from the coordinated ground-satellite ULF observation during the period from June 1 to July 10, 1975. Fig. 1 shows also relative positions of ATS 6 to the geomagnetic equatorial plane during the period. As shown in the figure, the position of ATS 6 was varied successively during the period, namely, ATS 6 was located 10° above the equator on June 6, while it was near the equator on June 19 and was 3° below the equator on June 24. Since June 24, ATS 6 was located 3° below the equator, stationary.

2. Simultaneous appearance of the *Pi*2 wave in the magnetosphere and on the ground

Two successive substorm onsets were estimated to start at about 0139 and 0145 UT on June 15, 1975 from the starts of the *H*-component decrease registered on the rapid-

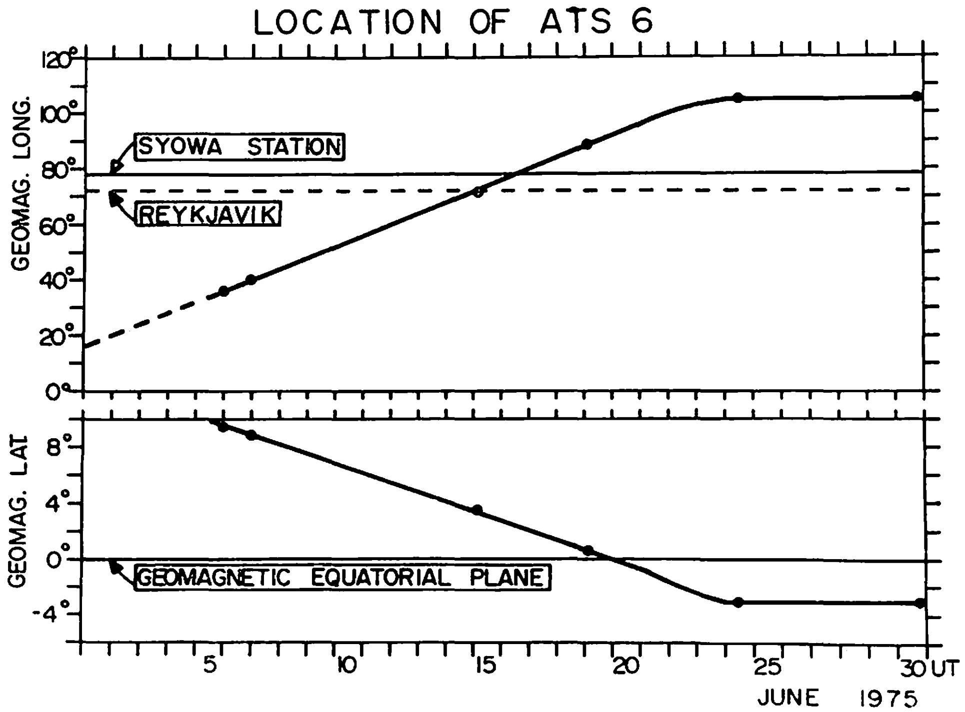

Fig. 1. Positions of the geosynchronous satellite, ATS 6, during the period from June 1 to June 30, 1975, when ATS 6 was located around the conjugate region of Syowa Station in Antarctica and Reykjavik in Iceland.

run magnetograms in the auroral region (Syowa Station and Reykjavik), and from the start of *Pi*2 at the low-latitude (Hermanus). In association with the two substorm onsets, two *Pi* events were also registered at ATS 6. It should be noted that, at that time, ATS 6 was located very closely to the conjugate point of Syowa and Reykjavik as shown in Fig. 1. Although the *Pi* oscillations at ATS 6 showed both the transverse and compressional characteristics, concerning to the perpendicular plane to the reference magnetic field (horizontal plane), the *Pi* oscillation was more dominant in the east-west component (*D*-component) than in the north-south component (*V*-component). In Fig. 2, band-pass filtered wave trains for the *Pi* oscillation at ATS 6 and on the ground are illustrated with the east-west component (*D*-component) and the north-south component (*H*-component), respectively. In association with the *Pi* event at ATS 6, the *Pi* oscillations with the similar waveforms to that at ATS 6 were also simultaneously observed at the ground-based stations over the wide latitudinal range from the auroral region through low latitudes as shown in Fig. 2. As discussed in the paper 1 (Kuwashima, 1978) and the paper 2 (Kuwashima, 1981), the *Pi*2 wave oscillation is

