WAVE CHARACTERISTICS OF MAGNETIC Pi 2 PULSATIONS: GROUND-MAGNETOSPHERE CORRELATIONS

Masayuki KUWASHIMA

Kakioka Magnetic Observatory, 595 Kakioka, Yasato-machi, Niihari-gun, Ibaraki 315-01

Abstract: The Pi 2 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 Pi 2 wave polarization rotates through 90° in a propagation from the magnetosphere to the ground through the ionosphere.

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 respect, Pi 2 is one of the important manifestations of the magnetospheric substorm. In the previous two papers (KUWASHIMA, 1978, 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, including Mawson (L=8.9), Mizuho Station (L=7.5), Syowa Station (L=6.1), Sanae (L=4.0) and Hermanus (L=1.8). From the study, the close relationship of the Pi 2 period to the auroral breakup position was clarified. The Pi 2 period increases with increase of the geomagnetic latitude where the associated auroral breakup started. The Pi 2 period behavior could be reasonably interpreted as the fundamental mode of the hydromagnetic torsional oscillation of the field lines anchored on the northern and southern nightside auroral ovals. The polarization behaviors of Pi 2 near the auroral electrojet strongly supported the idea of the hydromagnetic resonant oscillation of the field lines as a cause of Pi 2.

In the paper 2 (KUWASHIMA, 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. From 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 phase-relationship of the Pi 2 wave 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. This phase-relationship of the Pi 2 wave has been interpreted as a result of the odd-mode hydromagnetic torsional oscillation of the localized field lines as originally suggested by SUGIURA and WILSON (1964).

As mentioned above, 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 sufficiently clarified yet. 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 that obtained at the conjugate ground-based stations.

ATS 6 was placed in a 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

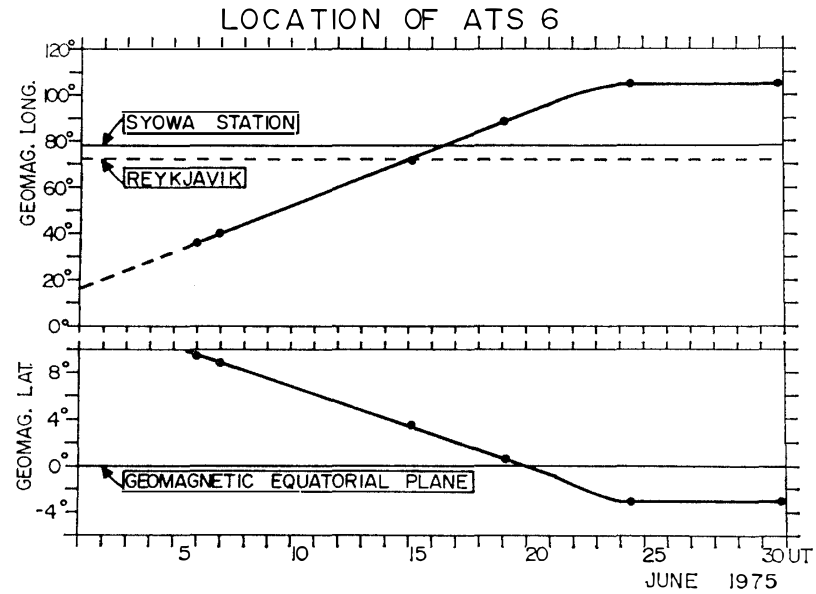

Fig. 1. Positions of the geosynchronous satellite, ATS 6, during the period from June 1 to June 30, 1975, when ATS 6 was located around the conjugate region of Syowa Station in Antarctica and Reykjavik in Iceland.

observation during the period from June 1 to July 10, 1975. Figure 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 was changed 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-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 close 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, with respect to the perpendicular plane to the reference magnetic field, 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 are illustrated with the east-west component (*D*-component). In association with the Pi event at ATS 6, the Pi oscillations were also simultaneously observed with the similar waveforms to that at ATS 6 on 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 more dominant in the north-south component than in the east-west one on the ground. Considering such a fact, Pi wave trains observed on the ground are 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 evidence 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

