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LOCALIZATION AND QUANTIFICATION OF THE ACOUSTICAL POWER OF LIGHTNING FLASHES

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ABSTRACT

Lightning is a ubiquitous source of infrasound, and an essential climate variable. To observe lightning flashes, thunder measurement efficiently complements electromagnetic methods. Using acoustical arrays, time delays between sensors inform on the direction of sound arrival, while the difference between emission time and sound arrival provides the source distance. Combining the two allows a geometrical reconstruction of individual lightning flashes, each viewed as a set of sound point sources. The measured sound amplitude can also be back-propagated, compensating for absorption and density stratification. This allows to evaluate the acoustical power of each detected source, and the total power of an individual flash. This methodology has been carried out to analyze data from two campaigns in Southern continental France in 2012, and in Corsica in 2018. In Corsica, power from reconstructed sources could also be forward-propagated towards several isolated microphones, and compared to measurement there, providing an additional validation of the method. Many events from the two campaigns were analyzed, including negative and positive cloud-to-ground discharges and intra-cloud ones. The analysis outlines the method efficiency, and the strong variability of lightning as sound sources in terms of both power spatial distribution and overall value.

Keywords: *3D, acoustic, power, localization*

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1. INTRODUCTION

Thunder has been studied since the 1960s to characterize lightning as an acoustic source, and to attempt to relate the mechanisms of thunder emission to a more global physical description of the discharge. Since, acoustical reconstruction methods have been proved to efficiently localize acoustic sources, either within the clouds or within the lightning strokes [1–4]. But for now, the acoustical energy emitted at the source by lightning has been estimated directly only by back-propagation of the whole received acoustic signal [5, 6]. We propose to combine and enhance these two methods, in order to estimate more precisely the distribution of acoustical power within the reconstructed sources, with the inversion of both geometrical and also stationary atmospheric propagation effects (absorption and density stratification). These compensations significantly affect the total acoustical power value of each flash. This power evaluation is applied to thunder recordings from two measurement campaigns, HyMeX-SOP1 in 2012 in Cévennes (southern France) and EXAEDRE in 2018 in Corsica [7, 8]. The validation by comparison to measurements at other locations highlights the necessity of these compensations.

2. ACOUSTICAL POWER LOCALIZATION IN 3D

2.1 Acoustical 3D reconstruction

Our work is based on 3D lightning reconstruction using acoustic measurements. The general principle was proposed in the early 1970s [1]. It is based on the cross-correlation of the signals detected by an array of microphones to estimate the direction of sound arrival, and select only the coherent part of the signal. The information of the emission time of the flash (given by optical or electromagnetic means) allows to calculate the propagation time and so the distance between the array and each acoustical source within the flash. In our study, we use a 4-microphones triangular array (AA) of 30 to 50-m wide (respectively for EXAEDRE and SOP1), the cross-correlation is performed by the PMCC algorithm (*Progressive Multichannel Cross Correlation* [9]) by frequency bands on sliding time windows. The emission time t_{LLS} is provided by the Lightning Location System (EUCLID for SOP1, Météorage for EXAEDRE). We assume a constant propagation speed equal to the ground sound velocity c_0, as wind and temperature profiles are poorly known [4].

Each acoustic detection is associated to its arrival time T at the array, and to the mean frequency F of the bandwidth in which it was detected. So each acoustical source is associated to a unique couple (T, F), while the reconstruction algorithm also provides the arrival azimuth A, and trace velocity V_h from which we obtain the elevation angle E. All these variables are represented on figure Fig. 1 for a single lightning flash which occurred on September 17, 2018 at 12:13:36.079 UTC in Corsica. We calculate the distance r_0, the elevation angle E and the Cartesian coordinates (x, y, z) of each detected source with:

$$\begin{aligned} r_0 &= c_0[T - t_{LLS}] \\ E &= cos^{-1}(c_0/V_h) \\ x &= r_0 \cos E \sin A \\ y &= r_0 \cos E \cos A \\ z &= r_0 \sin E. \end{aligned} \quad (1)$$

On Fig. 1 are represented all the variables we use to fully describe all the coherent detections corresponding to a single lightning flash, i.e. for each source the set: $\{T, A, E, \mathtt{P}_0, F\}$, where $\mathtt{P}_0$ is the RMS pressure level of each PMCC detection.

