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Matched filtering-parameter estimation method and analysis of whistlers recorded at Varanasi

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Abstract. The matched filtering technique is based on the digital-construction of theoretical whistlers and their comparison with observed whistlers. The parameters estimated from the theoretical and experimental whistler curves are matched to have higher accuracy using digital filters. This yields a resolution ten times better in the time domain. We have tested the applicability of this technique for the analysis of whistlers recorded at Varanasi. It is found that the whistlers have propagated along $L > 2$ and have wave normal angles after exiting from the ionosphere such that they propagate towards equator in the earth-ionosphere wave-guide. High-resolution analysis shows the presence of fine structures present in the dynamic spectrum. An effort is made to interpret the results.

Keywords. Matched filtering; fine structure; ducted mode propagation; banded whistlers.

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1. Introduction

The technique of whistler registration and analysis is being improved in order to understand the basic plasma processes and fine structures present in the medium. The accuracy and speed of analysis are enhanced by the application of digital method [1–4]. Digital methods involve construction of digital sonogram using moving frequency/time window in which precise determination of both frequency and time simultaneously is an inherent problem [4]. To over-come this difficulty matched filtering or correlation detection technique is developed in which the output of matched filter is proportional to the auto-correlation function of input signal. This technique has been applied in the analysis of whistlers recorded at ground stations as well as onboard rockets and satellites [5–7].

In the present paper we shall apply the matched filtering technique for the analysis of whistlers recorded at low latitude station Varanasi. As a result of enhanced resolution in time domain, it is shown that whistlers which appear as a single trace on a conventional spectrograms usually consist of many fine structure components with amplitudes differing in time and frequency. The fine structure components are useful in probing the duct structures and in understanding the ducted mode propagation of whistlers.

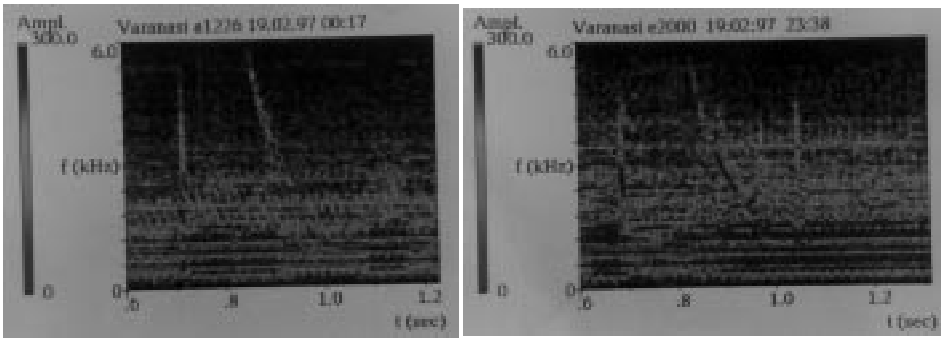

Figure 1. Dynamic spectra of whistlers recorded at Varanasi.

2. Whistler data and analysis

Whistlers are being recorded at Varanasi using T-type antenna, triangular loop antenna, pre/main amplifier and a cassette tape recorder. In the present analysis we have considered whistlers recorded by T-type antenna. The recorded data are stored in analog form on magnetic tapes. The selected data are digitized using sampling frequency of 12 kHz for digital analysis. An example of whistler spectrogram recorded at Varanasi is shown in figure 1, which shows a good quality whistler with strong background noise at the lower frequencies. The spectrogram is scaled visually and frequency time (f-t) pairs thus obtained are processed with the F/T method [8] to obtain the parameters of the whistlers and the medium.

In matched filtering technique a model theoretical whistler wave form is constructed using the whistler parameters such as source time t_0, zero frequency dispersion D_0 and nose frequency f_n which are derived from the scaled frequency-time pairs of the recorded whistler spectrogram [4,5,7]. For minimizing the error, the data obtained for the actual whistler and theoretically constructed whistler are subjected to least square curve fitting. To achieve refinements in the whistler and medium parameters, second and third filtering is also carried out.

The matched filtered frequency spectrum is shown in figure 2. It is clearly seen that the atmospheric and other noises have been eliminated. In the present analysis, the optimized filter bandwidth of 200 Hz was used. The digitized waveform, matched filter output, output envelope and smoothed output envelope are given in figure 3, which represent the main stages of the procedure. The above procedure helps in the determination of the initial time and the magnitude of all the local maximum of the smoothed envelope [4]. This procedure is repeated for every 5 Hz frequency step across the range of whistler frequency [7].