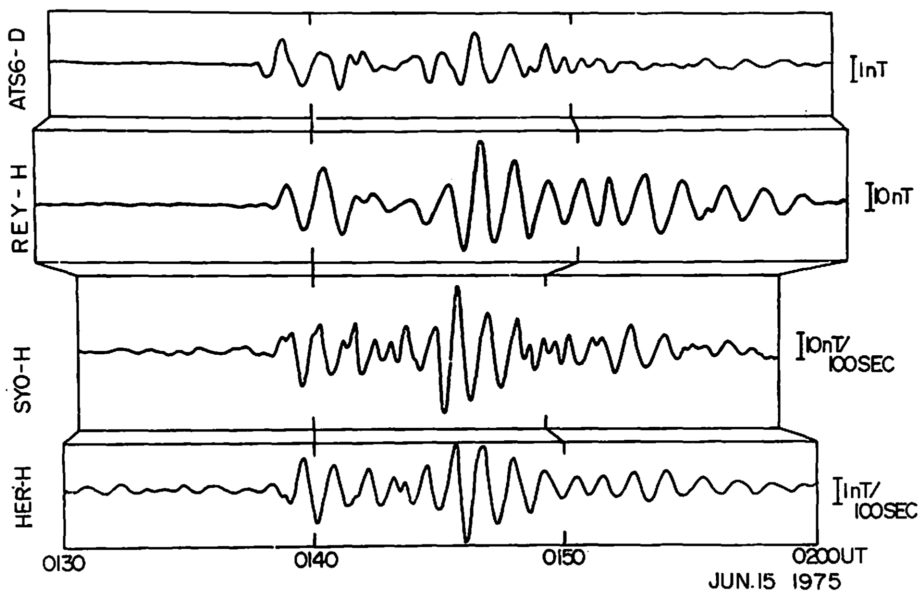

Fig. 2. Simultaneous appearance of *Pi*2 event at ATS 6 and at the ground based stations. Two substorm onsets started at 0139 and 0145 UT. The wave trains are illustrated with D (east-west) component for the data in the magnetosphere, while illustrated with H (north-south) component for the data on the ground.

more dominant in the north-sourth component than in the east-west one on the ground. Considering such the fact, *Pi* wave trains observed on the ground were illustrated with the north-south component (*H*-component) in Fig. 2. In the figure, it should be noted that the maximum peak-to-peak wave amplitude at ATS 6 was ~1 nT, while that at Reykjavik, which was the conjugate point of ATS 6, was more than 20 nT. This observational tendency is consistent with the result obtained from the study of ground-satellite correlations with *Pc*5 waves by Kokubun et al. (1976). The spectral analysis method was applied to the wave trains for the same intervals of 0138–0145 UT, and the derived spectra are illustrated in Fig.3. In the figure, a common dominant spectral component can be seen around 11 mHz both in the magnetosphere and on the ground, and this component will be identified as *Pi*2. It is clarified from the results shown in Fig. 3 that *Pi*2 was simultaneously observed at the geosynchronous altitude in the magnetosphere and the conjugate region on the ground with the similar spectral component.

It should be also noted that, in careful inspection, there are two peaks in the *Pi* spectra on the ground in Fig. 3, in which the lower frequency component (~11 mHz) is more dominant at the high latitude, while the higher frequency one (~14 mHz) is