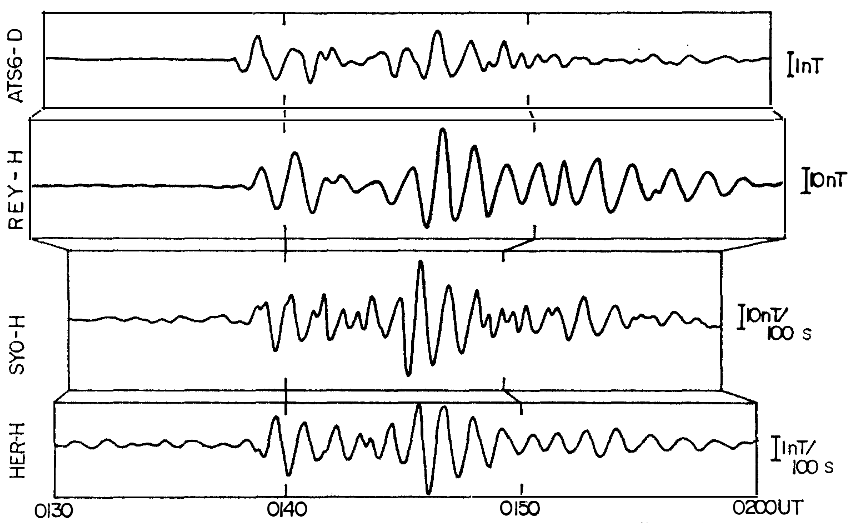

Fig. 2. Simultaneous appearance of Pi 2 event at ATS 6 and at the ground-based stations. Two substorm onsets started at 0139 and 0145 UT. The wave trains are illustrated with the D (east-west) component for the data in the magnetosphere, while illustrated with the H (north-south) component for the data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

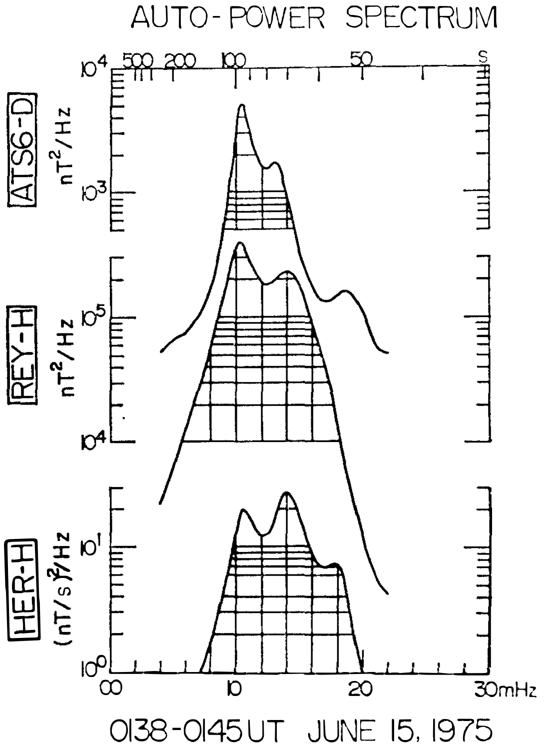

Fig. 3. The maximum entropy method of spectral analysis was applied to the Pi wave trains illustrated in Fig. 2 for the interval of 0138–0145 UT. The common spectral component can be seen around 11 mHz both in the magnetosphere and on the ground.