3. Results and discussions

The whistlers recorded at Varanasi usually have sharp dynamic spectra which clearly indicates that the ducts through which whistler waves have propagated are sharp and narrow in width. The banded nature of the whistler wave is visible in the dynamic spectrum,

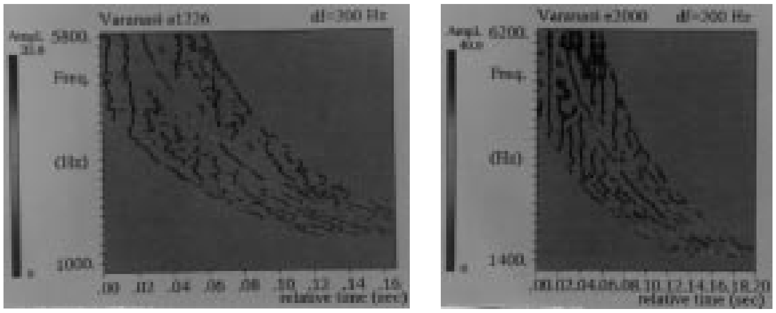

Figure 2. Dynamic spectra of whistlers shown in figure 1 after matched filtering analysis.

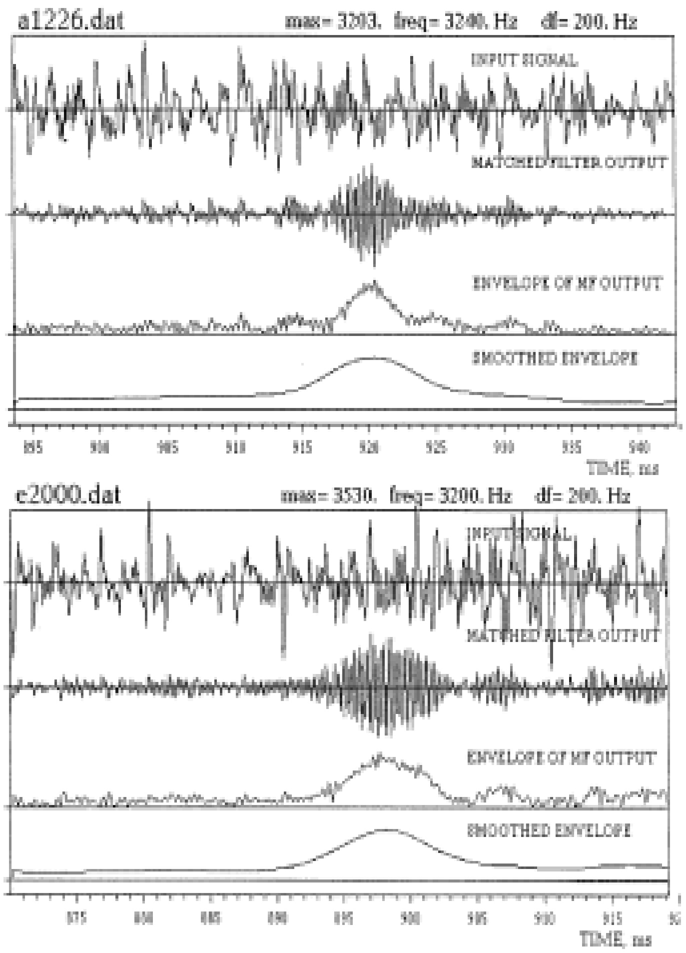

Figure 3. Digitized wave form, matched filter output, output envelope and smoothened output envelope corresponding to the dynamic spectra of whistlers shown in figure 1.

Table 1. Characteristic parameters of the whistlers and the plasma medium.

Date and time of whistler recording	19 Feb. 1997 at 0017 hrs IST	19 Feb. 1997 at 2338 hrs IST
Equatorial gyro-frequency (kHz)	103.5 $\pm$ 60	35.3 $\pm$ 3.1
Nose frequency f_n (kHz)	36.8 $\pm$ 2	13.1 $\pm$ 1.1
Dispersion D_0 $(s^{1/2})$	11.9 $\pm$ 0.3	13.5 $\pm$ 0.2
L-value $= (R/R_e)$	2.1 $\pm$ 0.4	2.9 $\pm$ 0.01
Equatorial electron density ($N_{\rm eq}$ (cm^{-3}))	247 $\pm$ 24.6	45 $\pm$ 5
Total electron content in the flux tube (electron cm^{-2} tube^{-1})	(1.4 $\pm$ 0.2) $\times$ 10^{12}	(1.2 $\pm$ 0.008) $\times$ 10^{12}