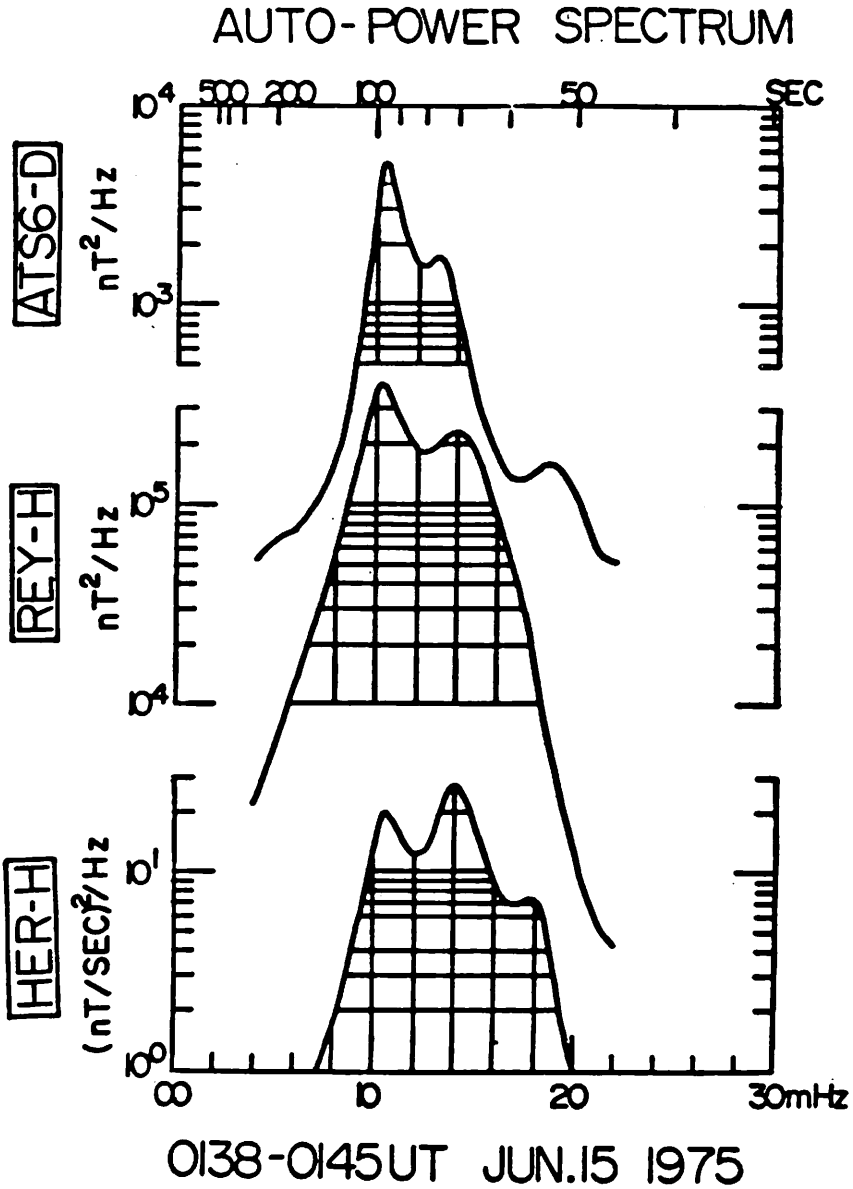

Fig. 3. The maximum entropy method of spectral analysis was applied to the *Pi* wave trains illustrated in Fig. 2 for the interval of 0138-0145 UT. The common spectral component can be seen around 11 mHz both in the magnetosphere and on the ground.

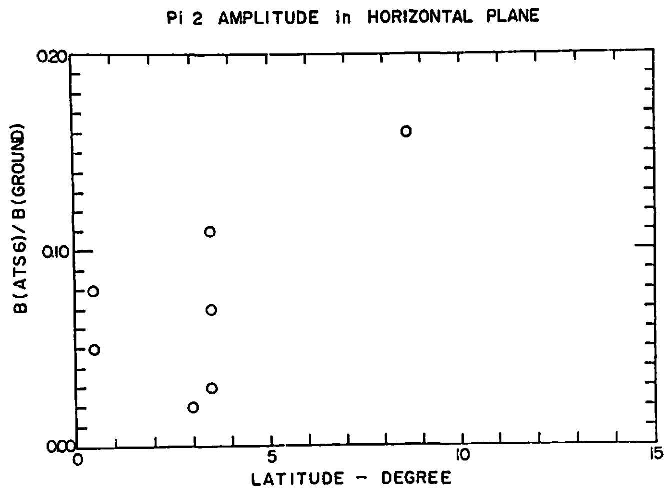

Fig. 4. Ratios of the *Pi*2 wave amplitude at ATS 6 to that at the conjugate ground-based stations (Syowa Station or Reykjavik) are plotted as a function of the relative latitude of ATS 6 to the geomagnetic equatorial plane.

more dominant at the low latitude. Such the tendency can be also found in Fig. 4 of Saito et al. (1976).

In this section, it has been clarified that the *Pi*2 wave exists with a common spectral component both at the geosynchronous altitude in the magnetosphere and at the conjugate region on the ground. The *Pi*2 wave amplitude observed on the ground is conspicuously larger than that observed near the equator in the magnetosphere as shown in Fig. 2 for example. This tendency was studied quantitatively and the results are summarized in Fig. 4. During the period from June 1 to July 10, 1975, seven *Pi*2 events were simultaneously observed at ATS 6 and at the ground-based conjugate stations, Syowa and Reykjavik, with similar sinusoidal waveforms. For these seven events, ratio of the *Pi*2 wave amplitude at ATS 6 to that at the ground-based stations was calculated in the perpendicular plane to the reference magnetic field (horizontal plane) using the derived *Pi*2 spectral component. In Fig. 4, the calculated ratios are plotted as a function of the magnetic latitude of ATS 6. The results in the figure suggest that the *Pi*2 wave amplitude shows a minimum at the geomagnetic equatorial-plane in the magnetosphere and becomes large with increasing the distance from there. This observational results will be examined theoretically later.

