Audible Frequency Analysis of Ground Flashes

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***Abstract*—Thunder signatures have been categorized into three types using recorded peak pressure. The variation in fundamental frequency initiated by ground flashes has been studied by using an acoustic spectrum of thunder. S-transformation has used to estimate the dominant frequency variation around the peak pressure. The mean fundamental frequencies of type 3 ground and cloud flashes are 160 Hz and 98 Hz respectively. The mean frequencies of type 2 ground and cloud flashes are 108 Hz and 82 Hz respectively. The mean fundamental frequencies of type 1 ground and cloud flashes are 88 Hz and 123 Hz respectively.**

Keywords—spectrogram, thunder, ground flash, cloud flash

I. Introduction

The electric field measurements and optical methods including video and still photography are more reliable and convenient when classifying lightning flash types. The other available feature of a lightning discharge is thunder, but less attention has been paid to explore its ability to distinguish flash types. The primary objective of this study is to find any significant variation of audible features of lightning initiated by ground flashes.

Thunder signatures initiated by ground flashes can be analyzed in different ways to study their characteristics. The relative amplitude method has been introduced to describe the subjective thunder features such as clap, peal, role, and rumble. The relative amplitude of the pulses of claps per flash has been observed with the variation of 1 to 5 in cloud flashes and of 1 to 3 in ground flashes [1]. The fundamental frequency variation of subjective thunder features have been observed and introduced a range for each characteristic sound, irrespective to the type of flash [2]. By considering the reciprocal of root distance and the magnitude of the observed pressure change, it is inferred that the thunder pressure waves are likely to be cylindrical. The estimated magnitude of the pressure change in the lightning channel has been compared with the measurements of pressure pulses from triggered lightning strokes. The comparison has suggested that the initiation of an acoustic wave is based on the cylindrical expansion of air around the lightning discharge [3]. Mainly, three types of pressure pulses have been introduced with the aid of sound intensity changes concerning the distance of flash origination: close flashes with a loud burst of sound, distant flashes that start with rumbling and develop into loud bursts, and very distant flashes with feeble rumbling [4].

In this study, recorded thunder signals are categorized into three types, regarding their peak pressure variation: pulses with peak pressure variation less than 1.5 Pa (type 1 in Fig. 1), peak pressure variation between 1.5 Pa and 3 Pa (type 2 in Fig. 2) and peak pressure variation greater than 3 Pa (type 3 in Fig. 3). The fundamental frequency of the maximum pressure variation has been estimated to study the features of a cloud to ground flashes in the frequency domain. The peak pressure of each ground flash was isolated from the main profile to quantify the thunder signals further, and the average sound level of the pulse was estimated. The time average of intensity level change lends an average intensity level of the captured part of thunder signature. This allows representing the fundamental frequency of the flash with time average sound level instead of the peak pressure of the sound.

II. Theory

A. Thunder generated by ground flashes

The initial electrical breakdown associated with ground flashes takes place between a negative charge center and a positive charge pocket at the base of the cloud. Consequently, the step leader is initiated inside the cloud and connecting leader is initiated from the ground. The first return stroke is initiated after the connecting leader meets the step leader propagating towards ground [5]. The adiabatic expansion of air around the channel produces cylindrical shock wave profiles and decelerates into the speed of sound in air, forming an audible thunder [6]. A ground flash can be conclusively identified with the assistance of electrical discharging processes associated with the preliminary breakdown and return stroke. These events connected to the discharging process of lightning can be effectively used to confirm whether the recorded thunder signatures are initiated from a given ground flash or not. The recorded thunder signatures in this study have been corroborated by electrical field measurements with the preliminary break down and return stroke captured by a fast field antenna.

