

NONLINEAR WAVE-WAVE INTERACTIONS IN THE SUBAURORAL IONOSPHERE  
ON THE BASIS OF ISIS-2 SATELLITE OBSERVATIONS OF SIPLE STATION VLF SIGNALS

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**Abstract.** Nonlinear wave-wave interaction between signals from a ground-based VLF transmitter and narrow-band ELF emissions in the subauroral ionosphere is studied by means of the bispectrum and bicoherence analysis. A bicoherence analysis has indicated that the sideband structures around the Siple transmitter signal received onboard the ISIS satellite are due to the nonlinear interaction between the Siple VLF signal and the pre-existing ELF emission.

Introduction

Many types of plasma waves can be found in the ionospheric and magnetospheric plasma, and their generation mechanism can generally be classified into two categories. The first generation mechanism is due to the wave-particle interactions (e.g., cyclotron resonance instability). A large number of magnetospheric VLF/ELF emissions are considered to be due to this wave-particle interaction, and extensive theoretical and experimental studies have been carried out (e.g., see the recent reviews by Sazhin and Hayakawa [1982] and Hayakawa and Sazhin [1992]). The second category is due to nonlinear wave-wave interactions, but these seem to be less understood. Theoretical wave-wave interaction mechanisms have been suggested to explain different kinds of magnetospheric wave phenomena [Roux and Pellat, 1979; Grabbe et al., 1987; Riggan and Kelley, 1992; Koons et al., 1987; Altman et al., 1987], but they are extensively proposed for the auroral kilometric radiation [Roux and Pellat, 1979; Grabbe et al., 1987; Altman et al., 1987]. However, there have been very few reports on the experimental confirmation of nonlinear wave-wave interaction in the magnetospheric and ionospheric plasma. Tanaka et al. [1987] were the first that found, on the basis of the bicoherence analysis, that the sideband structure around the VLF transmitter signals they observed was produced by the nonlinear interaction between the VLF transmitter signal and an ELF emission. Later, some extensive analyses have been performed by Lagoutte et al. [1989] and Sotnikov et al. [1991], but they used the same Auroral 3 data as Tanaka et al. [1987]. Hence further experimental investigation is required for elaborating the nonlinear wave-wave interaction.

ISIS Satellite Reception of Siple VLF Transmitter Signals and Observational Results

Monochromatic signals injected from ground-based VLF transmitters are often found to exhibit spectral broadening when observing on satellites traversing the ionosphere [Bell et al., 1983; Titova et al., 1984; Inan and Bell, 1985; Tanaka et al., 1987] and inner magnetosphere [Bell and Ngo, 1988]. Tanaka et al. [1987] have found, on the basis of a bicoherence analysis of Arcard-3 satellite observations of the Alpha transmitter VLF signal, that the spectral broadening in their case is not a nonlinear interaction between the VLF signal and an ELF emission as Titova et al. [1987] suggested, but is

a linear phenomenon such as the Doppler broadening of the signals scattered by the ionospheric irregularities. Tanaka et al. [1987] have discovered the sideband around the VLF signal, and their bicoherence analysis has confirmed the nonlinear coupling between the VLF signal and a natural ELF emission. In order to make further experimental investigation of nonlinear wave-wave interactions, we carried out a collaborative study concerning ISIS satellite receptions of Siple station VLF signals in the subauroral ionosphere. The campaign was made for two months in December 1987 and January 1988. Because the battery condition of the satellite was extremely bad, satellite observations were made only for a limited time period near Siple station and the telecommand was made from Terre Adelie station. The ISIS-2 satellite traverses the ionosphere at the height of about 1400 km for all the orbits and it carries only one electric field antenna. VLF signals are transmitted from the ground by a horizontal dipole with a full length of 42km.

Figure 1 illustrates nine orbits available during the campaign (indicated by broken lines), and the thin lines indicate the observing period. Among the nine orbits there were observed no VLF Siple signals on two orbits. On the remaining seven orbits VLF signals were detected aboard the satellite, and also four of these orbits included the sideband structures similar to those observed by Tanaka et al. [1987]. The parts of the orbits with sideband structures are indicated in Figure 1 by thick lines. The L.T.'s for all the orbits are in a range from L.T. = 16h to 20h, and it is generally found that the region of observation of sideband structures of VLF signals are relatively close to Siple station, suggesting a relatively high intensity of VLF transmitter signals in the ionosphere.