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

3. Wave-phase Relationship of Pi 2 Derived from the Satellite-ground Correlative Observation

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

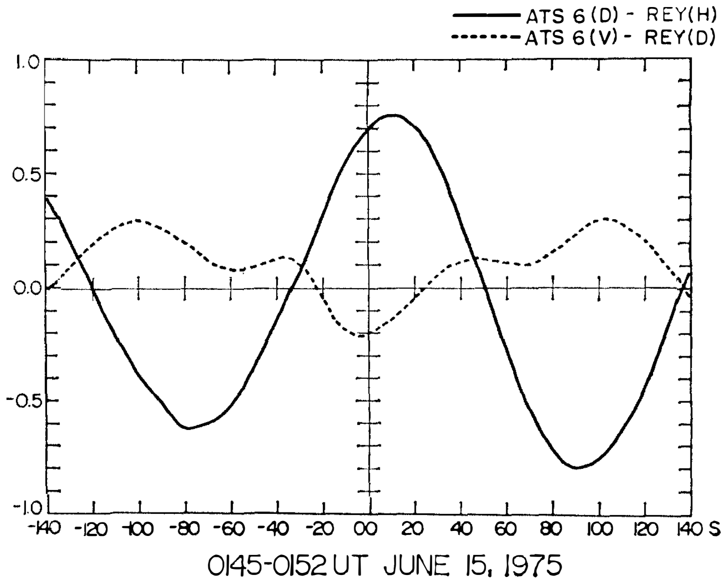

Fig. 4. Cross-correlation functions are calculated using the Pi 2 wave trains simultaneously observed both in the magnetosphere and on the ground. An in-phase relationship can be seen between the D (east-west) component in the magnetosphere and the H (north-south) component on the ground, while an anti-phase relationship can be seen between the V (north-south) component in the magnetosphere and the D (east-west) component on the ground.

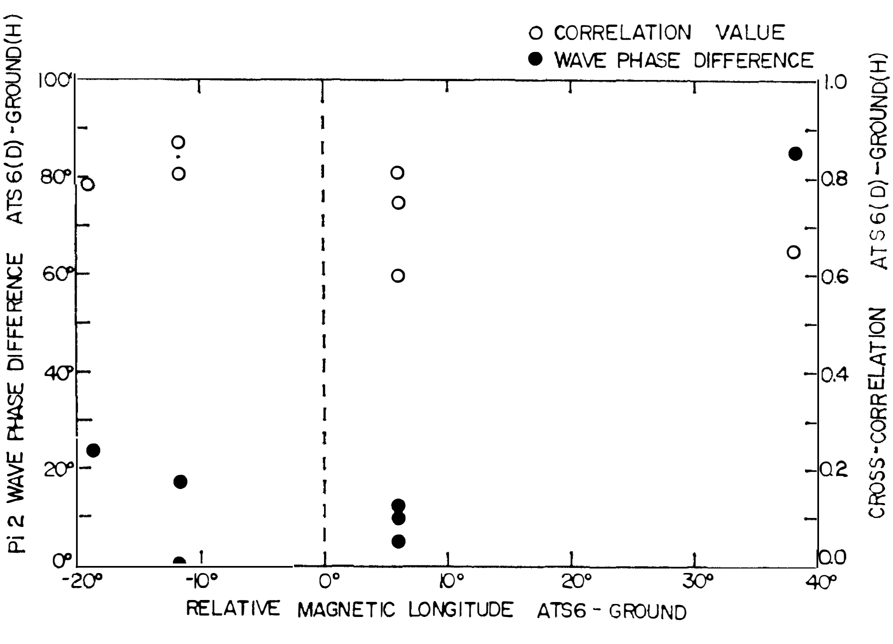

Fig. 5. Pi 2 wave-phase difference between the D (east-west) component at ATS 6 and the H (north-south) component on the ground (solid circle), and the maximum cross-correlation value derived from the cross-correlation function (open circle).

interval of 0145–0152 UT and the results are shown in Fig. 4. 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 values of 0.75. On the other hand, the north-south (V) component in the magnetosphere and the east-west (D) component on the ground show the anti-phase relationship with the correlation minimum value of -0.20.

