Theoretical and Experimental Analyses of Electromagnetic Measurements

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Abstract

Measurements of electric and magnetic (EM) fields have been proposed as a means of supporting and aiding infrasound (IS) signal analysis in context of the monitoring system of the Comprehensive Nuclear-Test-Ban Treaty (CTBT) [1]. As opposed to nuclear explosion, other natural and man-made IS sources do not produce an EM signal. Thus, if an IS signal is not accompanied by an EM pulse, it is known that it is not originated from a nuclear explosion. Lightning discharges are the main source of EM pulses. Due to their high abundance, fortuitous coincidence of lightning with an IS signal are a common situation. These events may be mistakenly assumed as a nuclear explosion. To avoid this obstacle, a reliable method for lightning detection and identification is required.

In this work we present results of continuous measurements of electromagnetic fields, adjacent to IAMR IS array at Mt. Meron, Israel. Lightning discharges are detected and analyzed, and their abundance is compared with theoretical predictions. We show how information about lightning location can be deduced from recorded waveform. Correlation with IS events is being examined as well. We conclude that lightning signals can be identified and filtered out, and thus the EM signal can be fused with the IS records to provide better performance of the CTBTO monitoring system.

1 Lightning Identification

1.1 Time Domain

There are several methods for extracting lightning discharge events out of a continuous EM measurement. Simplest approach is based on local extremum points in time domain. Any value which exceeds a pre-defined threshold is considered as an event. In Fig. 1 we present the number of detected events as function of the threshold, and compare it to a statistical estimation of expected event frequency [2].

The theoretical estimation is based on scaling relation between lightning discharge current and field strength, deduced from results described in [3]. It was found that the lightning radiated power scales with discharge peak current as $I_p^{1.62}$. From this, one can deduce that the electric field relates to the current as $E(r,I_p) \sim I_p^{0.81}$. In particular, the field strength at a distance r is given by

$$E(r, I_p) = \left(I_p/20\right)^{0.81} E(r, 20), \tag{1}$$

where $E(r, 20)$ is the field at distance r due to a reference lightning with a peak current $I_p = 20$ kA. The value of $E(r, 20)$ was calculated using the LWPC code [4].

Then, the lightning discharge current that will result in field strength equal to or larger than a threshold field E_{th} at a distance r is equal to or larger than

$$I_{th}(r) = 20 \left[\frac{E_{th}}{E(r, 20)}\right]^{1/0.81}. \tag{2}$$

Lightning peak current closely follows a lognormal distribution. Its cumulative distribution function (CDF) is given by

$$CDF(I) = \frac{1}{\sqrt{2\pi}\sigma} \int_I^\infty e^{-\frac{[\ln(I') - \mu]^2}{2\sigma^2}} \frac{dI'}{I'}. \tag{3}$$

CDF(I) is the fraction of lightning discharges whose peak current is larger than *I*. A comprehensive comparison of the distribution parameters in several independent studies is made in [5]. The median peak current (e^{μ}) in all these studies is very close to 30 kA, while $\sigma \approx 0.3$. Substituting the current from Eq. (2) into Eq. (3) yields the $CDF(r,E_{th})$ which has to be interpreted as the probability of a signal generated by a lightning at a distance r, to have at the receiving station a field strength higher than E_{th}. Integrating $CDF(r,E_{th})$ over $2\pi r dr$ and multiplying by the global average lightning rate per km^2 [6], we obtain an estimate number of lightning signals per second with strength higher than any given threshold, that can be collected at the receiving station. In the estimation presented in Fig. 1 we assume that the receiver collects only CG discharges, and we take IC/GC ratio of 2.5, which is a typical value for Israel.

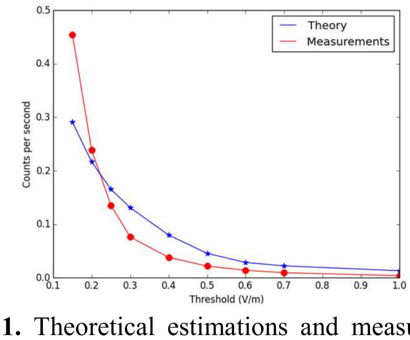

Figure 1. Theoretical estimations and measurements of lightning discharge events detected using different thresholds.

1.2 Frequency Domain

Another option is to identify lightning events from frequency domain. An abrupt rise in the field amplitude in the 5-20 kHz range is an indication to a lightning. This method identifies also weak signals whose peak is in the same order of magnitude as the noise. In addition, it avoids false positive identification due to random spikes. An example is presented in Fig. 2. In the plotted spectrogram there are clear time points where the frequency content exhibits rapid change. Width, frequency range, and power of the high amplitude area may provide important information about its source.

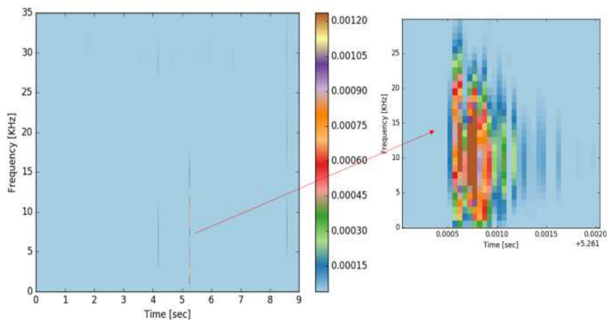

Figure 2. A spectrogram of the measured electric field. A lightning discharge can be identified by the increase in the 5-20 kHz range.