3. Phase-relationship of *Pi*2 derived from the satellite-ground correlative observation

As discussed in the previous section, although the *Pi*2 events were simultaneously

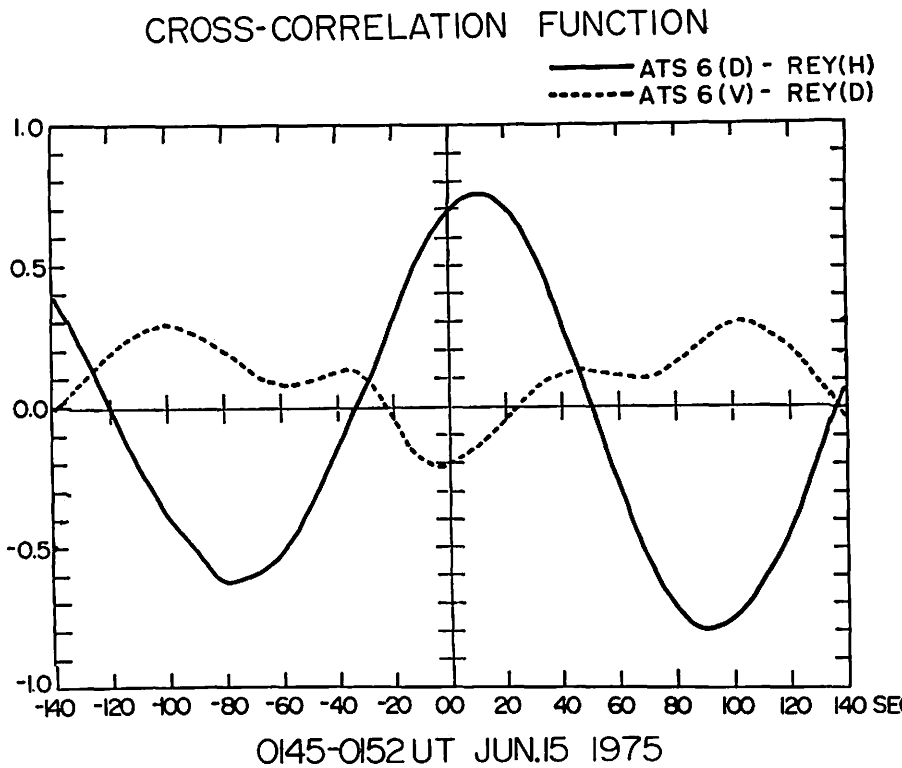

Fig. 5. Cross-correlation functions are calculated using the *Pi*2 wave trains simultaneously observed both in the magnetosphere and on the ground. An in-phase relationship can be seen between the D (east-west) component in the magnetosphere and the H (north-south) component on the ground, while an anti-phase relationship can be seen between the V (north-south) component in the magnetosphere and the D (east-west) component on the ground.

observed with similar waveforms both at ATS 6 and Reykjavik, the dominant oscillation in the perpendicular plane to the reference magnetic field was in the east-west (*D*) component in the magnetosphere, while it was in the north-south (*H*) component on the ground. This observational evidence suggests an occurrence of 90° rotation in the major axis of wave polarization in a propagation from the magnetosphere to the ground through the ionosphere. The above-mentioned relationships will be seen more clearly by calculating cross-correlation function between the two components. Using the wave trains discussed in Fig. 2, the cross-correlation functions were calculated for the interval of 0145–0152 UT and the results are shown in Fig. 5. In the figure, the east-west (*D*) component in the magnetosphere and the north-south (*H*) component on the ground show the clear in-phase relationship with the correlation maximum value of 0.75. On the other hand, the north-south (*V*) component in the