Figure 2 indicates an example of the sideband structure of the Siple signal observed on the ISIS-2 satellite on 6 January 1988. Figure 2 illustrates the spectrogram, in which Siple station transmitted signals with duration of one second

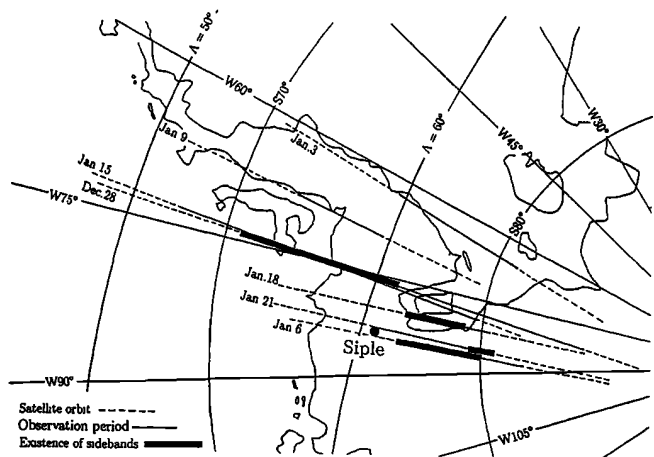


Fig. 1 Trajectories of the ISIS-2 satellite are shown in broken lines, and the solid lines indicate trajectories on which the satellite received VLF signals (~2.4 and ~7.2kHz) transmitted from Siple station (76° S, 84° N), designated by a large black dot. The thick part of the trajectories represents the region of the occurrence of predominant sideband structure. Invariant latitudes of  $\Lambda=50^\circ$  and  $60^\circ$  are also indicated.

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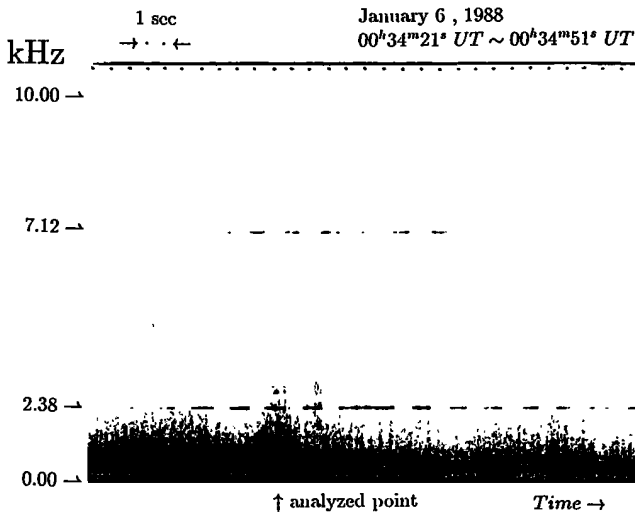


Fig. 2 Spectrogram of the wideband electric field component on ISIS-2 on January 6, 1988, and we can identify the Siple transmitter pulses and sideband structure around the carriers.

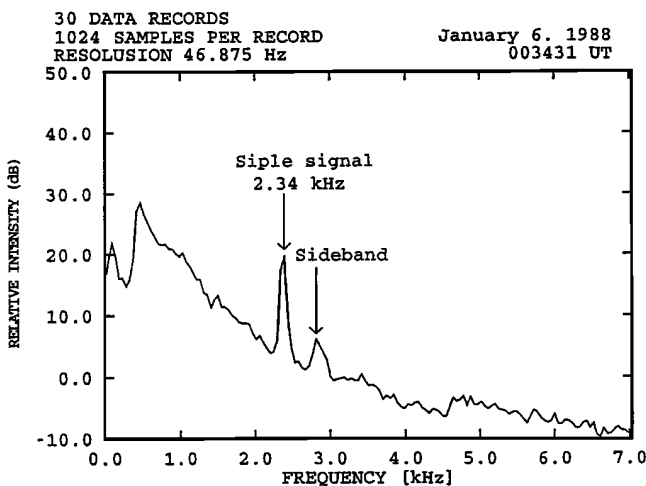


Fig. 3 Frequency spectrum of electric field intensity (in relative units) of the wideband signal for the analyzed point in Fig. 2. We find an ELF emission and an upper sideband structure.