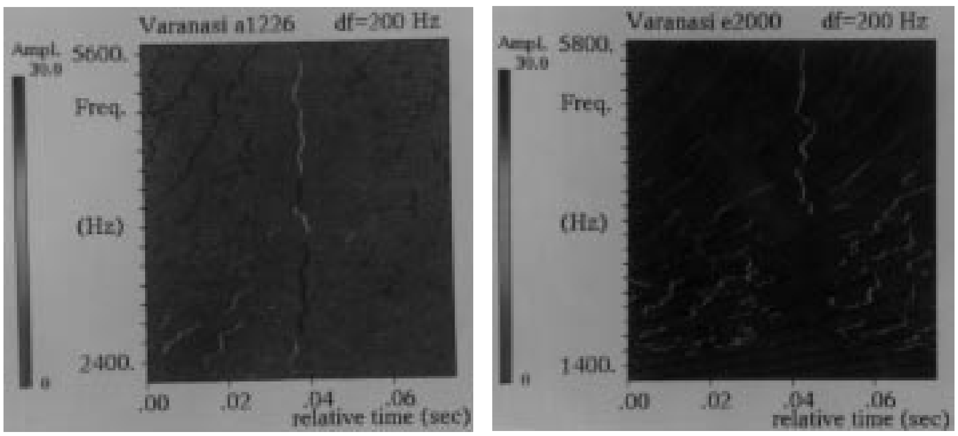

Figure 4. Isochrones of whistlers shown in figure 1.

which could be attributed either to the source or to the propagation effect. Two discharges separated by a very short duration of time or multiple discharges may explain the banded nature of the whistler wave. The interference of the wavelets propagating through the ducts in the magnetosphere or through the earth-ionosphere wave-guide may also produce banding structure in the spectrum. A proper explanation is still not available. The results of the analysis are given in table 1.

Where R_e is the radius of the earth and R is the distance from the center of the earth in the equatorial plane. From the table it is clear that these whistlers have followed the path for which $L > 2$. This clearly supports the propagation of whistlers in ducted mode through the magnetosphere along higher L-values and wave-guide mode propagation through the earth-ionosphere wave-guide after exiting the ionosphere [9]. The wave normal angle at the entrance of wave-guide is such that the waves propagate towards equator and are received at the low latitude station Varanasi.

The high resolution dynamic spectra using relative time obtained by subtracting the theoretical (fitted) travel time from the measured $t(f)$ data corresponding to whistlers shown in figure 1, are presented in figure 4. In this plot a model whistler appears as a straight line and sferics appeared as hyperbola as is shown in figure 4 [6–7]. The travel time residuals as a function of frequency is shown in figure 5. It should be noted that the residuals lie within 2.3 ms. The small values of residuals clearly support the idea that whistler wave has propagated through narrow ducts which is inferred from the sharpness of the dynamic spectrum. The residuals may have resulted due to (i) the omission of $a + 1$ term and ionic term in the refractive index expression (the refractive index at whistler wave frequency $> 10^3$. The contribution by the ion term $< 10^2$) and (ii) consideration of strictly