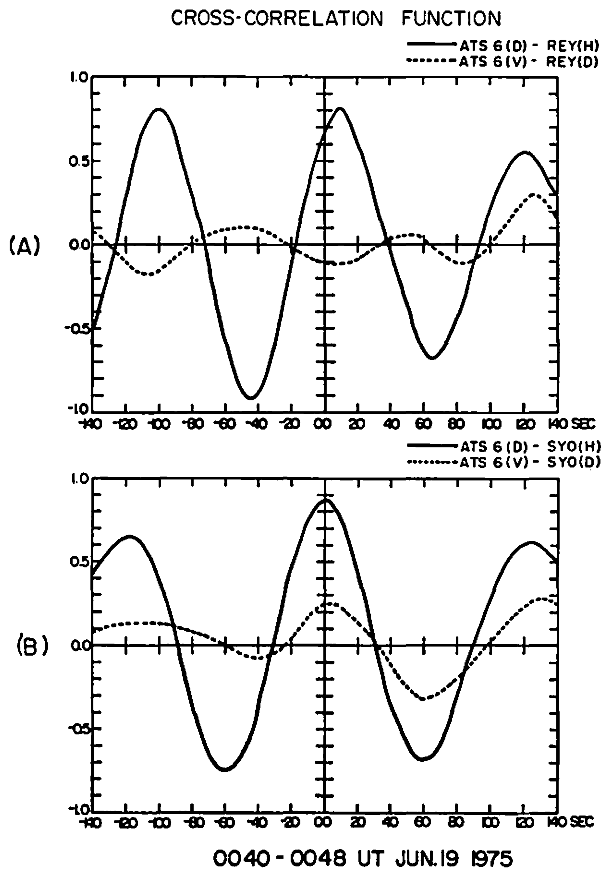

Fig. 6. Cross-correlation functions calculated using the *Pi*2 wave trains simultaneously observed at ATS 6 and the conjugate ground-based stations, Reykjavik (a) and Syowa Station (b), for the interval of 0040-0048 UT on June 19.

magnetosphere and the east-west (*D*) component on the ground show the anti-phase relationship with the correlation maximum value of 0.20 in the negative value.

Similar relationships are also seen in another example of the *Pi*2 event which was observed on June 19, 1975. ATS 6 was located near the geomagnetic field lines which were anchored at Syowa and Reykjavik during this event, too. The cross-correlation functions were calculated both between ATS 6 and Reykjavik, and ATS 6 and Syowa, and the results are shown in Figs. 6(A) and (B). For the correlation between the east-west (*D*) component in the magnetosphere and the north-south (*H*) component on the ground, the results in the figure show the in-phase relationship. On the other hand, for the correlation between the north-south (*V*) component in

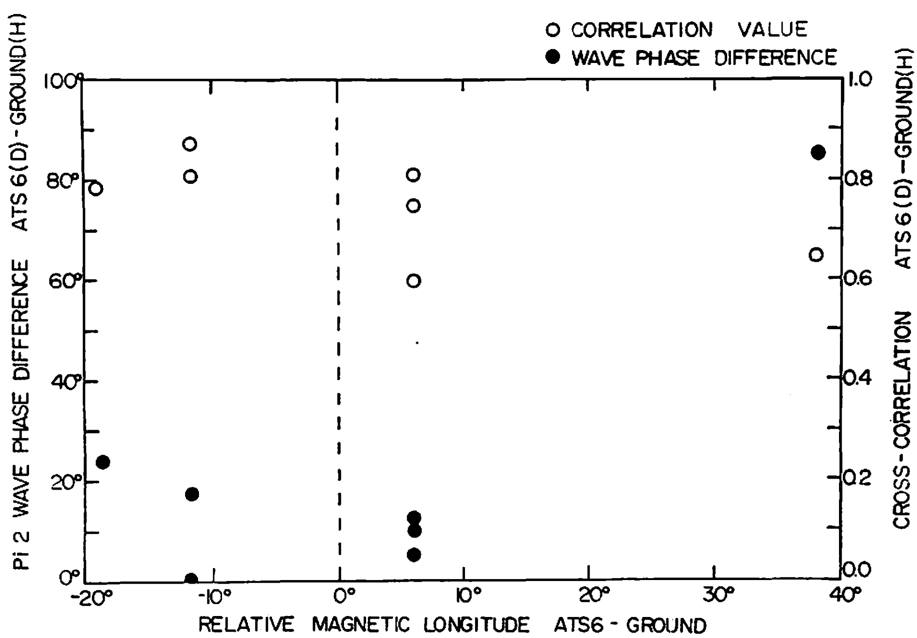

Fig. 7. *Pi*2 wave-phase difference between the D (east-west) component at ATS 6 and the H (north-south) component on the ground (solid circle), and the maximum cross-correlation value derived from the cross-correlation function (open circle).

the magnetosphere and the east-west (*D*) component on the ground, the anti-phase and the in-phase relationship are derived between ATS 6 and Reykjavik (Fig. 6(A)) and between ATS 6 and Syowa (Fig. 6(B)), respectively.