2 Locating the EMP Source

Propagation of lightning discharge signals have been simulated, using a standard lightning EMP model as a source. Signals were broadcasted from various distances to the receiver. Correlation of actual received signals with the simulated ones were calculated. It was found that actual signals are highly correlated with synthetic signals from certain distances, whereas their correlation with signals from other locations is poor. Thus, correlation with simulations serves as an indication to source location. In Fig. 3 we present two examples of detected signals and their correlation with simulation results. First, we have simulated the propagation of lightning discharge radiation originated at various distances from the receiver. A standard two exponents source was assumed. Then, for any measured signal, we have tried to correlate the waveform with simulations results. It comes out that each received signal is highly correlated with simulation of signals from a small range of distances, whereas its correlation with sources coming from other distances is much lower. Similar method was used to examine the parameters of the discharge function. It was found that the waveform sensitivity to distance is much greater than to other parameters.
Azimuth of source location is estimated by the ratio between the two magnetic field components. Putting together distance and azimuth yields an independent estimation of the location from which the signal had been originated.

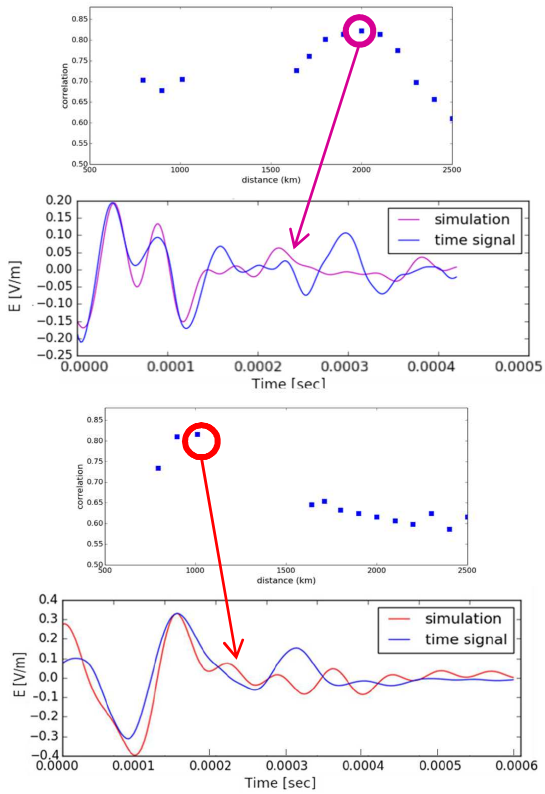

Figure 3. Two actual measured signals (second and fourth panels, in blue) and the simulated respective signals. Correlation with signals from other distances is shown in the first and third panels.

3 Infrasound Signal from Lightnings

On February 12th 2019, a thunder storm took place in vicinity of the IS station. A few hundreds lightning discharges have been recorded and located (by the WWLLN – World Wide Lightning Location Network) within 100 km to the station (Fig. 4). For each of these, the expected time of IS signal arrival was calculated, and the IS recorded signal was examined for traces of the lightning. About 25% of lightning taking place within 80 km from the station could be identified in the IS (Fig. 5). Above this radius, rate of identification was significantly lower, in accordance with previous reports [7]. This implies that as far as distant events are concerned, we do not expect a systematic coincidence of EM signals with IS events.
The difficulties in detecting lightning generated infrasound at distances larger than 100 km could be attributed, at least partially, to energy considerations. Estimates of the energy in lightning vary from a few 10^8 Joules to 10^{10} Joules [8]. Even if we consider the higher estimate it is equivalent to only few tons of TNT – way below the detection threshold of the CTBT International Monitoring System (IMS) stations. Other reasons may be related to the mechanism of infrasound generation. Consider for example the electrostatic mechanism suggested by Wilson [9]. According to [7] it should result in infrasound emission mainly in the vertical direction, thus at angles smaller than the critical angle and so are not expected to be reflected back toward the ground.

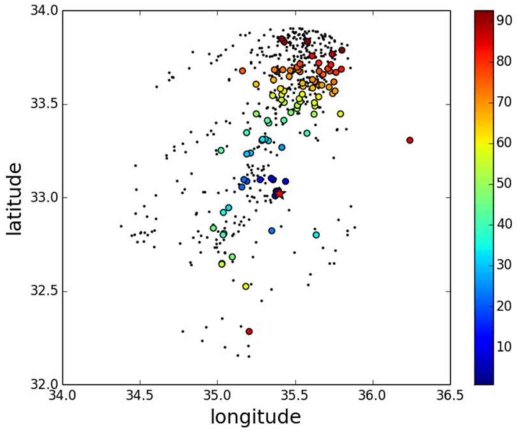

Figure 4. All lightning events (dots) and lightning events with IS signal detected (circles, colored by distance).

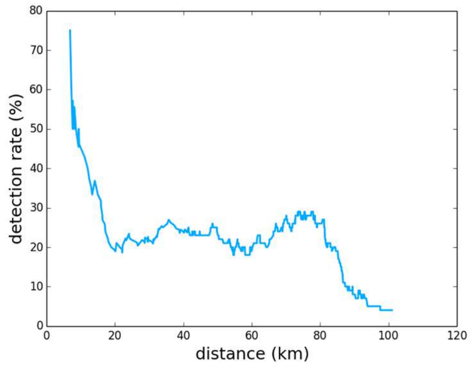

Figure 5. Coincidence rate of lightning and IS, computed as percentage of IS signals out of running window of 100 lightning discharges.

4 Conclusions

In this study we present results obtained from continuous measurements of electromagnetic signals. We compare the lightning detection rate as function of field threshold to statistical estimation, and find fair agreement. Incorporating electromagnetic measurements with infrasound data may assist analysis of infrasound measurements taking place under the CTBTO IMS on the one hand, and improve our understanding of the relation between lightning and thunder storm on the other hand.

5 References

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