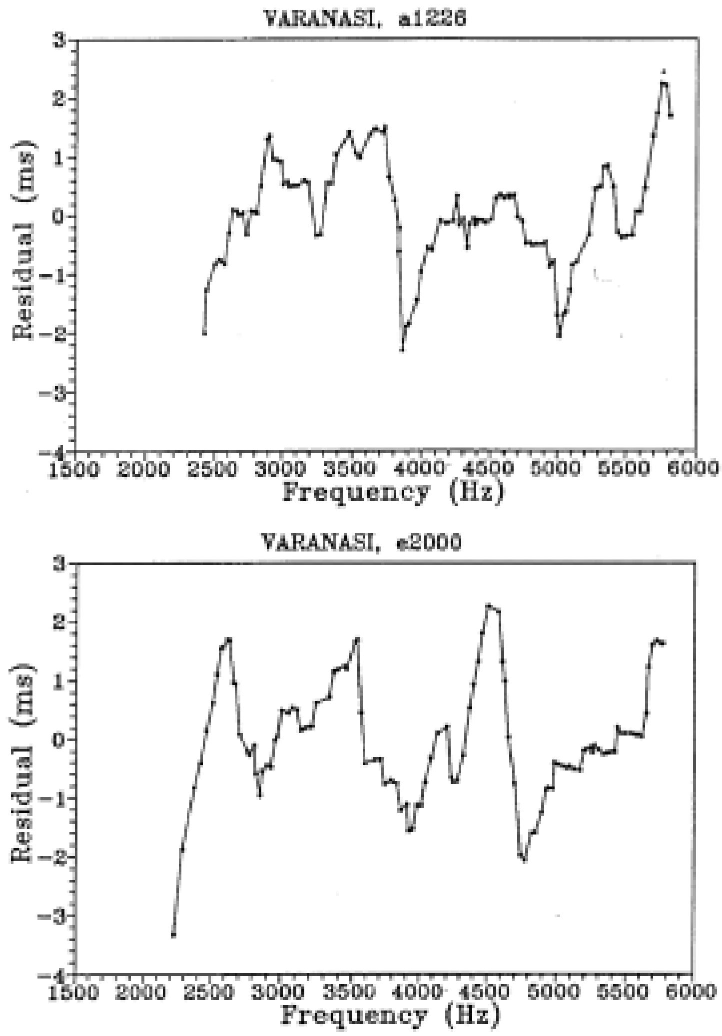

Figure 5. Travel time residuals for whistlers shown in figure 1.

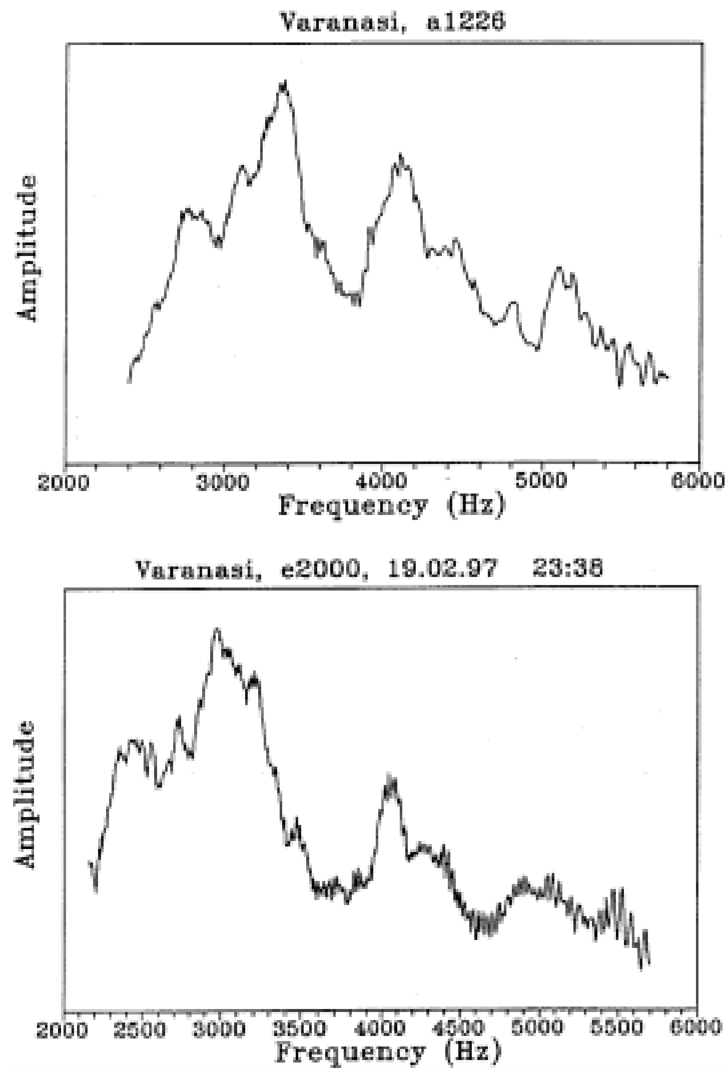

Figure 6. Amplitude variation with frequency for the whistlers shown in figure 1.

field aligned propagation instead of the actual snake like ray path. The amplitude variation with frequency is shown in figure 6. The amplitude maximum at different frequencies clearly correlate with the amplitudes represented by the intensities in the dynamic spectra. The amplitude variation with frequency is complex and may be due to frequency dependent absorption, amplification due to wave-particle interactions, focusing/ducting along the path of propagation etc.

4. Conclusions

The whistlers recorded at low latitude station Varanasi are analyzed using high-resolution digital matched filtering and parameter estimation technique. It is shown that whistlers have propagated in the earth-ionosphere wave-guide after exiting from the ionosphere towards the equator. The duct supporting the whistler waves must be narrow and sharp. The banded structure in the dynamic spectra of low latitude whistlers is also observed.

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