Using a cross-correlation function, a *Pi*2 wave-phase difference between the magnetosphere and the ground was calculated for the seven *Pi*2 events by using the filtered wave train at ATS 6 as a reference wave. The results are summarized in Fig. 7, which shows a phase difference between the east-west (*D*) component in the magnetosphere and the north-south (*H*) component on the ground (solid circles). When ATS 6 was located near the conjugate point of Syowa or Reykjavik within 10° in geomagnetic longitude, the wave-phase difference is very small (~0°) indicating the clear in-phase relationship. The wave-phase difference becomes large with increasing the distance from the conjugate point. The large wave-phase difference ~90° will be due to the effect of longitudinal propagation of the *Pi*2 wave. Fig. 7 also shows cross-correlation coefficients between the *Pi*2 wave in the magnetosphere and that on the ground (open circles). As shown in the figure, the cross-correlation coefficient is always higher than 0.6 independent on the longitudinal difference between the satellite and the ground-based station. This evidence indicates that the *Pi*2 wave observed in the magnetosphere has the same source as that observed on the ground.

4. Discussion

Wave characteristics of *Pi*2 have been studied by using ULF data obtained at the geosynchronous satellite, ATS 6, as well as those obtained at the ground-based stations. When the satellite is located near the conjugate point of the ground-based station, the *Pi*2 wave is simultaneously observed both in the magnetosphere and on the ground with similar waveforms. An important finding in the present study is the characteristic *Pi*2 wave-phase relationships between the magnetosphere and ground. The *Pi*2 oscillation shows a clear in-phase relationship between the east-west component in the magnetosphere and the north-south component at the conjugate ground-based station in the northern hemisphere as shown in Figs. 5 and 6. On the other hand, the *Pi*2 oscillation shows an anti-phase relationship between the north-south component in the magnetosphere and the east-west component on the ground. These wave-phase relationships will be closely related to the ionospheric screening effect, because the hydromagnetic wave generated in the magnetosphere must pass through the ionosphere before reaching the ground. The ionospheric screening effects have been studied theoretically by many researchers (Nishida, 1964: Tamao, 1964: Inoue, 1973: Hughes and Southwood, 1976a and b). They have theoretically predicted that the major axis of wave polarization should be rotated through 90° in a propagation from the magnetosphere to the ground through the ionosphere. According to their result, magnetic perturbations on the ground and in the magnetosphere should be represented by the following relation,

$$B_{NG}=\frac{\Sigma_H}{\Sigma_P}\exp(-|m|d)\cdot B_{EM}$$

where B_{NG} is the magnetic perturbation on the ground and shows the northward direction, while B_{EM} is the magnetic perturbation in the magnetosphere and shows the eastward direction. Σ_H and Σ_P are integrated Hall and Pedersen conductivities, while m and d are wave number in the perpendicular plane to the reference magnetic field and altitude of the ionosphere, respectively. The relation (1) means that the northward component on the ground is produced from the eastward component in the magnetosphere. In other words, the magnetic perturbation vector is rotated through 90° in the counter clockwise direction when viewed toward the ground in the northern hemisphere, while it is rotated through 90° in the clockwise direction in the southern hemisphere. These relations are illustrated schematically in Fig. 8. As shown in the figure, when the wave oscillation is dominant in the *D* (east-west) component in the magnetosphere, the wave oscillation on the ground is expected to be dominant in the *H* (north-south) component.