alternatively at the two frequencies (2.36~2.44kHz and 7.10~7.29kHz). At the time near 00h34m31s UT (see an arrow on time axis), we are able to find a sideband structure around the frequency of 2.38kHz, but such sideband structures are not so often detected at the higher transmitter frequency. The corresponding power spectrum at this time is given in Figure 3 with the frequency resolution of 46.875Hz, and the sideband in the upper side of the transmitter frequency is clearly demonstrated. During this observation the information on electron density is not available, but the electron gyrofrequency is estimated by using the model. The proton gyrofrequency at this time is 437.56Hz. The offset frequency is about 470Hz, and in the lower frequency range there is observed a natural ELF emission which is of relatively narrow

band. The spectral broadening as observed by Bell et al. [1983], Titova et al. [1984] and Tanaka et al. [1987] is not found in our observation data.

The analysis of bicoherence, which is the normalized bispectrum (see the details of the bicoherence and bispectrum in Tanaka et al. [1987] and Lagoutte et al. [1989]), is applied to a time interval of 625msec near 00h34m31s UT, and the corresponding results are illustrated in Figures 4(a) and 4(b) with a higher frequency resolution of 18.75Hz. Figure 4(a) refers to the bicoherence result among the frequencies,  $f_k$ ,  $f_l$ , and  $f_k + f_l$ , while Figure 4(b) refers to that among  $f_k$ ,  $f_l$ , and  $f_k - f_l$ . It is apparent that we notice a very significant peak in the bicoherence in Figure 4(a); that is,  $b^2(f_k, f_l) = 0.84$  with  $f_l = 2.38\text{kHz}$  and  $f_k = 0.45\text{kHz}$ . This implies that the upper sideband in Figures 2 and 3 is apparently produced by nonlinear coupling between the Siple VLF transmitter signal ( $f_l = 2.38\text{kHz}$ ) and a natural ELF emission ( $f_k = 0.45\text{kHz}$ ). Whereas, Figure 4(b) exhibits no conspicuous peaks. It seems to us that there may be a small peak of  $b^2(f_k, f_l) = 0.37$  with  $f_k = 0.43\text{kHz}$  and  $f_l = 2.38\text{kHz}$ , but it may not be so significant. This ELF emission is of narrow band, just like an artificial interference, but the detailed analysis of its lower cutoff frequency indicates that it varies very closely in association with the proton gyrofrequency estimated by the model magnetic field. This kind of characteristic is very peculiar to the natural ELF emission as was found by Hayakawa et al. [1990], so that this ELF emission is reasonably considered as being natural.

We have demonstrated only one example on 6 January 1988 in the present report, but we have examined many time intervals on the four orbits with the sideband structures. Hence, the following facts have emerged from the present study.

1. The spectral broadening of Siple VLF transmitter signals (~2.4kHz and ~7.2kHz) due to scattering from small scale density irregularities was not observed in our campaign.
2. Sideband structures of Siple VLF transmitter signals are observed on four orbits, and the regions where we observed such sidebands aboard the ISIS-2 satellite, are found to be relatively close to the Siple station.
3. Sideband structures are mainly detected around the lower transmitter frequency of ~2.4kHz, but rather infrequent at the higher transmitter frequency of ~7.2kHz. Table 1 summarizes the center frequency of ELF emissions, the offset frequencies of the upper and lower sidebands and the corresponding bicoherence values ( $b^2$ ) for several other selected events (only at the lower frequency), and this implies that the offset frequencies of the upper and lower sidebands are identical to the center frequencies of ELF emissions.
4. Such high bicoherence values as in Figure 4(a) and Table 1 imply that the sideband structures (upper and lower) are mostly likely produced by the nonlinear interaction between the Siple VLF transmitter signal and a natural narrow-band ELF emission.

