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COORDINATED OBSERVATIONS OF IONOSPHERE-ATMOSPHERE COUPLING IN THE ARCTIC USING AN HF DOPPLER SYSTEM AND AN INFRASONIC WAVE DETECTOR

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Abstract: In an attempt to observe the dynamics of the ionosphere and its coupling at lower heights in high latitudes, an HF Doppler measurement system was coordinated with an infrasonic wave detector at Fairbanks, Alaska. The preliminary results show several characteristics which were not observed at lower latitudes. Widely spread Doppler shifts, saw-tooth-like Doppler shifts *etc.* were observed. Quasi-sinusoidal Doppler oscillations (period of 1 min to 1 h) related to the medium scale traveling ionospheric disturbances (TID's), which were probably caused by atmospheric waves or by auroral dynamics, were also observed that were similar to those observed in the lower latitude ionosphere. Some of the HF Doppler data seem to be correlated with atmospheric waves observed on the ground by infrasonic wave detectors. These data suggest direct evidence of energetic coupling between the ionospheric F, E layer and the ground through the middle atmosphere. HF Doppler data also show Pc3 range oscillations correlating with cosmic noise absorption (CNA) data.

1. Introduction

It has been pointed out that atmospheric perturbations caused by typhoons, tornadoes, volcanic eruptions, above-ground atomic detonations *etc.* can propagate to the ionosphere through the middle atmosphere (HINES, 1960; GEORGES, 1973; OGAWA *et al.*, 1982). On the other hand, it has been reported that infrasonic waves generated by the supersonic motion of auroral forms often propagate through the middle atmosphere to the ground as impulsive perturbations. These perturbations are called auroral infrasonic waves (AIW) (WILSON, 1972; OLSON, *et al.* 1982). Impulsive perturbations at auroral latitudes and heights may also be a source of large scale traveling ionospheric disturbances (LS/TID's) propagating to the lower latitude ionosphere horizontally (MAEDA and HANDA, 1980; HUNSUCKER and TVETEN, 1967; HUNSUCKER, 1982; HAJKOWICZ and HUNSUCKER, 1987; HUNSUCKER, 1987; RICE *et al.*, 1988). KAHN (1970) presented evidence of E region ionosphere-ground level atmosphere couplings using HF phase measurement at low latitudes. BOWMAN and SHRESTHA (1966) introduced a possible pressure fluctuation on the ground due to ionosphere storms as the basis of $h'F$ variations.

HF Doppler shift measurements have been used for years to observe atmospheric waves and turbulence in the ionosphere (OGAWA, 1958; WATTS and DAVIES, 1960; DAVIES and BAKER, 1966; GEORGES, 1968; BAKER and COTTON, 1971). These data make clear the dynamic structure of the horizontally moving ionosphere by the use of multi-station systems. For the study of atmospheric wave propagations, observations of the vertical component of waves using incoherent scatter radar (BANKS and DOUPNIK, 1975), satellites (KAYZER *et al.*, 1979) and rockets (MINAMI *et al.*, 1982) are also important. In this paper, we report preliminary experimental results using HF Doppler systems at high latitudes (Fairbanks, Alaska) for the further development of multi-station systems.

The goals of these experiments were:

(1) To study the propagation of radio waves in the high latitude ionosphere by analyzing the different Doppler shift patterns caused mostly at reflection points.

(2) To study the propagation of atmospheric waves (wavelength of several km to 100 km) and gravity waves driven by auroral dynamics and to analyze the relationship between such ionospheric disturbances and infrasonic waves on the ground (GEORGES, 1973; WILSON, 1972).

(3) To investigate the origin of large scale gravity waves (wavelength of nearly 1000 km) propagating from polar regions to lower latitudes (MAEDA and HANDA, 1980).

(4) To carry out multi-station measurements of the HF Doppler shift along the auroral oval or at the polar cap in order to observe the ionospheric drifts continuously.

(5) To study vertically propagating atmospheric waves through the D layer correlated with signal variations of VLF radio waves, such as the Omega system.

2. Observations

HF Doppler observation is based on the measurement of frequency shifts of highly-stable-frequency, HF radio waves reflected from the moving ionosphere (OGAWA, 1958; DAVIES and BAKER, 1966). The system is illustrated in Fig. 1. An instantaneous frequency shift, df (Doppler shift of the radio wave), is a function of the time rate

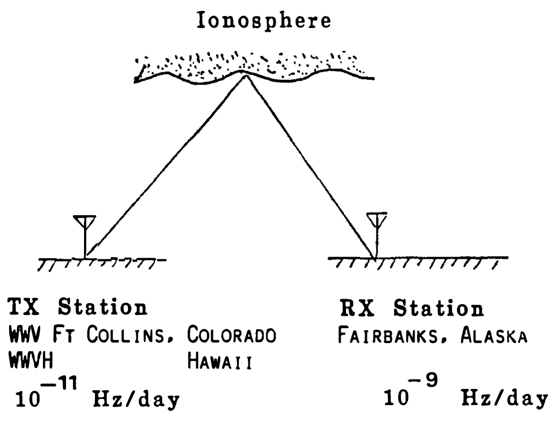

Fig. 1. HF Doppler measurement system.

of the change of the wave path, p,

$$df = -(f/c)\frac{dp}{dt} \tag{1}$$

where c is the light speed in a vacuum. By introducing the refractive index, n, for the radio wave, df is expressed as

$$df = -(f/c)\int \frac{dn}{dt}\, ds \tag{2}$$

where s is the path length. It shows that df is a function of the time rate of the change of refractive index along the path. Neglecting collisions and magnetic field effects, the refractive index is