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B. The time average sound level (Leq) of thunder

The averaged linear integral of sound level, or the equivalent continuous sound level can be effectively used to develop an understanding of the sound level variation in predefined time duration. It gives a constant, which would produce the same energy as the average fluctuating sound level within the time interval. The integrated, normalized sound pressure of thunder has been divided by the time duration of interest to estimate $L_{eq,}$ and the result is represented in logarithm basis. The resultant sound level of thunder does not represent any specific frequency band of captured signal because of the calculation of L_{eq} has been performed in time domain.

$$L_{eq} = 10\log_{10}\left[\frac{1}{\Delta\tau}\int_{t}^{t+\Delta\tau}\frac{P(t)^2}{P_0^2}dt\right] \quad (1)$$

Here, Δτ is the time duration of interest of thunder signature, and P(t) is the acquired sound pressure level. L_{eq} is in dB, and the reference pressure level (P_0) is 20μPa.

When the lightning strike is far away from the position of recording, the sound pressure level recorded by the microphones is considerably low. The time duration,Δτ, is set to 1 second to estimate the equivalent continuous sound level in this study.

C. Spectrogram

The frequency variation of a signal can be demonstrated by many time-frequency representations such as Short time Fourier transformation (STFT), Pseudo Winger distribution (PWD), and Continuous wavelet transformation (CWT). S-transformation has been introduced to generate the spectrogram to depict an explicit representation of time and instantaneous frequency of sound of thunder. It provides a more efficient method to localize the spectrum and retains the phase properties of the signal [7]. For a finite time window, the local spectral density of audible pressure variation, *P(t),* can be estimated by equation (2):

$$S(\tau, f) = \int_{-\infty}^{\infty} P(t)\frac{|f|}{\sqrt{2\pi}}e^{-\frac{(\tau-t)^2 f^2}{2}}e^{-i2\pi ft}dt \quad (2)$$

Where τ is the finite time window, and *f* is the instantaneous frequency. The estimation uniquely combines the frequency dependent resolution in time-frequency representation and the phase information of thunder signatures. To generate the spectrogram, it requires more computing time because the S transformation has based on STFT and CWT.

III. MEASUREMENT AND DATA

Outdoor Microphone Unit type 4198 (Bruel & Kjaer) equipped with Falcon range ½"pre-amplifies type 2669 C has been introduced to capture the pressure variation initiated by thunder. The Omni-direction microphone and the preamplifier respond over a wide range of temperatures, humidity, and other environmental conditions. The sensitivity of the preamplifier is -26 ± 2 dB with regard to 1 V/Pa and 50 mV/Pa. The frequency response at 0^0 incidences is ± 1 dB 10 Hz to 8 kHz, and lower limiting frequency (-3 dB) is 2 Hz to 4 Hz. The disturbance produced by the wind is eliminated by introducing windscreen filters and the wobbling of microphone stands due to wind has been eliminated after the capturing. The wobbling of stands produces very low-frequency noise in the recordings, and it is filtered by introducing digital filters.

The pressure variation sensed by the microphone was transmitted by 100 m cable drivers to the Nexus Range of conditioning amplifier type 2690 (Bruel & Kjaer) with the frequency response of 0.1 Hz to 100 kHz to gain less than or equal to 60 dB. Data acquisition card (USB 4432 National Instruments) has been equipped to acquire and convert the signal captured by the conditioning amplifier. Thunder signatures were recorded at 100 kS/s with a 40 kS buffer size. The voltage variations of recorded thunder signal were converted into pressure variation using the voltage sensitivity (i.e., 100 mV/Pa) of the conditioning amplifier maintained during the measurements.