This method has been shown to give satisfying results at a distance of less than 15km from the lightning. Within this range, it allows to better reconstruct the channel connection to the ground than the Lightning Mapping Array (LMA) VHF electromagnetic detections [4, 10].

2.2 Source acoustical power

As the method gives the source position as described in Eqn. (1), the propagation effects can be compensated. In this study we consider:

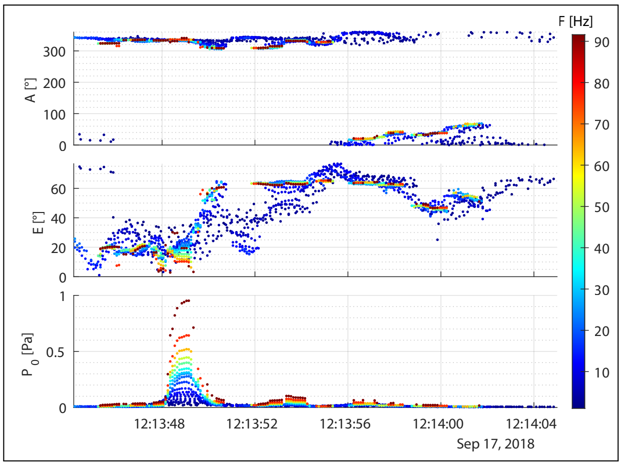

Figure 1. PMCC outputs as function of arrival time T, from top to bottom: A (azimuth), E (elevation), P_0 (RMS Pressure). Color: F (mean of the frequency band of detection). Event of September 17, 2018 at 12:13:36.079 UTC, EXAEDRE campaign.

- spherical divergence: pressure varies with distance as $\frac{1}{r_0}$ for a spherical source,
- rigid ground reflection: pressure is amplified by a factor 2,
- atmospheric absorption: pressure decays exponentially with distance as $e^{-\alpha r_0}$,
- atmospheric density stratification: pressure varies with altitude as $\sqrt{\frac{\rho_0(z)}{\rho_0(0)}}$.

We introduce here α, the air absorption coefficient depending on the atmosphere humidity and temperature, and on the acoustic wave frequency [11]. We chose a humidity rate of 70%, a temperature of $28.6\,°\mathrm{C}$ (measured at the time of the recorded flash) and we approximate the frequency as the value F corresponding to the detected source. Between the source and the ground and according to ray theory [12], pressure amplitude is also reduced by the ratio $\sqrt{\frac{\rho_0(z)}{\rho_0(0)}}$ where $\rho_0(z)$ is the density at altitude z of each source in the standard atmosphere [13]. We invert the listed propagation effects to get the RMS pressure amplitude near the source $\mathtt{P}_{src}$, at the distance $r_{ref} = 1\,\mathrm{m}$ from the source, as:

$$\mathtt{P}_{src} = \frac{1}{2}\frac{r_0}{r_{ref}}\sqrt{\frac{\rho_0(0)}{\rho_0(z)}}\mathtt{P}_0 e^{\alpha r_0}. \quad (2)$$

The acoustical power $\mathcal{W}_{src}$ of a single source is:

$$\mathcal{W}_{src} = \frac{2\pi r_{ref}^2 \mathrm{P}_{src}^2}{Z_0(z)}, \quad (3)$$

where $Z_0(z) = \rho_0(z)c_0$ is the acoustical impedance of air at the altitude of the source. The total power of the flash is simply the sum of the power of all of its sources:

$$\mathcal{W}_{tot} = \Sigma \mathcal{W}_{src} \quad (4)$$

The 3D reconstruction with representation of the acoustical power location of all sources is represented for event of September 17, 2018 at 12:13:36.079 UTC on Fig. 2. We observe a good matching between the acoustical reconstructed sources and LMA detections. We also clearly see a single return stroke connecting the intracloud sources to the ground LLS location indicating a single negative cloud-to-ground (-CG) event. As already observed, there are much more acoustical sources than LMA ones within the lightning channel. Moreover, these ones are the most powerful ones. We thus recover the previous observation [10] that the return stroke is generally more powerful than the intracloud. In addition, we observe the most powerful sources are located in the bottom of the stroke, below $2\,\mathrm{km}$.