$$n = \sqrt{1 - \left(\frac{Ne^2}{m\varepsilon_0}\Big/ f\right)^2} \tag{3}$$

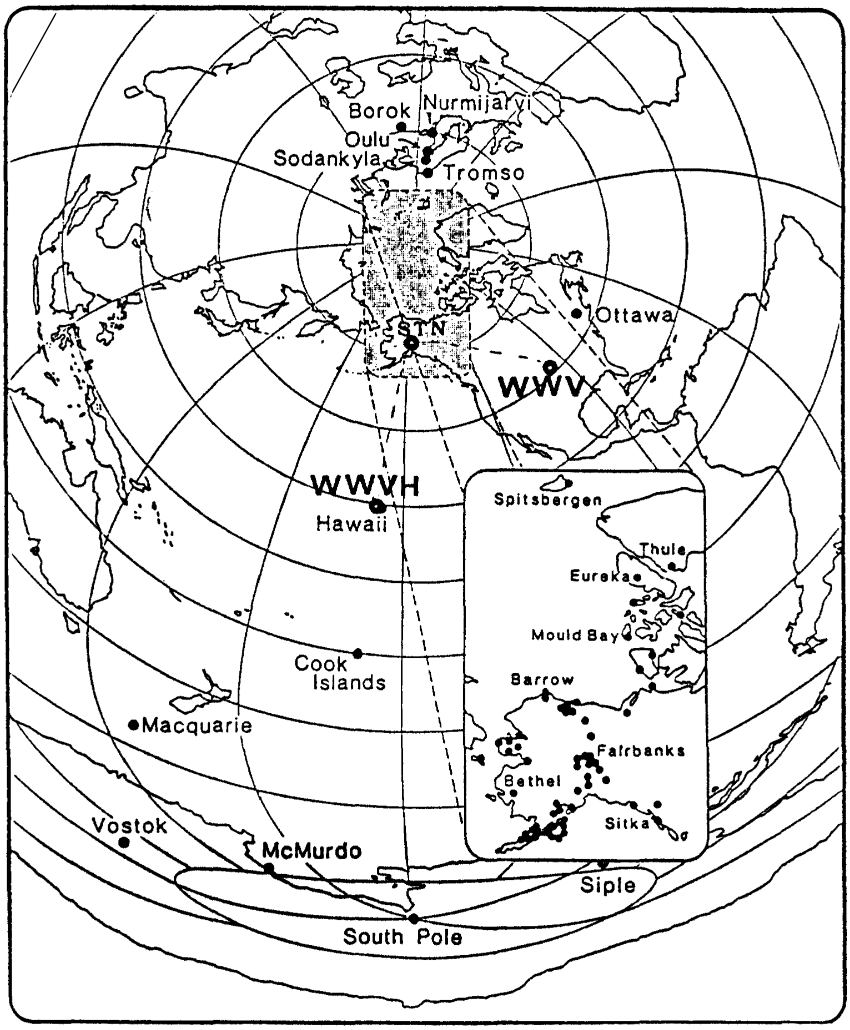

Fig. 2. Locations of WWV, WWVH stations (STN) and the receiving station at Fairbanks.

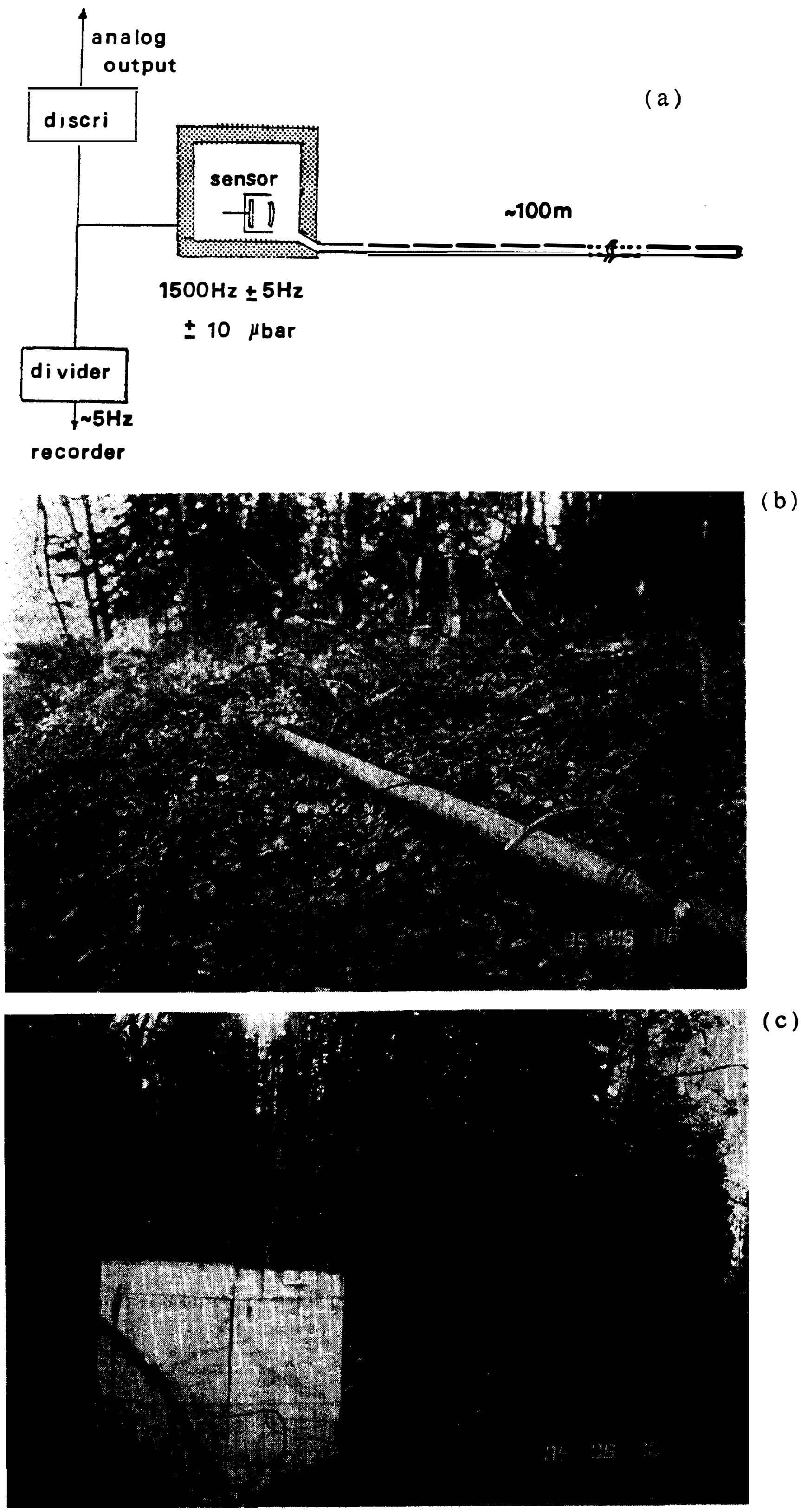

Fig. 3. (*a*) *Schematic diagram of infrasonic wave detector using a capacitance microphone and a 100 m line filter.* (*b*) *Photograph of the line filter.* (*c*) *Photograph of the infrasonic wave detector system on the campus of the University of Alaska, Fairbanks.*

where N is the plasma density in the path. For vertical propagation, $\mathrm{d}f$ is expressed as,

$$\begin{aligned} \mathrm{d}f &= -(f/c)\int_{h_1}^{h_2} \frac{\partial n}{\partial N}\frac{\partial N}{\partial t}\,\mathrm{d}h \\ &\doteqdot \left(\frac{1}{2m\varepsilon_0 cf}\right)\frac{\partial N_t}{\partial t} \end{aligned} \tag{4}$$

Equation (4) shows that the Doppler frequency shift is proportional to the time rate of change of the total electron content, N_t, along the path length (h_1–h_2) in the ionosphere. It means that the Doppler shift frequency deviations are also caused by the electron density perturbations along the path.