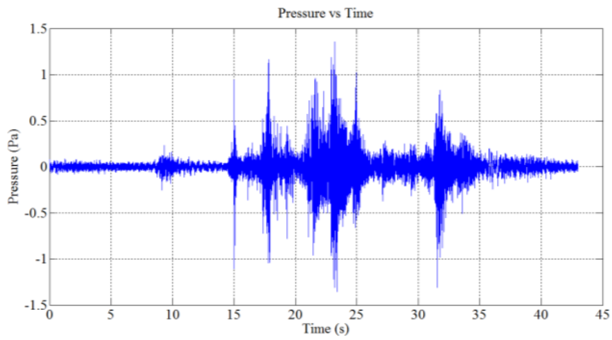

Fig. 1. Type 1 ground flash 04172014_081013_PM1

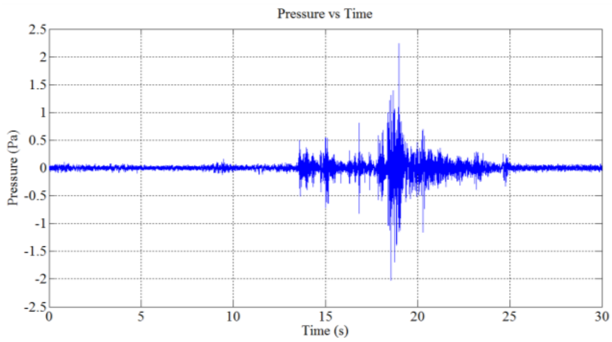

Fig. 2. Type 2 ground flash 04172014_084659_PM1

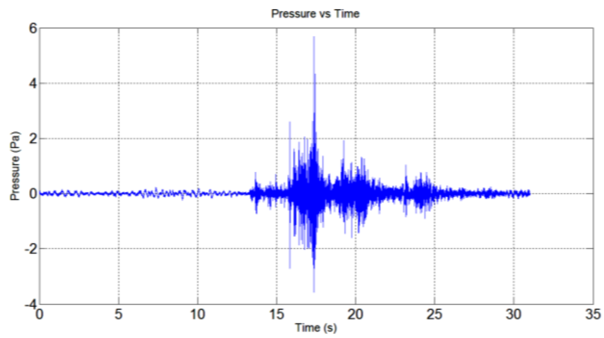

Fig. 3. Type 3 ground flash 04172014_080916_PM1

As per Fig. 4, 1-second time window was selected from the main profile to analyze the pressure and frequency variation in the vicinity of the peak value of the thunder signal. The signal was downsampled to 20 kS/s from the recorded rate of 100 kS/s to study the audible frequency variation of thunder profiles.

The fundamental frequency has been estimated considering the maximum audible power received by the microphone array. For the convenience of representation, the relative intensity level has been introduced with respect to the maximum intensity level estimated by power spectrum coefficient by Stockwell transformation. The spectrogram of captured part of the thunder signature was used to compute the fundamental frequency. The spectrogram analysis of thunder profiles indicates that there is no significant power in the frequencies higher than about 500 Hz (Fig. 5). Hence, the instantaneous frequency was set to estimate below 500 Hz. The coloration of the spectrogram was adjusted to observe the the frequency which dissipated the maximum acoustic power.

The fundamental frequency has been estimated considering the maximum coefficients of S transform spectrum for each time lapse. This leads to a sensible representation of fundamental frequency variation of the audible part of thunder with time. The variation in intensity level was significant in each spectrogram. Hence, the relative intensity level was represented as a percentage of the maximum intensity within the timespan of the profile (see Fig. 6).

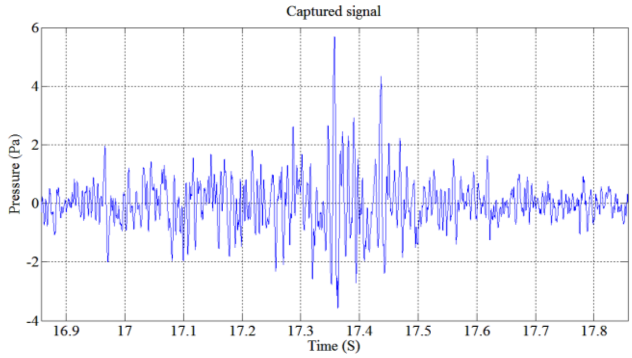

Fig. 4. Peak pressure variation of the ground flash 04222014_012402_PM1 in 1-second time duration

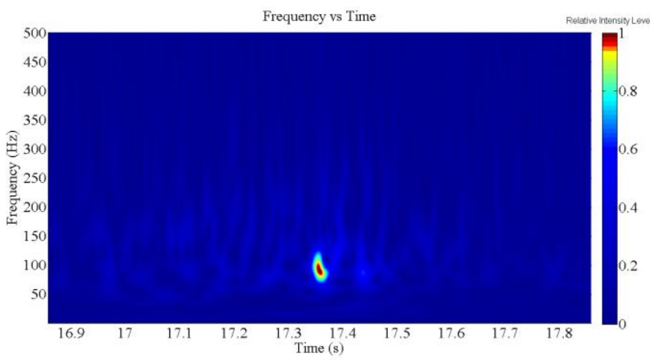

Fig. 5. The fundamental frequency of the pressure fluctuaton has been localized at 91 Hz. The color bar has been adjusted to observe the intensity maxima.