Since the paper by Tanaka et al. [1987], some others [Lagoutte et al., 1989; Sotnikov et al., 1991] have worked on the experimental investigation of the nonlinear wave-wave interaction based on the same data as Tanaka et al. [1987]. This present paper has provided much more data based on the ISIS satellite reception of Siple VLF signals.

Frequency matching in the nonlinear wave-wave interaction is confirmed, but we comment on the  $k$  matching. In the study of  $k$  matching we are obliged to carry out direction finding measurement [Hayakawa, 1991], but no such measurements are available on the ISIS-2 satellite because it carries only an electric antenna. We then attempted to use the spin modulation in the observed field intensity instead of the direction finding in order to obtain some information on the wave normal directions of the Siple VLF signal, sideband wave and ELF emission. The analysis has indicated that there seems to exist a small spin modulation in the intensity of Siple trans-

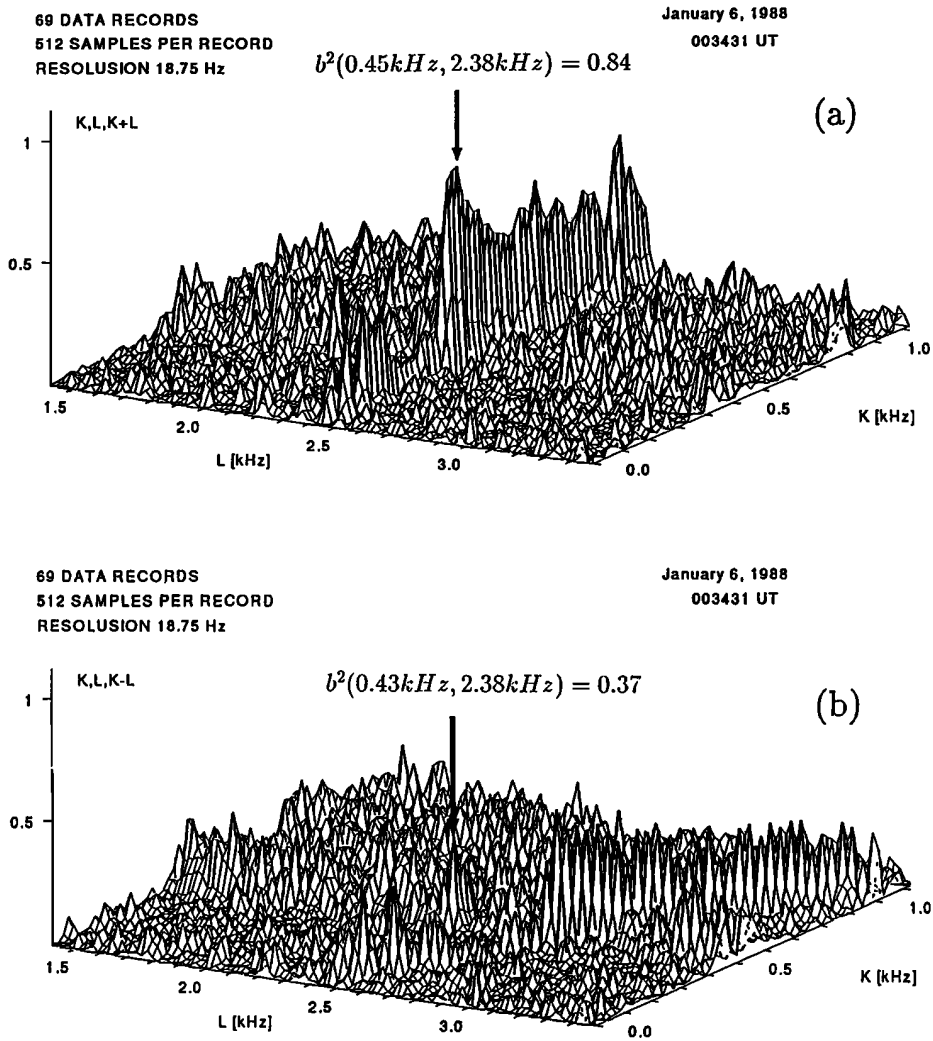


Fig.4 A typical result of the bicoherence computation for electric field data with a frequency resolution of 18.75Hz. (a)Bicoherence results to show the upper sideband component being caused by a nonlinear process between the transmitter

pulse ( $f_1=2.38\text{kHz}$ ) and ELF emission( $f_k=0.45\text{kHz}$ ) because of a significant bicoherence value of 0.84. (b)Bicoherence value for the transmitter pulse, ELF emission and the lower sideband component is 0.37.