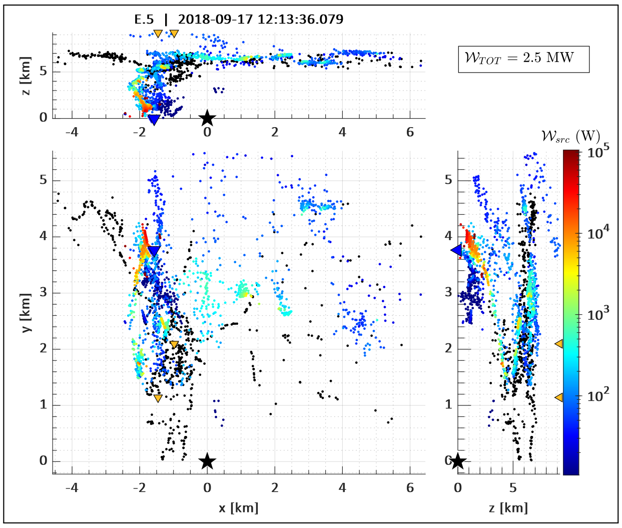

Figure 2. Acoustical reconstruction in 3D of event of September 17, 2018 at 12:13:36.079 UTC, with a West-East vs. Altitude projection on the first panel, a top view on the middle panel and an Altitude vs. South-North on the right panel. The reconstruction is colored with source acoustical power (see colorbar in logarithmic scale). LMA VHF detections: black dots. Blue downward triangle: LLS ground location of -CG. Black star: AA.

2.3 Validation with isolated microphones

2.3.1 Approach

In order to validate our 3D acoustical reconstruction and inversion method, we simulate the RMS amplitude received at any other microphone from the source power reconstructed from the microphones array AA. This is done for EXAEDRE campaign, for which a set of 8 isolated microphones (SA) is deployed in a range of $10\,\mathrm{km}$ around AA. Since we cannot directly compare a set of acoustic detections to a raw pressure signal, we convert both of them into a RMS pressure envelope. Here, the purpose is not to obtain a perfect matching, since the propagation remains simplified and the isolated microphones could receive other signals from coherent or incoherent nearby acoustical sources. But we intend to recover some key properties of the predicted envelope in the measured one.

2.3.2 Method

If we consider a single acoustical source of RMS level P_{src} at distance $r_{ref} = 1\,\mathrm{m}$, the theoretically received RMS level P_n at the n-th SA station is simply given by:

$$\mathrm{P}_n = 2\,\frac{r_{ref}}{r_n}\sqrt{\frac{\rho_0(z)}{\rho_0(0)}}\exp\left(-\alpha r_n\right)\mathrm{P}_{src}, \quad (5)$$

with r_n the distance between the source and the n-th receiver. Then, the RMS levels of all the sources received at the same time are quadratically summed to get the envelope. Both this envelope and the one obtained from the measured signal are re-sampled at the same frequency, to be comparable with the same temporal basis. As we do not model the variability of the propagation conditions, we manually time-shift the estimated envelope to best fit the measured one. These envelopes are represented on Fig. 3 for recordings at array AA and four out of the eight microphones SA.