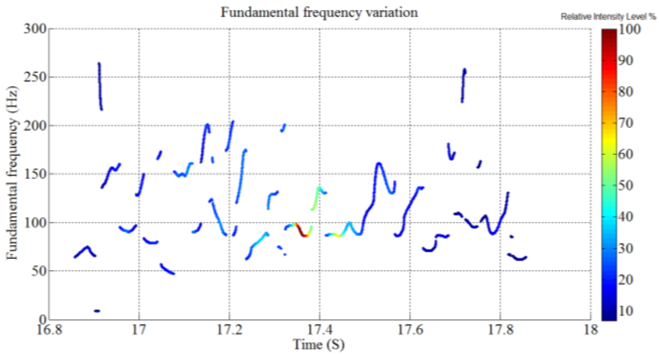

Fig. 6. The instantaneous frequency variation of a ground flash in 1-second window (04222014_012402_PM)

IV. RESULTS AND DISCUSSION

The purpose of this study is to present the fundamental frequency variation of ground flashes concerning the loudness and its capability to distinguish the flash type. The fundamental frequency variation has been observed according to the flash type categorized by the peak pressure recorded. The sound pressure of lightning discharging event lends reasonable support to get the picture of distance to thunder source. Considering the peak pressure of the thunder signature, three major types were used to analyze the fundamental frequency variation with the distance. The intensity level change strengthened the information about the distance of the thunder sound source; it can use to observe the fundamental frequency with the distance effectively. Fifty-seven records of ground flashes and twenty-four records of cloud flashes have been used in the study.

A. Type 3 flashes

For type 3 flashes, the relative intensity level percentage has been limited up to 40% of the maximum to observe the apparent variation of the frequency. Ground flash and cloud flash were selected in the same pressure variation according to the categorization introduced above to make a reasonable comparison of the frequency variation. Figs. 7 and 8 contain the instantaneous frequency variation of the type 3 ground flash and cloud flash. The instantaneous frequency of the ground flash shows a rapid variation compared to the cloud flash in the same category. The relative intensity level above 75% was in a short time duration, irrespective of the flash type. The fundamental frequency of the ground flash (91 Hz) was observed during the falling part of the variation that gradually developed into a maximum (137 Hz). The frequency then suddenly drops and follows the same pattern of increasing to maximum, which is higher than the previous maximum with the relative intensity level of less than 25%.

The spectrogram of a thunder signature imparts the audible instantaneous fundamental frequency variation with time. The segmentation of thunder signal into finite timespan lends to estimate the fundamental frequency with regard to each time window. The technique of quantization of thunder signature allows an inference that the thunder signature is a resultant of a series of cylindrical channel oscillators. Hence, the first loudest part of the ground flash might be initiated by the return stroke which releases the maximum audible power. The following high-frequency maxima may perhaps be from the subsequent strokes. The observation accords with the energy per unit length of lightning discharge, which is inversely proportionate to the fundamental frequency [3]. The subsequent stroke contains less energy per unit length. Hence, the fundamental frequency is high compared to the return stroke.

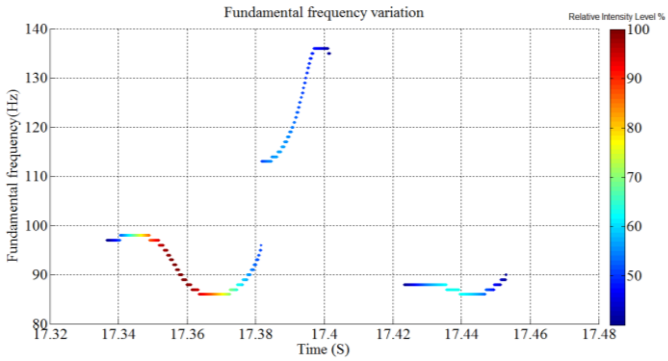

Fig. 7. The fundamental frequency of the ground flash 04172014_080916_PM1 (type 3) is 91 Hz