At the receiving points, a stable local oscillator is used to obtain a beat frequency of several Hz to 10 Hz. We have used a receiver to measure 10 MHz WWV and WWVH standard frequency signals as shown on the map in Fig. 2.

The infrasonic wave was measured at the ground with a pressure sensitive condenser microphone which was configured as one leg of Wien Bridge oscillator. A 100 m line filter was installed at the input to the microphone to reduce the local wind noise (OLSON *et al.*, 1982). The block diagram of the system is shown in Fig. 3(a). Figure 3(b, c) shows photographs of the line filter and the electronics box which contained the condenser microphone. The variation of the atmospheric waves are converted into frequency modulated signals and transmitted on a telephone line to a recording point.

The HF Doppler measurement is useful to detect perturbations of the ionosphere in the period range of a few minutes to 2 hours. The infrasonic wave detector can detect atmospheric pressure changes in the 10 to 1000 s range. Using these methods, ionospheric disturbances in the period range of several minutes to a couple of hours are detected. Thus, vertical and horizontal motion, wide period range of the atmospheric waves and drifts will be determined when our all observing stations work.

3. Results and Discussion

Figure 4 shows some typical HF Doppler shift traces of 10 MHz WWV (Ft. Collins, Colorado) and WWVH (Hawaii), measured at Fairbanks, Alaska (65°N, 148°W). The beat frequency of several Hz is analyzed quickly with a high speed FFT analyzer at about 500 times play back speed. A dipole antenna was used for signal reception. The directional selection of WWV and WWVH is necessary, but cannot be done azimuthally due to the broad antenna pattern. The FFT analyzed data (such as Figs. 5, 9) suggest, however, it is actually possible to distinguish both signals by the difference of the Doppler shift signatures. South-north propagation of WWVH is usually more stable compared with the WWV signal which propagates from an almost east-west direction. During this test operation period, only one receiving station was used. To detect the horizontal ionospheric drifts, a multi-station system will be necessary.

The Doppler shift pattern in Fig. 5, observed at Fairbanks, shows a characteristic

