Time-Frequency Analysis of Narrow Bipolar Pulses observed in Sri Lanka

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Abstract— **Narrow Bipolar Pulses (NBP) of a single thunderstorm from a coastal location in Sri Lanka were subjected to S-transformation in order to study their time-frequency information. This study is an extension to a similar study carried out by the authors where properties of NBPs were analyzed using the wavelet transformation. Keeping in line with the previous study, 18 events pertaining to equal number of positive and negative NBPs with the narrowest temporal widths were studied. The data was obtained from the southern coastal area of Sri Lanka (Matara - 5.95^0 N, 8.53^0 E) from a highly active thunderstorm, which occurred during the month of May in 2013. The waveforms were recorded with a 10 ns resolution within a 100 ms time window. The spanning (width) and the ratio of peak power amongst the initial and overshoot pulses were measured and compared for each polarity. The negative NBPs had an average spanning of 134 - 371 kHz. The overshoot of the same had an average range of 127 - 255 kHz. The positive NBPs had an average spanning of 103 - 245 kHz. The overshoot of the same had an average range of 102 - 195 kHz. The ratio of peak power of NBPs to overshoot had an average of 1.08 for both positive and negative pulses. The spectrogram reveals the initial and overshoots pulses to be relatively equal in power intensities.**

Keywords-Lightning, Narrow Bipolar Pulses, Spread Distribution, Peak Power Ratio, S Transformation

I. INTRODUCTION

Narrow Bipolar Pulse (NBP) is an intra cloud activity, which is known to occur mainly in the initial stages of the lightning thunderstorms. It is also known as a Compact Intra-Cloud Discharge (CID). The names itself signifies its main property of being narrow or compact temporally when compared to other lightning related activities. These were initially observed by [1] where its high frequency and highly energetic nature was noticed. Yet it was [4] which provided a detailed study on the NBPs and observed its isolated nature and the dual polarity. Also [4] concluded them to be having comparatively large amplitudes and radiation power than that of a return stroke of the same thunderstorm. Since its discovery, various studies have been carried out on NBPs but majority of them were restricted to the study of either their temporal [10] or frequency properties. The attempts on studying both properties simultaneously have been rare.

The daily use of sensitive electronic devices in critical tasks has increased significantly at present. High to medium frequency electromagnetic radiations in the atmosphere are known to be hazardous to these devices [2, 3]. NBPs are known to emit similar radiations, which make them an important candidate in most recent studies. With the continuous improvement in signal acquiring devices/techniques, the detail levels of the temporal properties observed in recent NBP studies have displayed them to have very narrow durations. This suggests them to be having abundant high frequency components, which in turn radiate more high energies.

The use of frequency transformations in NBP studies provided valuable information on the frequency values and their relative powers. However, they lacked the ability to localize the occurrence of the event and its relative frequencies, which is valuable when studying transients such as NBPs. This limitation could be addressed by employing a time-frequency analysis which use various mathematical methods to compute both time and frequency information of a given signal. Nevertheless, the uncertainty principal affects all such methodologies, which make the time and frequency resolutions to be of limited nature. In a previous study [11] the authors' employed the wavelet transformation to the same data set. The results were of higher accuracy compared to other such studies [7, 8] carried out in with wavelet transformations since the wavelet transformation has its own drawbacks, which did cause the results to be of limited nature.

In order to mitigate the limitations of wavelet analysis, the authors opted for the S-transformation [5], which was in reality a generalized version of the Short Time Fourier Transform (STFT) and the Continuous Wavelet Transform (CWT). It directly relates to the Fourier spectrum by retaining referenced phase information and by having a frequency invariant amplitude response. The comparatively better frequency localization of smaller time intervals is ideal when analyzing transients such as NBPs when compared other similar methodologies such as Gabor Transforms in STFT. Localized spectrum of a signal in infinite time window τ is given by:

$$S(\tau, f) = \int_{-\infty}^{\infty} x(t) \frac{|f|}{\sqrt{2\pi}} e^{-\frac{(\tau-t)^2 f^2}{2}} e^{-i2\pi ft} dt \qquad (1)$$

The signal of interest is $x(t)$ and frequency is represented by f. By replacing $f \rightarrow n/NT$ and $\tau \rightarrow jT$, equation (1) translates to S-transform of a discrete time series as depicted below.

$$S\left[jT, \frac{n}{NT} \right] = \sum_{m=0}^{N-1} H\left[\frac{m+n}{NT} \right] e^{-\frac{2\pi^2 m^2}{n^2}} e^{-\frac{i2\pi mj}{N}} \qquad (2)$$

Discrete frequencies are denoted by n, m and T is the sample time where H is the discrete Fourier transform of $m + n$ shifted frequency components. The Fast Fourier Transform (FFT) algorithm was utilized to reduce the computational complexity of the S-transform coefficients and according to [5, 9], they appear to be directly related to the power spectrum of the signal as well.