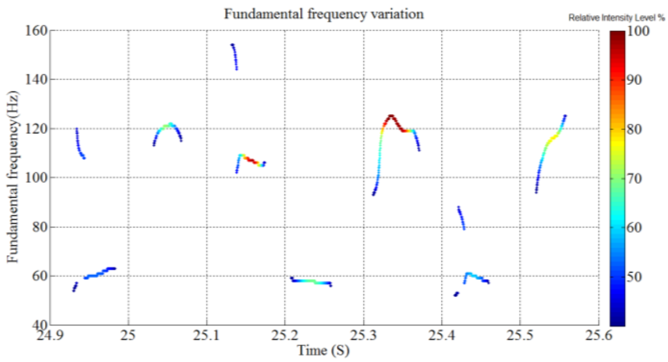

Fig. 8. The fundamental frequency of the cloud flash 04222014_012137_PM3(type 3) is 124 Hz

For the same kind of cloud flash, the relative intensity level above 75% shown in the Fig. 8 implies three maxima at distinct time locations in the spectrum. The most intense point on the spectrogram was considered as the fundamental frequency, 124 Hz. In addition to the fundamental frequency, two more significant frequency peaks noted at 114 Hz and 118 Hz. There is an even frequency response (60±5 Hz) in the range of 40% and 50% of relative intensity level. The slight frequency variation appears along the thunder signature, producing an inference of carrier frequency for cloud flashes different from ground flashes. In the case of the cloud flashes, there were many frequency peaks with relative intensity levels above 75% except the fundamental frequency. The other peak frequencies in the spectrogram did not expose a particular behavior of increase or decrease observed in ground flashes. There are two possible reasons for the variation of peak frequencies. One is the attenuation of the high-frequency component inside the cloud compared to the air during the propagation. The other might be the repeated breakdowns between the lower and upper levels along the channel.

In order to consider the fundamental frequency details of type 3 flash category, 24 ground flashes, and 8 cloud flashes have been analyzed, and its variation is represented with respect to the equivalent continuous sound level or time average sound level in Fig.9. The time average sound level lends an average value for the intensity level change in 1-second time window containing the peak pressure of thunder signal.

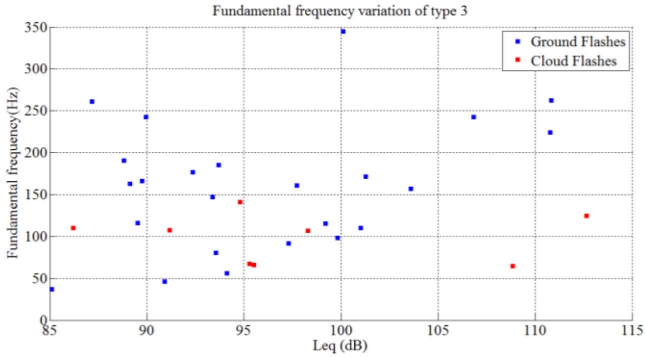

Fig. 9. Fundamental frequency distribution of type 3 flash category represented with the time average sound level

B. Type 2 flashes

Thunder signatures associated with the peak pressure between 1.5 Pa to 3 Pa have been categorized into type 2 flashes to get approximate details about the distance. The relative intensity level has been considered above 10% level to obtain the dominant frequency variation of the flash near the peak pressure recorded. For ground flashes, the fundamental frequency during the falling part of the frequency variation is similar to the type 3 ground flashes. Fig. 10 contains the dominant frequency variation of type 2 ground flash in 1-second time lapse around the peak pressure. The fundamental frequency (69 Hz) is computed by the relative intensity maximum of the spectrum. In addition to this characteristic, there are several local intensity maxima above 75% in the spectrum before receiving the maximum intensity. The effect of the wind during the propagation might be one possible reason to get this odd feature for some spectra. Otherwise, the sequence of high frequency in the spectrum is similar to type 3 ground flashes. This observation reasonably supports to strengthen the existence of subsequent strokes.