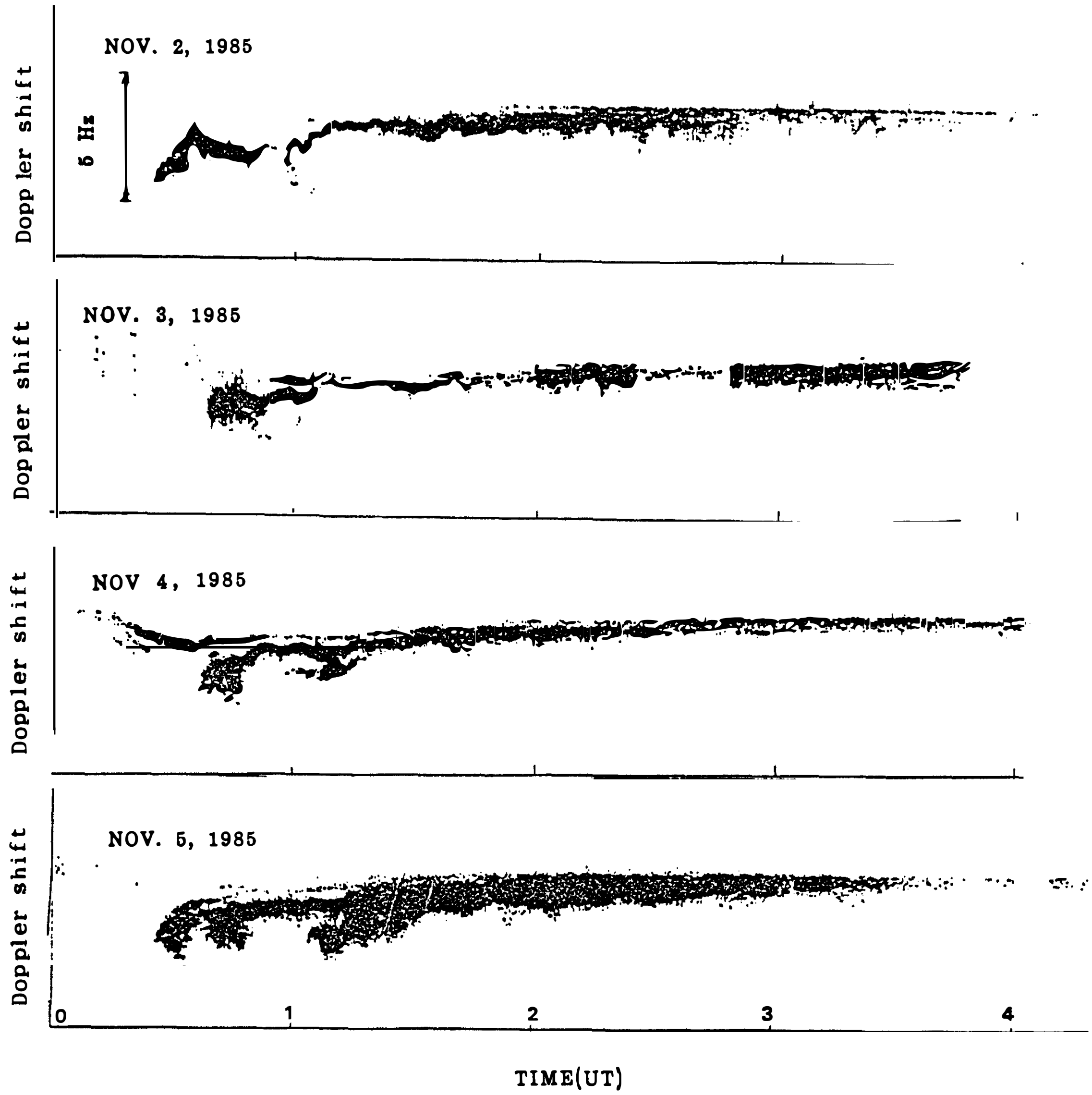

Fig. 4. *Example of WWV and WWVH HF Doppler shift patterns.*

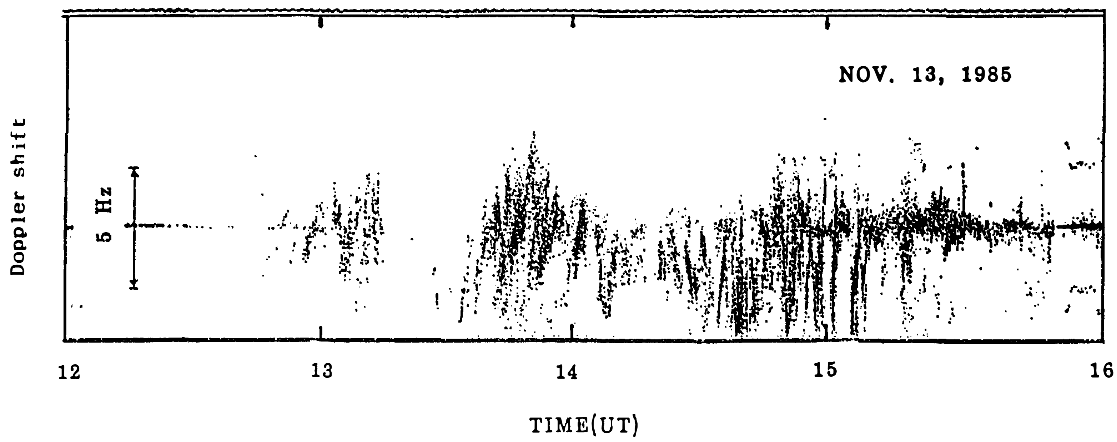

Fig. 5. *A typical sawtooth-like Doppler shift pattern having a wave period of a few minutes.*

of widely spreading Doppler shift. The sawtooth-like Deppler shift trains as shown in Fig. 5 might be caused by spatial ionospheric drifts. Here we assume that the radio wave is reflected from a horizontally moving and perfectly reflecting surface whose shape is sinusoidal (GEORGES, 1967). The Doppler shift is calculated from a model shown in Fig. 6a in which the shape of the surface is assumed as

$$Y=H+\frac{D}{2}(1-\cos 2\pi X/L) \tag{5}$$

where X is the horizontal position, Y is the height of an arbitrary point of the reflecting surface above the ground, H is the height of bottom of the reflector, $D/2$ and L are the amplitude and wavelength of the ripple of the reflector. The Doppler shift of the wave reflected back to the source is,

$$\begin{aligned} \mathrm{d}f &= -(2f/c)(\mathrm{d}p/\mathrm{d}t) \\ &= -(2f/c)v \sin\theta \end{aligned} \tag{6}$$

where p is the phase path, v is the horizontal velocity of the mirror surface, θ is the angle between the ray path and the vertical direction. The value θ changes periodically. Therefore it is possible to deduce the period of the moving ionosphere at the reflection point. According to the resultant of the Doppler shifts due to different shapes of moving sinusoidal reflector, the Doppler patterns show a sawtooth-like wave train (TSUTSUI, 1983) (Fig. 6b). The cause of such periodic patterns at 14–15 UT in Fig. 5 may be explained by ionospheric drift of the auroral form (KITAMURA *et al.*, 1982; TSUTSUI, 1983).

When it is assumed that the ionospheric reflection surface is wavy as shown in Fig. 6a and when the characteristic wavelength of the irregularity in the ionosphere is constant (periodic wavelength, L), and moving with a velocity, v, the periodic sawtooth-like Doppler shift pattern (the period, T) occurs. When $L=1$ km, and $T=2$ min (the case in Fig. 5), the ionospheric horizontal drift velocity along the propagation path, v, is $\sim$10 m/s (1000 m/2 min). This velocity is consistent with the ionospheric drift due to the electric field (TSUTSUI *et al.*, 1988). When a ground based multi-point observation is made, wavelength L can also be deduced from the difference in phases of the Doppler shifts. The tilting direction of line traces in the sawtooth structure is changed by the drift direction to the radio propagation path as shown in Fig. 6b. When the ionospheric drift direction is (A) in Fig. 6a, the tilting direction becomes (a) in Fig. 6a.

As shown in Fig. 7, the Doppler shift trace obtained at high latitudes often shows a widely spreading pattern (range of over 5 Hz) which does not appear at lower latitude stations (range $<$1 Hz). In Fig. 7, there is another signal which is not diffuse. The stable frequency trace is WWVH and the disturbed frequency trace is WWV according to our aural monitoring of both signals. Internal and external noises are small enough compared with these signals. The result in Fig. 7 suggests that the reflection region which causes such diffusive Doppler shift is local depending on an existence of irregularity region along the path.

Let us examine the auroral effects on the signal path. Figure 8 shows the ap-

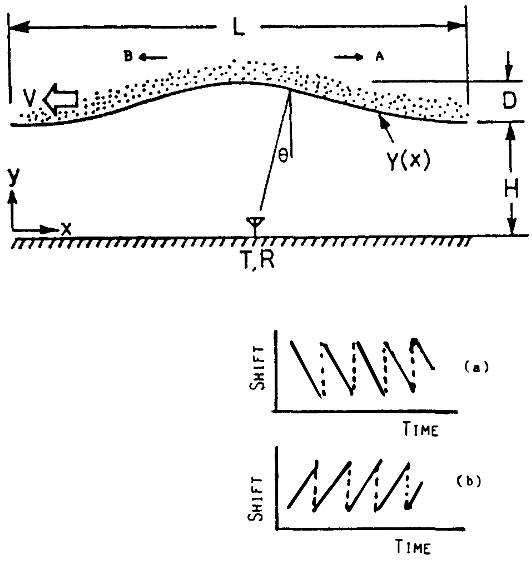

Fig. 6a. A model surface which is a mirror-like reflector with the shape of a sinusoid whose wavelength is L, and is moving horizontally to explain the sawtooth-like Doppler shift pattern (from GEORGES, 1967).