The current study follows the previous study [11] done by the authors, by utilizing the same input data with the only difference of employing the S-transform for time – frequency analysis. In addition, it is considered to be the first instance that an S-transformation has been done on NBP data. Thus, provisions for comparisons with previous studies are unavailable. Yet the results from the studies of [8] and [11] have been compared here although they both employ the wavelet transformation in obtaining the results.

II. MEASUREMENT AND DATA

During the month of May, the lightning activity level was significantly high due to the South-West monsoon season. The measurement site was setup in the region of Matara (latitude 5.95° N, longitude 80.53° E), a popular tourist destination in the coastal belt of southern part of Sri Lanka. Majority of NBPs were biased to be of one polarity on most of the recordings. A single thunderstorm that occurred on the 3rd of May 2013 between 02:30 pm (UTC) and 04:30 pm (UTC) yielded a polarity wise balanced output of NBPs. These were recorded using a parallel plate antenna that was set approximately 50 m above sea level and 50 m away from the shore. The recorded vertical electric field signatures were fed to a high speed data acquisition unit (PicoScope 6404B, 4 channels) through a high speed, high bandwidth buffer circuit based on MAX460 integrated circuit. The decay time of the buffer system was around 18 ms. RG-58 coaxial cables with proper 50 Ω terminations were used to connect the buffer and the data acquisition unit with lengths around 10 m. The data acquisition unit was set to trigger in window mode enabling to trigger for both positive and negative signals. The trigger threshold was set to 50 mV. Before employing the S-transform, measured values were adjusted using a system factor calculation corresponding to a 1.5 m height parallel plate antenna [6]. The study did not include a lightning location system. Thus, the exact locations of the events were

not available. Instead, satellite imagery (See Fig.1) was obtained for the measured thunderstorm duration. The scaled figure depicts that the thundercloud in concern spanned well over 200 km in width, which made the localization attempt of the NBP difficult. Thus, a similar approach as in [7] was used where a fixed window of 100 μs was selected for each signal analysis instead of normalizing it.
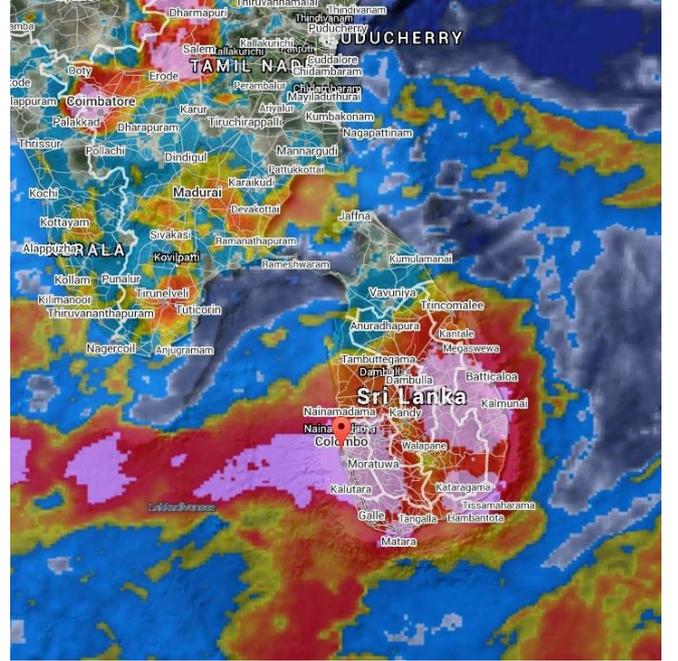

Figure 1. Satellite imagery above Matara on the 3rd May 2013 at 03:30 pm (UTC). The areas in red to pink denote cooler cloud regions which are considered to be as the origins of lightning activity. The cloud cover spanning the large area makes the localization possibilities for the NBPs difficult. (Image obtained from http://www.wunderground.com)