The dominant frequency variation of a cloud flash of the same category is represented in Fig. 11. The time duration is set to 1 second around the peak pressure recorded. The fundamental frequency is 88 Hz and lies in the falling part of the variation. The frequency fluctuation is less compared to ground flashes of the same category. In many cases, the occurrence of high-frequency maxima is indistinguishable above the threshold level of relative intensity (i.e., 10%). There are more than two intensity maxima above 75% level in many cloud flashes of this category. The frequencies estimated for consecutive intensity maxima are close to the fundamental frequency (80 Hz and 90 Hz regarding Fig. 11). The existence of repeated breakdowns inside the cloud or the attenuation of sound pressure of distinct parts of the same channel might be the reason to receive frequencies close to fundamental values. The main audible characteristic of cloud flashes of type 2 is that the pressure variation gradually increased to a maximum and became into feeble variation at the latter part. The direction of propagation might be the cause to receive the change in thunder sound loudness, and it consists of the results produced by the spectrogram.

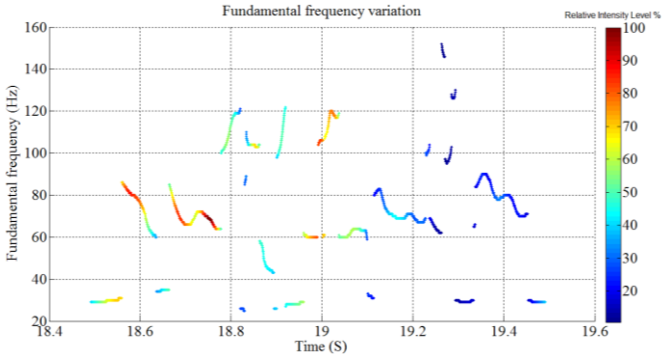

Fig. 10. The fundamental frequency variation of the ground flash 04172014_084659_PM1(type 2)

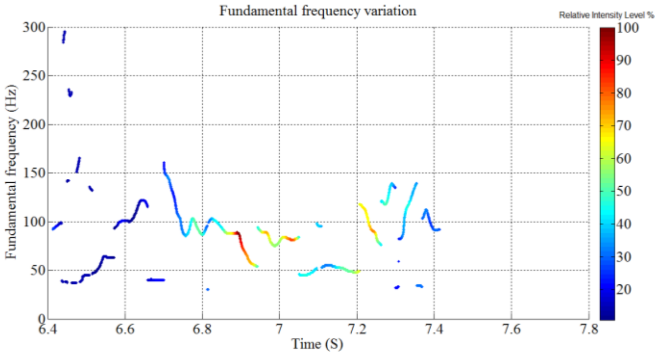

Fig. 11. The fundamental frequency variation of the cloud flash 04172014_081536_PM1(type 2)

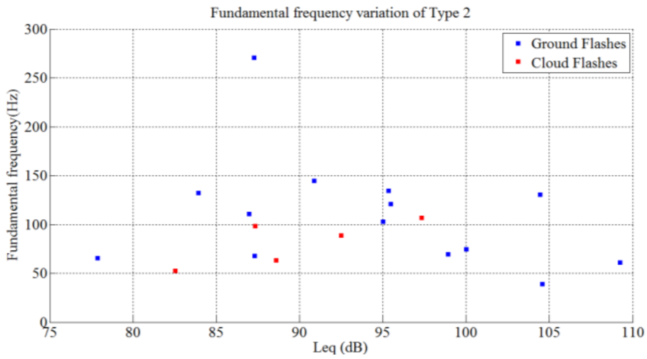

Fig. 12. The fundamental frequency distribution of type 2 flashes

Fourteen records of ground flashes were considered to observe the fundamental frequency variation compared to cloud flashes of type 2. The time average sound level was estimated in the 1-second time window to represent the fundamental frequency around the intense pressure fluctuation of flashes in Fig. 12.