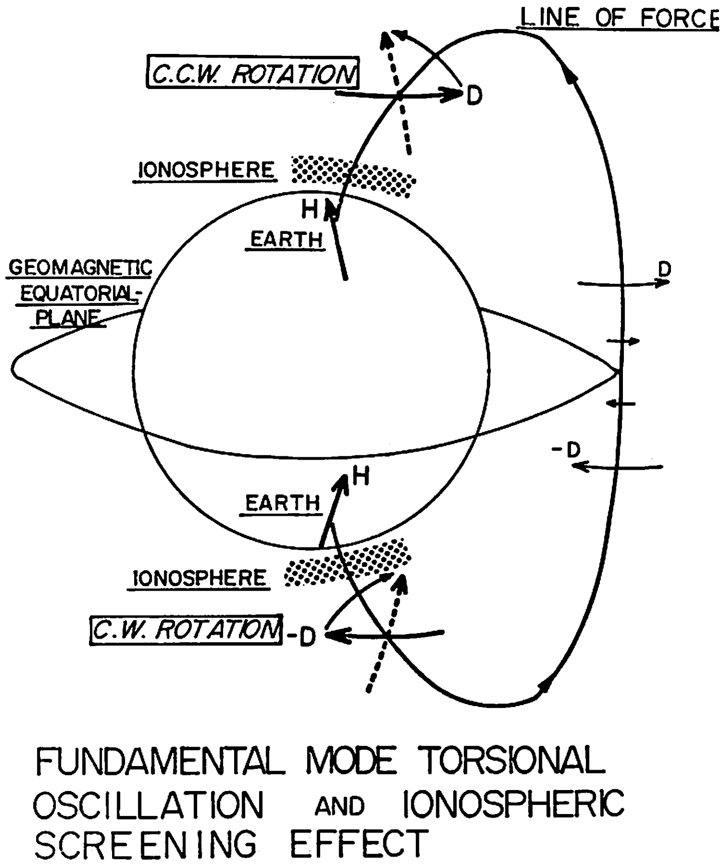

Fig. 8. Schematic profile for the ionospheric screening effect with the *Pi*2 wave. In the northern hemisphere, the major axis of polarization ellipse is rotated through 90° in the counter clockwise direction when viewed toward the ground. In the southern hemisphere, the major axis is rotated through 90° in the clockwise direction.

Fig. 8 also shows that, in fundamental mode of the hydromagnetic standing oscillation, the following wave-phase relationships are expected between the magnetic perturbation on the ground and that in the magnetosphere: When the satellite is located above the equatorial-plane, the D component in the magnetosphere shows an in-phase relationship to the H-component on the ground in both the hemispheres. On the other hand, when the satellite is located below the equatorial-plane, the D-component in the magnetosphere shows an anti-phase relationship to the H-component on the ground. For the relationship between the V (north-sourth) component in the magnetosphere and the D (east-west) component on the ground, an anti-phase (in-

Table 1.

		D – COMPONENT IN THE MAGNETOSPHERE	
		ABOVE GEOMAGNETIC EQUATORIAL PLANE	BELOW GEOMAGNETIC EQUATORIAL PLANE
H – COMPONENT ON THE GROUND	NORTHERN HEMISPHERE	IN-PHASE	ANTI-PHASE
	SOUTHERN HEMISPHERE	IN-PHASE	ANTI-PHASE

		V – COMPONENT IN THE MAGNETOSPHERE	
		ABOVE GEOMAGNETIC EQUATORIAL PLANE	BELOW GEOMAGNETIC EQUATORIAL PLANE
D – COMPONENT ON THE GROUND	NORTHERN HEMISPHERE	ANTI-PHASE	ANTI-PHASE
	SOUTHERN HEMISPHERE	IN-PHASE	IN-PHASE

phase) relationship is observable between the satellite and the ground-based station in the northern (southern) hemisphere, independent on the location of the satellite. These relations are summarized in Table 1.

The ground-satellite coordinated observation in the present study was carried out during the interval from June 1 to July 10, 1975, when the northern hemisphere was in the summer solstice. Considering the inclination of dipole axis about 30° (Mead and Fairfield, 1975), the geomagnetic equatorial-plane shifts about $-5°$ at the geosynchronous altitude so that the relative position of ATS 6 to the equatorial-plane in Fig. 1 should shift to the higher-latitude side about $+5°$. Therefore, ATS 6 was always located above the equatorial-plane during the interval of the present satellite-ground coordinated observation. Considering the situation, the theoretical result shown in Fig. 8 and Table 1 is consistent with the present observed results shown in Figs. 5 and 6.

The existence of the 90° rotation of the major axis of the *Pi*2 wave polarization means an existence of a propagation of the Alfvén-mode along the field line causing the hydromagnetic standing oscillation, because the above-mentioned 90° rotation can be deduced for only the Alfvén-mode (Hughes and Southwood, 1976a and b). The evidence is consistent with the following previous result derived from the paper 1 (Kuwashima, 1978) and the paper 2 (Kuwashima, 1981) that *Pi*2 is caused by the fundamental-mode of the torsional oscillation of the field lines anchored on the night-side auroral ovals.