Table 1 : Summary of characteristics of the center frequency of ELF emission  $f_k$ , the offset frequencies of the upper and lower sidebands and bicoherence values (The frequency resolution is 18.75 Hz)

Date	Time(UT) h,m,s	$f_k$ [Hz]	offset frequency [Hz]		bicoherence value $b^2(f_k, f_l)$	
			upper	lower	$f_k, f_l, f_k + f_l$	$f_k, f_l, f_k - f_l$
Dec. 28	00 : 39 : 01	431	431	431	0.89	0.83
Dec. 28	00 : 39 : 03	413	413	413	0.92	0.93
Dec. 28	00 : 39 : 05	413	413	413	0.94	0.89
Dec. 28	00 : 39 : 06	413	413	413	0.81	0.78
Jan. 6	00 : 34 : 31	450	450	none	0.84	—
Jan. 18	00 : 34 : 31	488	488	none	0.84	—
Jan. 21	23 : 14 : 08	431	431	431	0.89	0.42

mitter signal. A combined consideration of this with its no spectral broadening and the relative configuration of the whistler-mode electric field with the antenna, may imply that the wave normal of the VLF signal is reasonably considered to make very small angles with the Earth's magnetic field (small  $\theta$ ). This kind of spin modulation was already seen for quasi-longitudinal plasmaspheric ELF hiss [Ondoh et al., 1982]. Whereas, it seems to us that the observed electric field intensities for plasmaspheric ELF hiss and sideband wave, exhibit no spin modulation in intensity and frequency. The spin modulation might be useful only for the two extreme cases when the wave normal is either nearly parallel to the Earth's magnetic field [Ondoh et al., 1982] or it is very close to the oblique resonance angle ( $\theta_{res}$ ) [James and Bell, 1987] for which the wave electric field behaviour is simple. Whereas, for the intermediate (oblique, but not so very close to  $\theta_{res}$ ) wave normal angles, the whistler-mode wave has its electric field components both parallel and perpendicular to the  $\mathbf{k}$  vector, which makes the spin modulation very complicated such that the spin modulation seems to be much less pronounced. It is then difficult to infer the wave normal directions of the plasmaspheric ELF hiss and sideband wave by means of the present data. But, the previous direction finding result for plasmaspheric ELF hiss on the basis of Arcard-3 satellite, has yielded that the wave normal angles of ELF emissions are relatively large at the relevant latitude ranges [Hayakawa et al., 1990]. Hence, the  $\mathbf{k}$  matching requires again a large wave normal angle for the sideband structure, indicating an electrostatic nature, which is easily detected by the ISIS electric antenna.

#### Concluding Remarks

The nonlinear three wave process has been confirmed and elaborated by using extensive data from the ISIS satellite reception of Siple VLF signals.

We comment on our further elaboration of nonlinear wave-wave interactions. The  $\mathbf{k}$  matching should be verified by means of direction finding as mentioned before, and another subject is concerned with the amplitudes of the waves. Absolute intensities of the waves are important in the wave-wave interaction, as noted by Trakhtengerts and Hayakawa [1993], but absolute measurements are not available in the present study. However, when the sidebands are detected, it is found that at least either the VLF signal or ELF emission is strong enough. Trakhtengerts and Hayakawa [1993] have recently indicated that the spectral broadening and side band structure are the common physical process which is the whistler wave scattering by field-aligned irregularities, and the difference between the two is irregular or regular behaviour of inhomogeneities responsible for scattering. Further, they have presented the quantitative theory for wave-wave interaction coefficients, which are determined by the amplitudes of the VLF signal and ELF emission and also the phase of the latter. The experimental relative amplitudes of the VLF signal, natural ELF emission and the sideband wave will be used in the future quantitative investigation. They have also suggested the bicoherence as a diagnostic tool to study whether the phase of ELF wave is deterministic or random, which is also being examined.

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