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. 5, 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 ($\sim 0°$) indicating the clear in-phase relationship. The wave-phase difference becomes larger with increasing distance from the conjugate point. The large wave phase difference $\sim 90°$ will be due to the effect of longitudinal propagation of the Pi 2 wave. Figure 5 also shows cross-correlation coefficients between the Pi 2 wave in the magnetospheres and that on the ground (open circles). As shown in the figure, the cross-correlation coefficient is always higher than 0.6 independent of the longitudinal difference between the satellite and the ground-based station. This fact 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 the ground. The Pi 2 oscillation shows a clear in-phase relationship between the east-west component in the magnetosphere and the north-south component on the conjugate ground-based station in the northern hemisphere as shown in Fig. 4. 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. This 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 to be detected as magnetic pulsations. The ionospheric screening effect has been studied theoretically by many researchers (NISHIDA, 1964; TAMAO, 1964; INOUE, 1973; HUGHES and SOUTHWOOD, 1976a, 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,

$$\boldsymbol{B}_{\mathrm{NG}} = \frac{\Sigma_{\mathrm{H}}}{\Sigma_{\mathrm{P}}} \exp(-|m|d) \cdot \boldsymbol{B}_{\mathrm{EM}} , \quad (1)$$

where $\boldsymbol{B}_{\mathrm{NG}}$ is the magnetic perturbation on the ground and shows the northward direction, while $\boldsymbol{B}_{\mathrm{EM}}$ 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 counterclockwise 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. 6. 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.

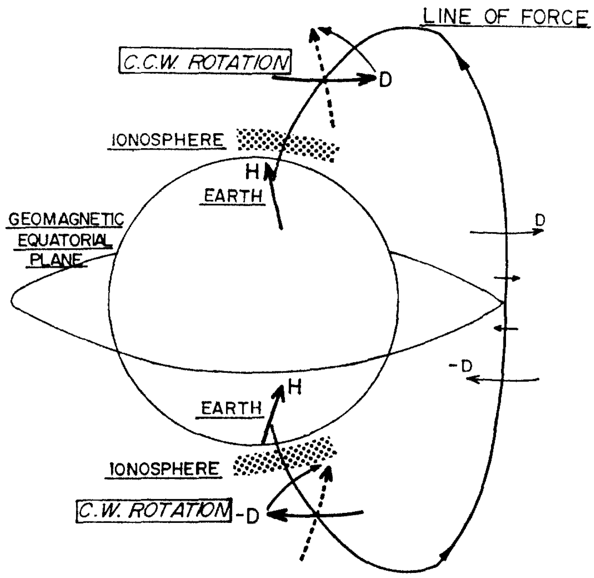

Fig. 6. Schematic profile for the ionospheric screening effect with the Pi 2 wave. In the northern hemisphere, the major axis of polarization ellipse is rotated through 90° in the counterclockwise direction when viewed toward the ground. In the southern hemisphere, the major axis is rotated through 90° in the clockwise direction.

Figure 6 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-south) component in the magnetosphere and the D (east-west) component on the ground, an anti-phase (in-phase) relationship is observable between the satellite and the ground-based station in the northern (southern) hemisphere, independent of 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

Table 1. Wave-phase relation of the fundamental HM oscillation between the magnetosphere and the ground.

		D-component in the magnetosphere: Above geomagnetic equatorial plane	D-component in the magnetosphere: Below geomagnetic equatorial plane		V-component in the magnetosphere: Above geomagnetic equatorial plane	V-component in the magnetosphere: Below geomagnetic equatorial plane
H-component on the ground	Northern hemisphere	In-phase	Anti-phase	D-component on the ground	Anti-phase	Anti-phase
	Southern hemisphere	In-phase	Anti-phase		In-phase	In-phase

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. 6 and Table 1 is consistent with the present observed results shown in Figs. 4 and 5.

The existence of the 90° rotation of the major axis of the Pi 2 wave polarization means that 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, b). The fact 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 nightside 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, 1964; INOUE, 1973; HUGHES, 1974; HUGHES and SOUTHWOOD, 1976a, b; WALKER *et et.*, 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 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 hydromagnetic 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 $\sim 10°$) was 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 60–600 s. They concluded that within the resolution of the normal-run magnetograms (20 mm/h) 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. 4, for example, shows that the Pi 2 wave vector was rotated through 90° in the counterclockwise 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 theoretical 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 wave 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 is minimized on the geomagnetic equatorial plane, increases with increasing 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, 1981; KUWASHIMA and SAITO, 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 nightside auroral ovals.

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