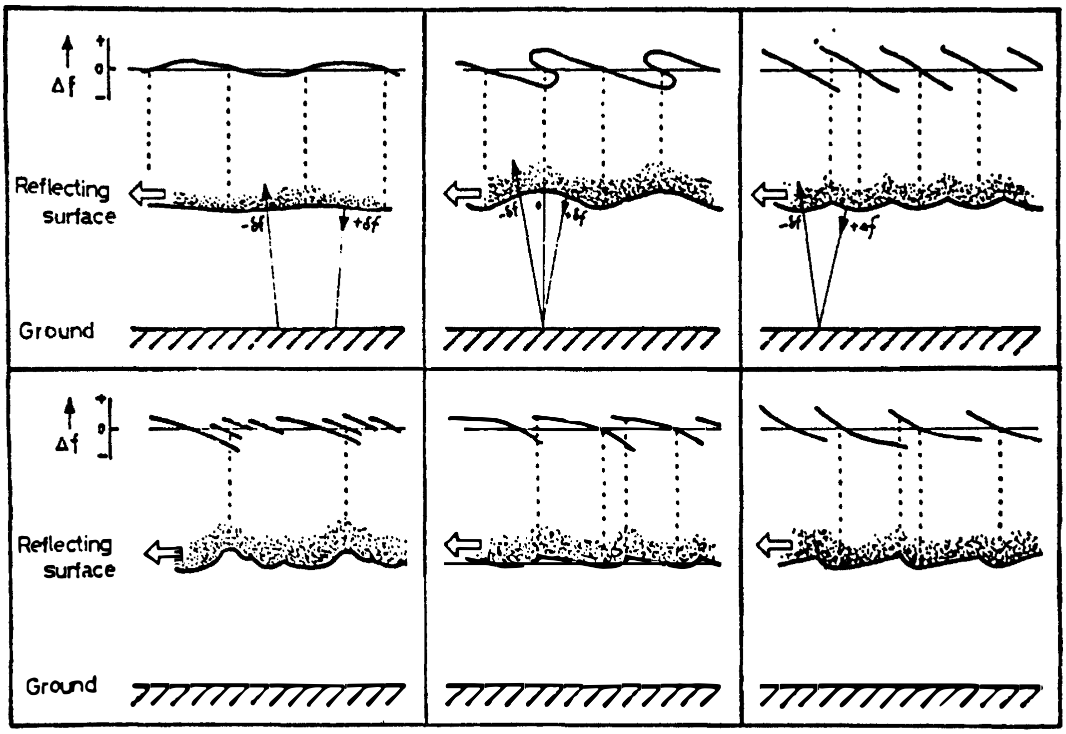

Fig. 6b. Resultant Doppler shifts due to different shapes of moving reflectors (from TSUTSUI, 1983).

proximate position of the auroral oval for $K_p = 5$ at the time of the data in Fig. 7 (ARGO and HUNSUCKER, 1988). The reflection point (MP) for a 1-hop path is 1000 km equatorward of the auroral oval, but even it was a 2-hop mode, the poleward reflection points (circle) would still be about 500 km south of the oval. The reflection

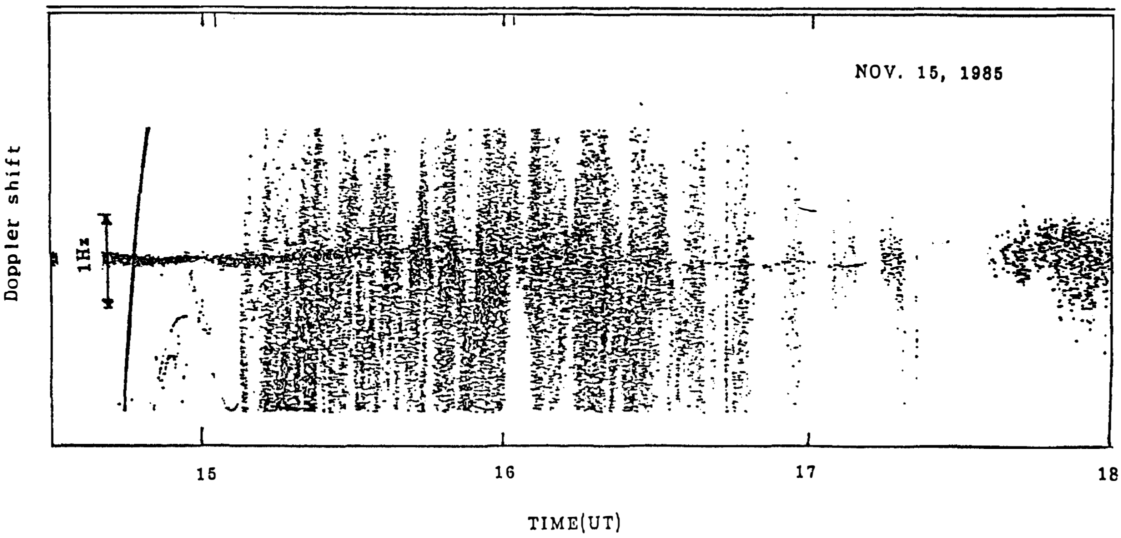

Fig. 7. An example of widely spreading Doppler shift. Note that there exists another non-disturbed signal at the same time.

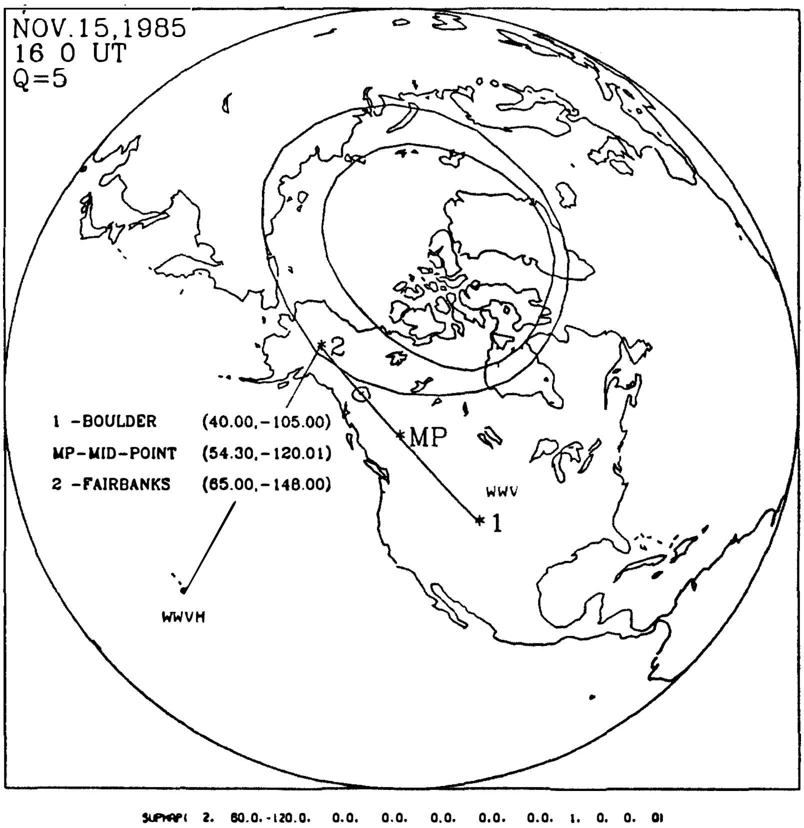

Fig. 8. Approximate position of the auroral oval at the time of the data in Fig. 7.

points on the WWVH paths are even further equatorward of the oval. It can be concluded that the WWV signal is modulated during the passage as shown in Fig. 8 by an ionospheric perturbation probably generated at the oval.