The problem of the conversion of the hydromagnetic wave to the electromagnetic induction in the ionosphere has been theoretically studied in the following two aspects, which are the heating of the ionosphere (Newton et al., 1978: Allan and Knox, 1979), and the transmission of the waves through the ionosphere (Nishida, 1964: Tamao, 1965: Inoue, 1973: Hughes, 1974: Hughes and Southwood, 1976a and b: Walker et al., 1979). One of the most interesting results derived from the theoretical study is the 90° rotation of the major axis of the polarization ellipse between the geomagnetic equator in the magnetosphere and the ground as discussed in the present study.

However, an experimental evidence for the wave ellipse rotation was very rare because of quite small existing sets of data which can be used to investigate possible ionospheric effect on the orientation of the hydromagnetc wave. The study has been restricted to a statistical nature until the present paper. The one observational evidence came from the satellite (ATS 6) statistical results by Arthur et al. (1977) for the *Pc*3–4 type magnetic pulsations in comparison with the data by Lanzerotti et al. (1972) from Lac Rebours and Siple, which were located near the same meridian of ATS 6. According to their results, the major axis of the polarization ellipse at the geosynchronous orbit (magnetic latitude ~10°) located in the north-east quadrant during local morning and in the north-west quadrant during local afternoon in the perpendicular plane to the ambient magnetic field. These orientations were opposite on the ground suggesting the rotation of the major axis between the magnetosphere and the ground. Another evidence for the wave ellipse rotation was derived by Andrews (1977) and Andrews et al. (1979) using the Doppler shift of fix-frequency VLF signals. They reported a significant number of occasions that the whistler duct was apparently affected by the electric field of the hydromagnetic wave in the period range of 60–600s. They concluded that within the resolution of the normal-run magnetograms (20 mm/hour) the wave perturbation vector was rotated 90° between the magnetosphere and the ground.

Until the present study, there has not been any direct single-event satellite-ground comparison that can unambiguously establish the experimental evidence for the 90° rotation of the major axis of the polarization ellipse. The result shown in Fig. 5, for example, shows that the *Pi*2 wave vector was rotated through 90° in the counter-clockwise direction when viewed toward the ground in the northern hemisphere, while through 90° in the clockwise direction in the southern hemisphere. The strongest experimental evidence is found in the present study for the rotation of the orientation angle of the wave polarization ellipse from the simultaneous *Pi*2 measurement near the equator in the magnetosphere and at the conjugate ground-based stations. The theoretically expected ionospheric modulation effect is clarified experimentally in the present study. The 90° rotation is also the conclusive evidence for the incident Alfvén wave along the localized field line to the auroral ionosphere.

When the geosynchronous satellite is located near the conjugate point of ground-based stations, a *Pi*2 event is simultaneously observed both in the magnetosphere and on the ground with similar waveforms. However, the observed *Pi*2 wave amplitude is not similar at the two as shown in Fig. 2, where the amplitude observed on the ground is conspicuously larger than that near the equatorial plane in the magnetosphere. This result is also consistent with the tendency derived from the fundamental-mode of the hydromagnetic torsional oscillation of the field lines. In the oscillation, the wave amplitude minimizes on the geomagnetic equatorial-plane in the magnetosphere, increases with increasing the distance from there and reaches the maximum at the ionosphere.

5. Conclusion

The 90° rotation of the *Pi*2 wave vector in the ionosphere has been experimentally confirmed by the ground-satellite coordinated ULF observation. The result is consistent with the previous results on *Pi*2 (Kuwashima, 1978 and 1981), because the 90° rotation is the conclusive evidence for the incident Alfvén wave along the localized field lines from the magnetosphere to the auroral ionosphere (auroral oval). The result supports the following model that *Pi*2 is caused by the fundamental-mode of the hydromagnetic torsional oscillation of the localized field lines anchored on the night-side auroral ovals.

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地上および磁気圏における Pi2 型磁気脈動の波動特性

桑 島 正 幸

概　　要

静止軌道衛星 ATS 6 と地上における共役点（南極昭和基地とアイスランドのレイキャビック）で同時に得られた ULF 資料をもとにして，Pi2 脈動の波動特性の研究を行った。その結果，Pi2 の偏波面の主軸が電離層効果によって 90° 回転することがわかった。この事実は，オーロラルオーバルに根をもつ磁力線の standing oscillation によって，Pi2 が発生するという仮説を指示する。この仮説は，ATS 6 における Pi2 の振幅のふるまいからも指示される。