C. *Type1 flashes*

The type 1 flashes are initiated by a feeble fluctuation of pressure, which holds aconsiderable time duration producing rumbles. After the occurrence of several peaks, it gradually reaches to the maximum sound pressure. According to spectral information, the pressure peaks can be considered as distant thunder claps because of the high dominant frequency compared to the rumbling frequency. The sound pressure is diminished into feeble rumbling at the concluding parts of the thunder. The impulsive nature of ground flashes of type 1 is significant compared to the cloud flashes in the same category. The time duration of the impulsive segment is broad compared to the previous two types of flashes.

The instantaneous frequency variation of a ground flash of type 1 is presented in Fig. 13, and its fundamental frequency has been estimated by a maximum relative intensity level (120 Hz). More than 30% of instantaneous frequencies in the spectrogram can be filtered by introducing 40% of cut-off relative intensity level. The timespan of occurrence of intensity maxima is not much deviated as previous types because the restoration of sound pressure can happen with the distance of propagation. The mean fundamental frequency and the clarity of subsequent dominant frequencies are less compared to previous types as the propagation of thunder is profoundly affected by distance, humidity conditions, and wind.

In the cloud flashes of the sample considered, the sporadic, sudden pressure fluctuations have been observed in a high-frequency range. In addition to the irregular impulsive nature, low-frequency pressure variations have been observed in many spectrograms of type 1 cloud flashes. The low-frequency components responsible for rumbles have been observed in the full extent of thunder signature represented in Fig. 14. The observation infers an interference of several sound sources initiated by cloud flashes. The interference might have caused by the occurrence of repeating breakdowns or vertical channel, and the extended lower level channel branches of the same discharging process. The high-frequency components are distinguishable in instantaneous frequency variation spectrogram even though the propagation distance is a prominent factor. These high-frequency components might be initiated by the latter part of the discharge close to the cloud base. Hence, there is a fair chance of interference of thunder generated by the vertical channel and the horizontal extension of channels in the latter part of the activity.

Nineteen ground flashes and eleven cloud flashes have been considered under the type 1 category to study the fundamental frequency variation. The time average sound level and corresponding fundamental frequency of the flash are represented in Fig. 15. The mean fundamental frequency of ground flashes can be estimated, and over 70% of frequencies were less than the 100 Hz. The fundamental frequency of cloud flashes is scattered in the same range as the ground flashes. Therefore, the sample size does not assist in estimating a fair mean value.

The peak pressure of a thunder signal provides a reasonable measure of the distance of the sound source, and it is subjective to the sensitivity of the diaphragm of the microphone. Therefore, it is necessary to calibrate the instrument before and after the measurements. The microphone kit used in this experiment provides software included a calibration tool. Hence, pressure and frequency sensitivity can be adjusted according to calibration parameters. Wind and the refraction can be affected by the peak pressure of thunder recordings, and they are unavoidable aspects of outdoor acoustic measurements. Therefore, peak pressure can be considered as a subjective feature of thunder, which provides a primary sensation of the power dissipation and the propagation distance. The time average sound level provides an average response on the audible power within 1-second time duration around the peak pressure. The dominant frequency variation with the time lends some specific features of thunder initiated by ground flashes. The study can be extended with considerably large time durations to find more frequency components of ground flashes with high computing power.

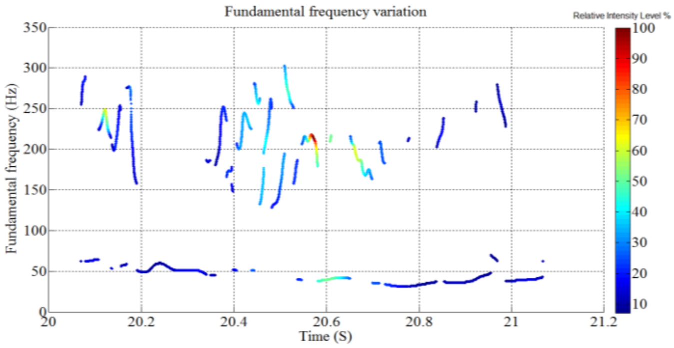

Fig. 13. The fundamental frequency variation of the ground flash 04172014_081013_PM1(type 1)