Figure 9 shows a typical sinusoidal-like Doppler shift pattern superimposed on the

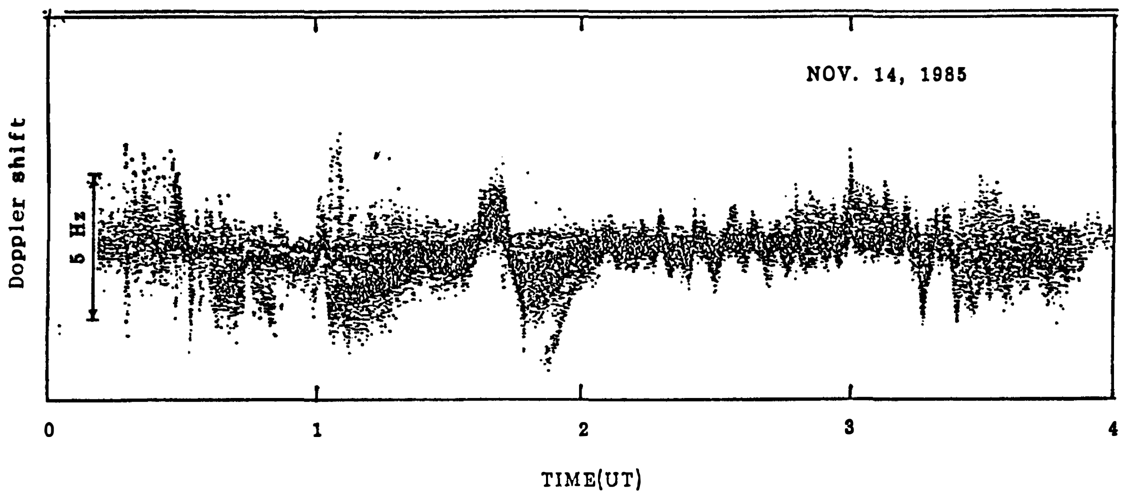

Fig. 9. A typical short period oscillations of HF Doppler shift.

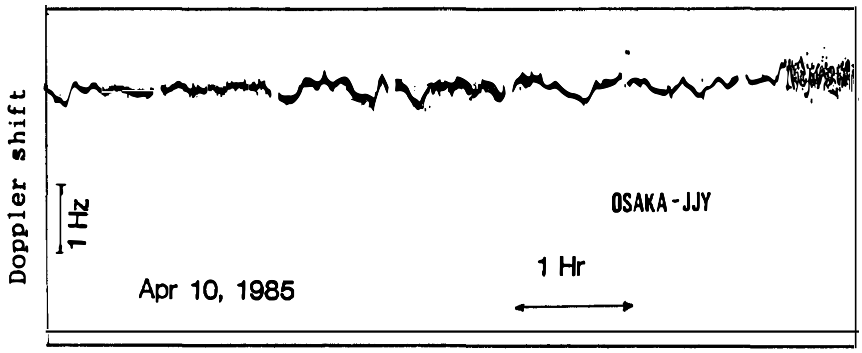

Fig. 10. A typical HF Doppler shift pattern obtained at mid-latitude ionosphere. Osaka (35°N, 135°E)-JJY (Ibaraki, Japan).

diffusive signal which is nearly the same as those observed in lower latitude stations as shown in Fig. 10. An example of a Doppler pattern is shown from a mid-latitude station (Osaka 35°N, 135°E) using JJY station (Ibaraki, Japan) 8 MHz for a comparison (Fig. 10). In Fig. 9, there exist characteristic periods of 1 to 15 min on the Doppler shift trace. According to multi-station observations of the HF Doppler shift at lower latitudes (HUNSUCKER, 1982), it is pointed out that the wavy shift pattern obtained at lower latitude stations (period, $1 \sim 10$ min) is caused by the medium scale (wavelength of about 10–100 km) atmospheric waves (TSUTSUI and OGAWA, 1973). In polar regions, it would also be desired to carry out multi-station HF Doppler measurements to investigate the relationship of the short period atmospheric waves (1–10 min).

Furthermore, a long-period component (about 1 hour) of Doppler shift in Fig. 9 indicates the origin of large scale atmospheric waves, with wavelength about 1000 km, or so-called, large scale traveling ionospheric disturbances (LS/TID), propagating from polar regions to low latitudes (MAEDA and HANDA, 1980; HAJKOWICZ and HUNSUCKER, 1987).

4. Coordinated Study with a Ground Based Infrasonic Wave Observation

The infrasonic wave detector using a capacitance microphone (WILSON, 1967; WILSON *et al.*, 1976) is located on the campus of the University of Alaska, Fairbanks. In winter, the sensor and the line filter (about 100 m long) with about 50 holes are covered with up to 1 meter of snow. The signal of the acoustic wave has a longer wavelength than 100 m. Wavelengths of local wind noise are short enough to have their power canceled by a spatial integration of their signals. The snow is also effective in keeping the detector temperature constant and equalizing the regions in front of the individual holes in order to reduce wind noise.