III. RESULTS AND DISCUSSION

The temporal values of the measured eclectic field were fed to a program based on the S-Transform, which outputs the time domain signal as well as the time-frequency domain output with the relative power intensity levels in color code. Fig. 2 and 3 depict the outcome of the process. Fig. 2 corresponds to narrow negative NBP recordings of the data set. The Fig. 3 depicts the same for the positive NBP. The colors provide the variations of the relative intensity of power in each frequency. Similar to [11], the dark blue region denotes the background system noise. The spread region was considered as the areas of above 90% intensity levels, which are denoted by the colors in dark red to maroon in the color scale. This area is considered to be the region where maximum power from the NBP is radiated [7].
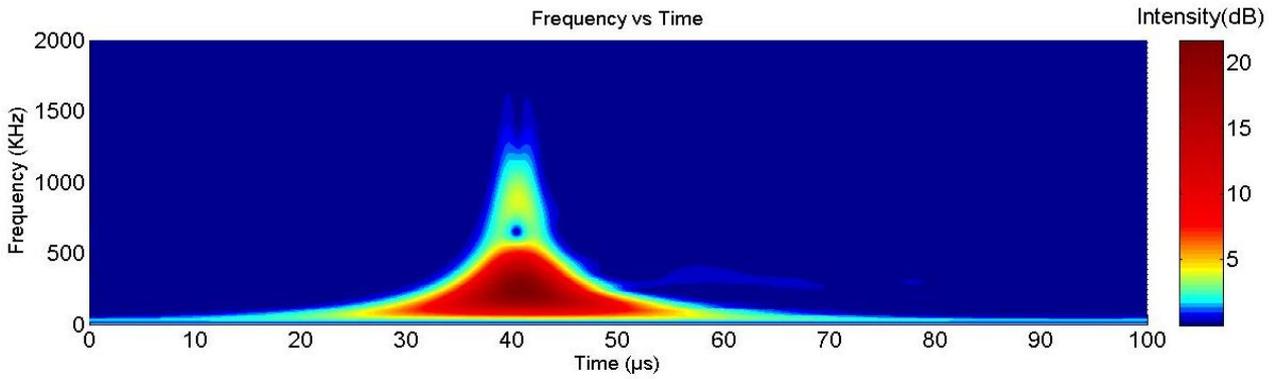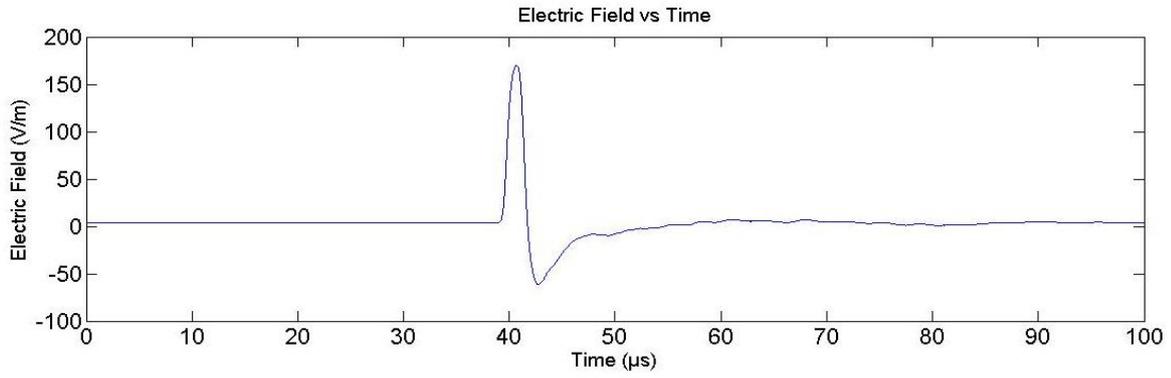
Figure 2. S-Transform spectrum of a negative narrow bipolar pulse.
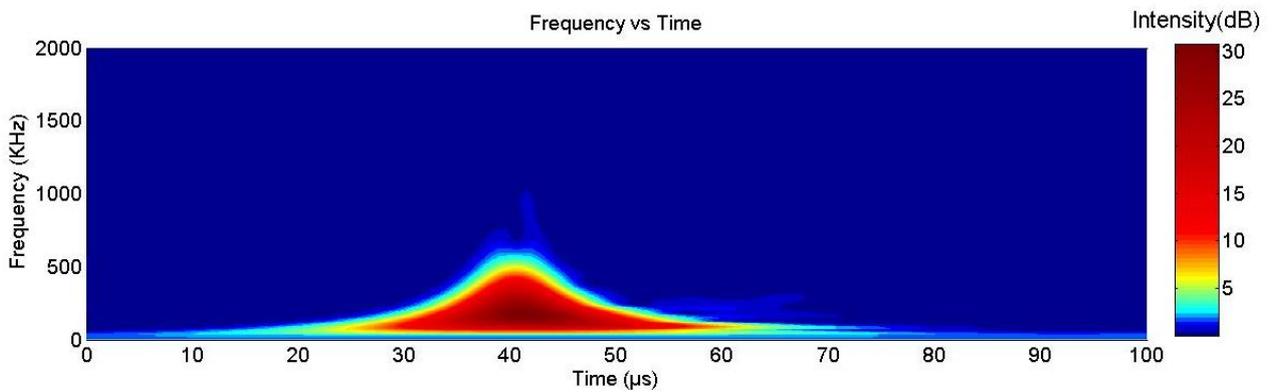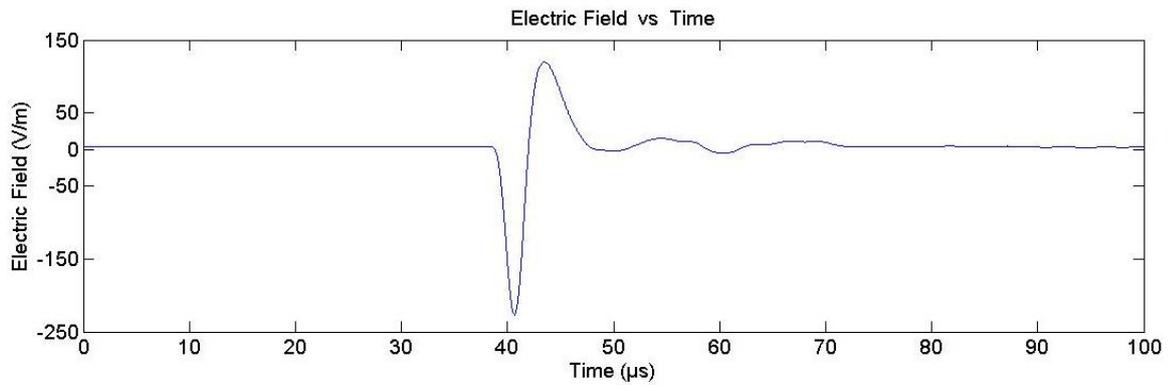