We observe that the predicted and measured RMS pressure envelopes have very similar shapes and values. The first strong peak is visible at each sensor and is also well estimated by the retro-propagation model. We obtain a very good agreement for the peak pressure amplitude, its width and its decay. It confirms the fact that most of the acoustic energy was emitted by the bottom of this lightning as shown on Fig. 2. Note however the measured

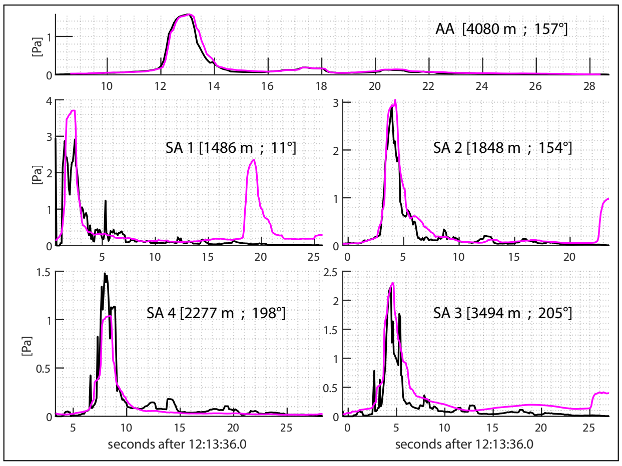

Figure 3. Estimated (black) and measured (magenta) RMS envelopes of event of September 17, 2018 at 12:13:36.079 UTC, at one microphone of the acoustical array (top, AA) and 4 out of the 8 isolated microphones (SA). The relative distance and azimuth of the flash to each sensor is annotated next to the sensor's name.

envelope may contain also other sound arrivals not correlated to the considered event, as shown by the secondary peaks around t_{LLS} +20 sec for SA 1 and +25 sec for SA 2 and SA 3. We also notice a peak on SA 1 at t_{LLS} +5 sec which is predicted but not measured. It can be justified by several possible reasons: (i) we only sum amplitudes, without access to a temporal form of the emitted sound, (ii) the sensor is at 1486 m from the LLS position, so in the range where near-field variability due to return stroke tortuosity can be significant [14], (iii) the propagation is very simplified and does not take into account the influence of wind or temperature variations.

3. DISCUSSION

During SOP1 and EXAEDRE campaigns, four thunderstorms were studied, for a total of 78 flashes. Each of these 78 events was acoustically reconstructed and the total power of all its sources was estimated as described in section 2.2. We observe that, put on a logarithmic scale on Fig. 4, the distribution of the total acoustical power of these events is centered on 1 MW, and spans 4 orders of magnitude, from 10.6 kW to 165 MW. This variability is similar to the one observed for optical and electromagnetic data [15–17], and extends the previously estimated ranges [5, 6, 18]. The causes of these variations remain to be explored, to determine whether they are due to the acoustic propagation, the source model or some other physical parameters (as the current, charge or temperature of the channel...). The heterogeneity between the acoustical sources of a single flash also contradicts the common assumption of a homogeneous distribution of injected energy in the lightning channel that is used for thunder models [14, 18–20]. This observed heterogeneity also needs further investigation, to give it a quantification and a physical explanation.

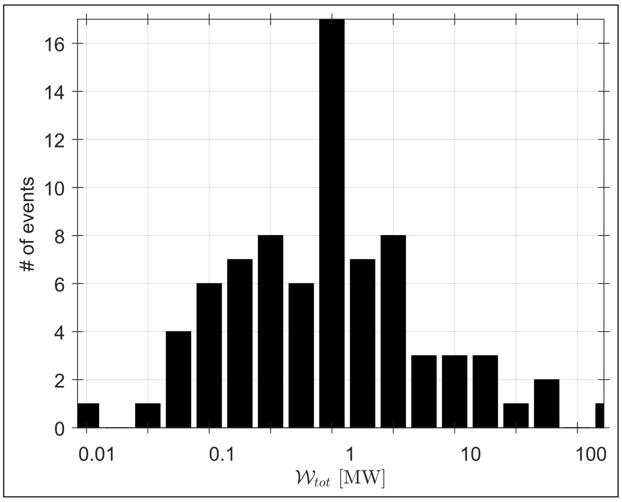

Figure 4. Distribution of total acoustical power $\mathcal{W}_{tot}$ for the 78 events.

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