Sometimes as shown in Fig. 11 very rapid atmospheric pressure waves (about 1 min) are recorded. These are probably caused by the strong winds over a mountain (Mountain associated atmospheric wave) (TSUTSUI and OGAWA, 1973) (especially

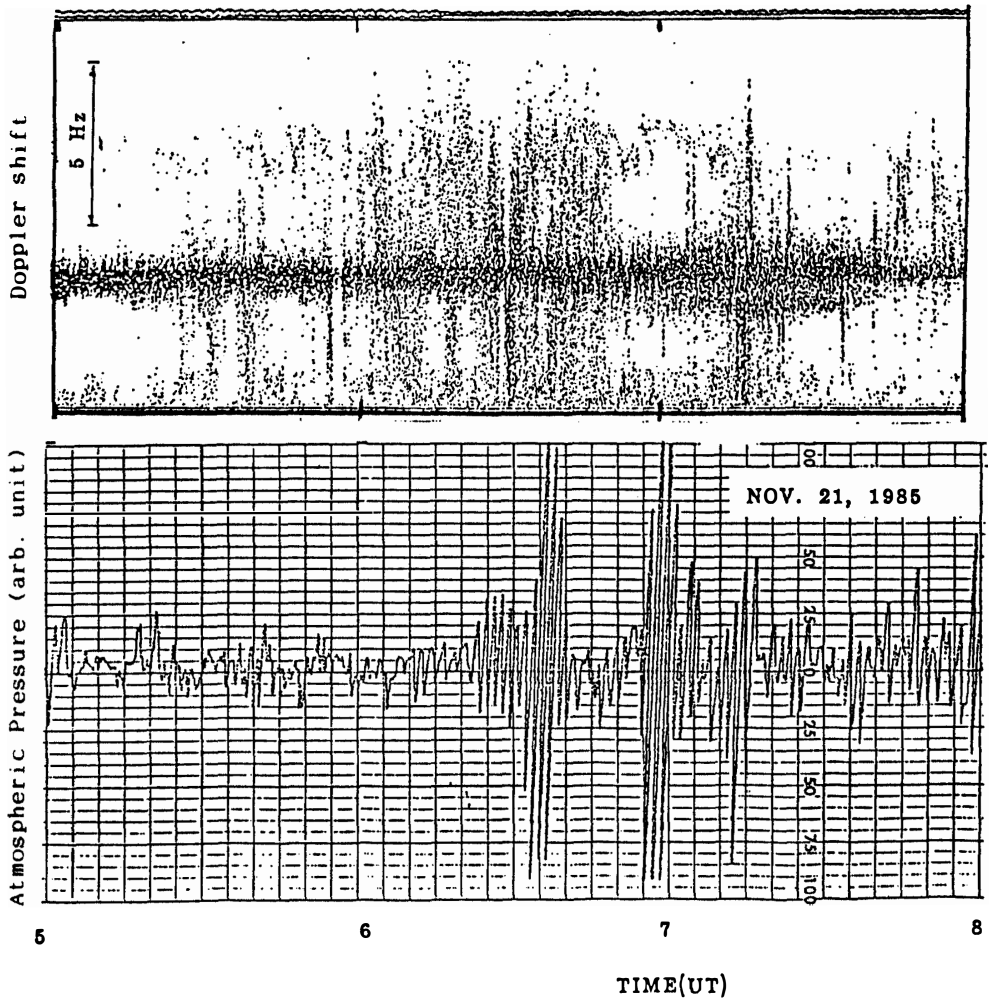

Fig. 11. Lower panel shows oscillations at 06–07 UT, on the infrasonic wave recorder which might be originally caused by strong winds passing over a mountain. Upper panel shows short period oscillations of Doppler shift at the same time. During the period 06–07 UT, both oscillation patterns seem to be correlated.

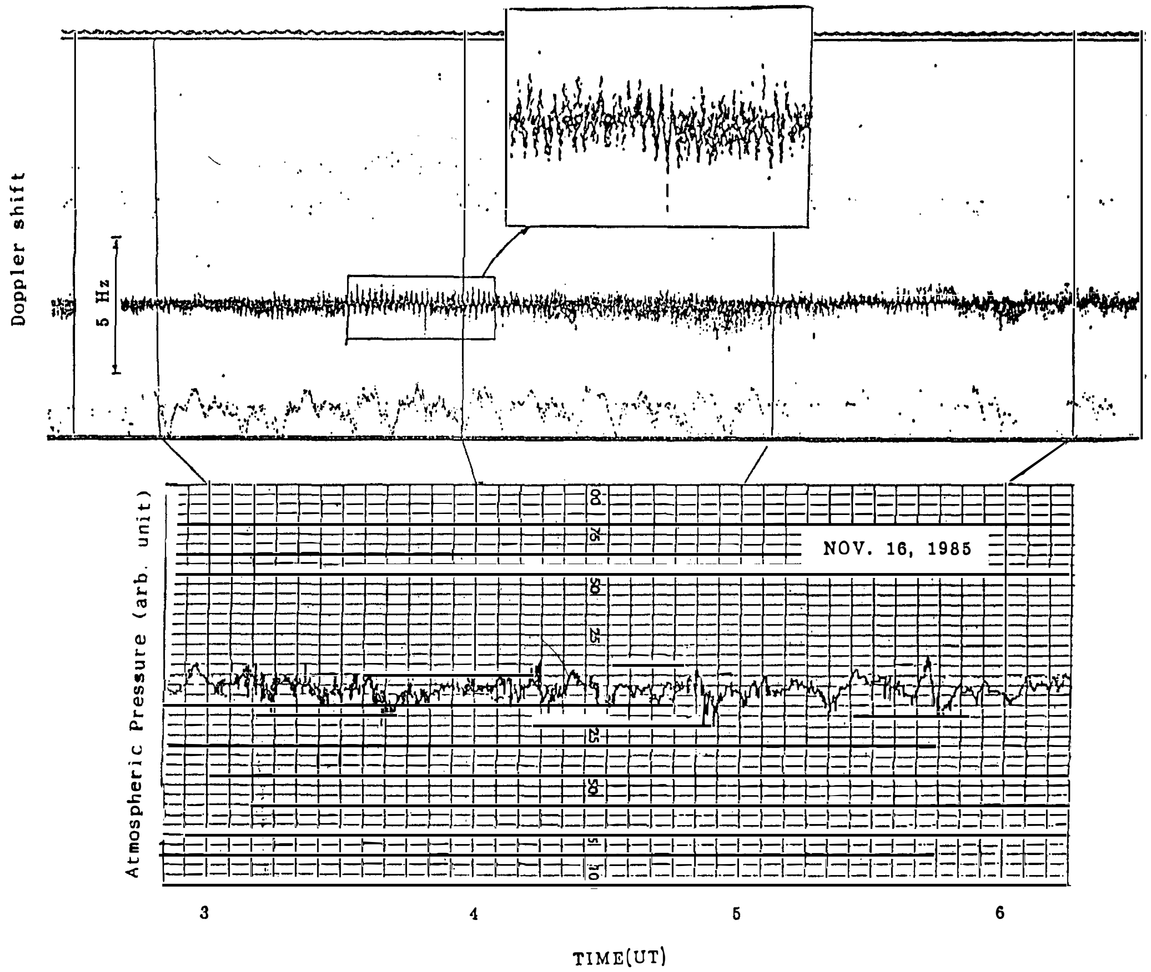

Fig. 12. Upper panel shows an HF Doppler oscillation with period of about 1 min. Lower panel shows the infrasonic waves at the same time. These data seem to correlate with each other.