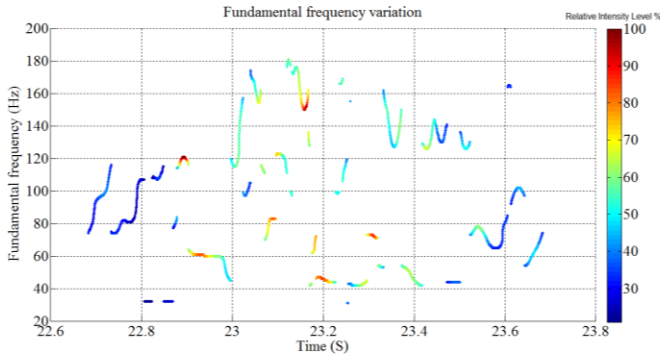

Fig. 14. The fundamental frequency variation of the cloud flash 04172014_084253_PM1(type 1)

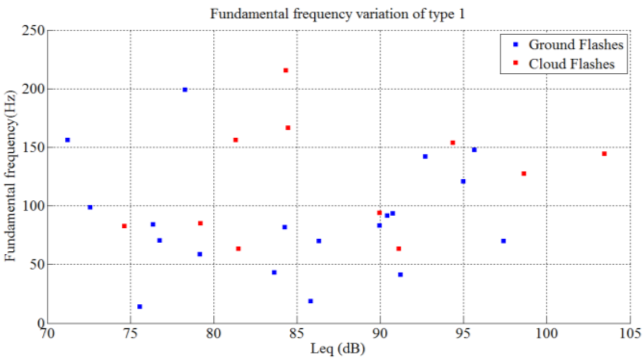

Fig. 15. The fundamental frequency variation of type 1 flashes

V. CONCLUSIONS

It revealed that no two spectrograms are identical and the fundamental frequency varies from spectrum to spectrum. For type 2 and 3 ground flashes, the subsequent dominant frequencies taken place after the fundamental frequency are high while those from cloud flashes have no such pattern in many studied observations. The following high frequencies in the tested ground flashes might be attributed to subsequent strokes followed by the return stroke, which produces the fundamental frequency.

Type 2 and 3 ground flashes can be identified relative to the cloud flashes by the impulsive nature of thunder signature. Estimating the mean fundamental frequency is possible from the sample considered under type 3 flashes, and was 160 Hz with a standard deviation of 76 Hz for ground flashes and 98 Hz with the standard deviation of 29 Hz for cloud flashes. The mean frequency of type 2 ground flashes is 108 Hz with the standard deviation of 57 Hz, and for cloud flashes, 82 Hz with the standard deviation of 23 Hz. The mean frequencies for type 1 flashes are estimated as 88 Hz with the standard deviation of 47 Hz for ground flashes, and 123 Hz with the standard deviation of 49 Hz for cloud flashes.

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REFERENCES

[1] J.A.P. Bodhika, W.G.D. Dharmarathne, M. Fernando, and V. Cooray, “A preliminary study of characteristics of thunder pulses of lightning,” in International conference on lightning protection, Shanghais, pp. 2019-2023, 2014.

[2] S. Abegunawardana, J.A.P. Bodhika, S. Nanayakkara, U. Sonnadara, M. Fernando, and V. Cooray, “Frequency Analysis of Thunder Features,” in International conference on lightning protection, Estoril, Portugal, 2016.

[3] Bhartendu,“Audio frequency pressure variations from lightning discharges,” J. Atmos. Sol. Terr. Phys., vol. 31, pp.748-747, September 16, 1969.

[4] Bhartendu, “A study of atmospheric pressure variations from lightning discharges,”Institute of Space and Atmospheric Studies, University of Saskatchewan, Saskatoon, Saskatchewan, 1967.

[5] Vernon Cooray, “An introduction of lightning,” Springer, pp. 97-116, 2015.

[6] A. A. Few, and A. J. Dessler, “A Dominant 200 Hz Peak in Acoustic Spectrum of Thunder,” J. Geophys. Res., vol 72, no. 24, pp. 6149-6154, December 1967.

[7] R. G. Stockwell, L. Mansinha, and R. P. Lowe, “Localization of the Complex Spectrum: The S Transform,” IEEE Trans. Signal Process., vol. 44, no. 4, pp. 998-1001, April 1996.