Figure 3. S-Transform spectrum of a positive narrow bipolar pulse.

TABLE I. STATISTICS OF THE TIME-FREQUNCY ANALYSIS OF NARROW BIPOLAR PULSES

	Positive Narrow Bipolar Pulse Spread Region (kHz)		Negative Narrow Bipolar Pulse Spread Region (kHz)		Ratio of Power Peak of initial and overshoot pulses
	Initial	*Overshoot*	*Initial*	*Overshoot*	
Maximum	370	280	360	310	1.27
Minimum	95	90	120	100	1.00
Average	103-245	102-195	134-371	127-255	1.08

The unique signature of any NBP is that its amplitude starts to first increase rapidly in one direction (polarity) and returns to zero immediately and keeps on increasing in the opposite direction and returns back to zero where there after begins to settle down to zero. These transient pulses are known as the initial and the overshoot of the NBP. Thus, the high radiation frequency components are expected to be present in this area of the NBP.

Table 1 summarizes the results of the S-transform analysis where the maximum, minimum and the average values were obtained based on the polarity. The spread region (distribution) for the initial pulse of positive NBPs had a maximum of 370 kHz with a minimum of 95 kHz and a average range between 103 – 245 kHz. The overshoot pulse had a maximum of 280 kHz but with a similar minimum of 90 kHz. Its range was between 102 – 195 kHz, which indicated a much compact spread compared to the initial pulse.

The Negative NBPs displayed a much larger average ranges for both initial and overshoot pulses. The initial pulse ranged from 134 to 371 kHz while the overshoot was in between 127 to 255 kHz. In addition, the initial pulse had a maximum of 360 kHz while the overshoot had 310 kHz as its value. The minimum values for the initial pulse was 120 kHz and for the overshoot, it was 100 kHz.

When compared to the results of [11] it is visible that the current study yields larger values for both minimum and maximum of the initial and overshoot pulses irrespective of the polarity. In addition, the spread ranges for both initial and overshoot pulses displayed a larger value irrespective of its polarity.

The ratio of peak power amongst the initial and overshoot pulses yielded a maximum of 1.27, a minimum of 1.00 and an average of 1.08. Although the initial pulse displays a minute increase in power, it can be said that on average radiations from both pulses to be of equal nature. Although the minima and maxima values of the current study and the previous study of [8] differ in this regard, the average value seems to once again agree.

IV. CONCLUSIONS

S-Transformation was implemented on NBP events, to perform a Time-Frequency analysis. According to authors' knowledge, this is the first instance that, this methodology has been implemented to such a study where as other similar methods [7, 8, 11] have been employed in the past. The main reasons for employing the S-Transform was its advantages such as absolute referenced phase information and frequency invariant amplitude response when compared to the wavelet transformation, which was used in an earlier similar study [11] by the same authors. The NBPs analyzed were of the same data set as of [11]. Thus, it was of significantly narrow nature due to the propagation effects witnessed in the recording site as mentioned further in [11].

The resultant values (maximum, minimum and average) of initial and overshoot pulses were larger when compared to that of [11] irrespective of their polarities. This could be due to the higher resolution that is generated in S-Transform outputs than that from a wavelet transformation; which causes high frequency signals to be attenuated comparative to its low counterpart. In keeping with the other properties of [11], the polarity wise spread densities showed the expected nature where the positive NBPs showed a compact spread when compared to the negative ones.

The peak power ratios amongst the initial and overshoots of each polarity produced an equal value on average. This suggests that both the initial and overshoot pulses of the NBPs were equally strong in radiation energy irrespective of their polarities.

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