0630–0730 UT). The atmospheric waves on the ground are not random and the period is exactly 1.5 min which is almost the same as that on the HF Doppler trace. It is not easy to deduce the propagation time delay by the use of these periodic waves.

Figure 12 also shows an atmospheric wave perturbation of about 1 min observed by the HF Doppler system in the ionospheric F region for 3 hours. The lower panel shows the atmospheric wave on the ground, observed by the infrasonic wave detector at the same time. Both signals contain same periodic perturbations. The ionospheric oscillations of about 3 min in the low latitude region may have been caused by a low pressure area or typhoon *etc*. (GEORGES, 1968; SMITH and HUNG, 1975). However the actual identification of ground and ionospheric signals has not yet been done. Figures 11 and 12 may be evident results showing the couplings of the atmospheric waves of short period of about 3 min.

For the longer wave period (about several hours), BOWMAN and SHRESTHA (1966) suggested a possible coupling of ionospheric perturbations with same periodic atmospheric fluctuations on the ground. KHAN (1970) suggested the time variation of the 3 min component in sporadic E structures, evidently couples with pressure oscillation

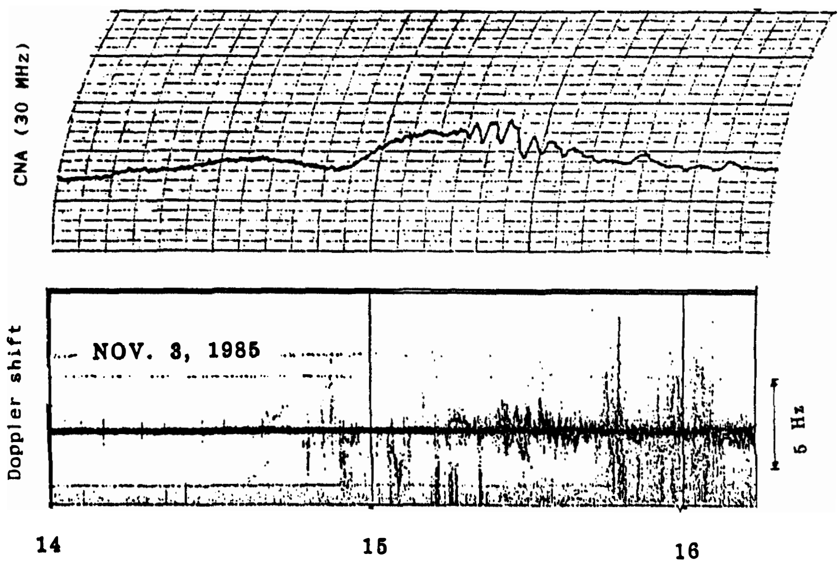

Fig. 13. Upper panel shows PC3 oscillations of cosmic radio noise absorption (CNA) data. Lower panel shows the HF Doppler shift data at the same time.

at ground level.

Such ground based observations of pressure variations are important to investigate whether the energy of ionospheric perturbations could couple and propagate to the ground and vice versa. As a special case, supersonic equatorward movement of aurora driven by the auroral electrojet current is reported as a source of auroral infrasonic wave (AIW's) (Georges, 1973; Wilson *et al.*, 1976). We are interested in the phenomena how the periodic or impulsive perturbation of atmospheric waves in the ionosphere could propagate to the ground through the middle-atmospheric region. Any evident propagation of AIWs from the ionosphere to the ground has not yet been observed directly.

The HF Doppler shift also measures the movement of plasma irregularities. CNA (Cosmic Noise Absorption) data are related to the plasma density variation in the D layer. The upper panel in Fig. 13 shows a PC3 type variation of CNA observed around 1520 UT, while the lower panel shows the disturbance of the Doppler shift at the same time. The time delay of these perturbations is, however, very small. It suggests that these perturbations were not caused by an atmospheric energy propagation, but were related to direct particle precipitations. A monitoring of propagation of energy excited by the PC3 pulsation at D layer to E or F layer is also interesting. D layer is the most sensitive region for the atmospheric perturbation, because the kinetic energy of waves interacts with electrons most effectively and the electron content is controlled by optical and chemical reactions whose time constants are faster than the period of the atmospheric waves at D layer. The CNA data is also useful as well as VLF propagation measurement to know the perturbation of D layer. Coordinated study of such D layer data, HF Doppler data for E, F layer, and infrasonic waves on the ground would be very effective to investigate vertical propagation of atmospheric waves.

5. Conclusion

Coordinated observations have just started using an HF Doppler system and an infrasonic wave detector to study dynamic behavior of the high latitude atmosphere and ionosphere. Although multi-point observations have not yet been done, several interesting results were obtained.

The Doppler shifted signal is often spread, probably when the propagation path crosses the auroral ionosphere which contains small scale irregularities. The disturbed region is, however, rather local because sometimes the WWV and WWVH signals do not show such phenomena at the same time. The periodic Doppler shift pattern (a so-called line structure or sawtooth-like structure) often appeared. The possibility of deducing such as the ionospheric drift velocity from the wave period and wavelength, would be obtained from an array of spatially distributed stations is described.

Medium and long period ionospheric wavy structure were detected by the Doppler system. Short period of a few minutes were also observed on both the HF Doppler signal and the infrasonic wave data. They seem to correlate well with each other. CNA data is found to correlate with the HF Doppler data during times when PC3 pulsations occur. The usefulness of CNA data for the D region perturbation is presented.

In future experiments, multi-station measurements to determine the direction of waves will provide much more information. In order to obtain more precise data for the HF Doppler measurements, a separation of a transmission station of 100–200 km from the receiving stations seems to be effective. The propagation of HF radio waves through the high latitude ionosphere is rather unique, and the Doppler traces will describe some of the dynamics of the ionosphere more dynamically and precisely when we can operate more receiving stations. It is concluded that our Doppler system is portable and useful enough to be employed at different locations for continuous monitoring of the dynamical structure of the ionosphere and atmosphere in the polar regions.

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