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Compensation of integrator time constants for electric field measurements

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ABSTRACT

Rubinstein et al. (2012) [1] examined a method to compare electric fields from lightning discharges measured with analogue integrators of different time constants. The time constant distorts the waveforms and has to be corrected numerically. We have extended the work of Rubinstein et al. (2012) [1] by considering the antenna characteristics in the system equations. In this paper we focus on the compensation of the integrators time constant and present some cases and results after applying the method. Furthermore we discuss the importance of any existing offset errors. A simple approach for handling the offset will be presented. Examples and determination of continuing currents are given in section IV. Advantages of the compensation method are mentioned in the conclusion. Together with Appendix A (system equations) this paper can be seen as a reference to a profound understanding of the measurement methods of E-fields with flat plate antennas for lightning researchers.

1. Introduction

Lightning electromagnetic fields (E-fields) are often measured with so called flat plate antennas whose output signal (current) is proportional to the derivative of the field. Active or passive circuits with integrating behavior are used to partially reconstruct the waveform of the E-field. Depending on the *RC* time constant, where *R* and *C* are resistor and capacitor parameters of the corresponding integrator circuit (see Appendix A), the resulting fields are called slow E-field (E-slow) or fast E-field (E-fast).

Recently Rubinstein et al. [1] presented a method to transfer electromagnetic fields measured with an *RC* time constant τ_1 to a theoretical time constant τ_2. This gives the possibility to compare electromagnetic fields measured with different resistor and capacitor values. In the paper of Rubinstein et al. [1] the transfer mainly applies to different integrator time constants, with the outlook to a theoretical transition of $\tau \to \infty$ ([1], Eq. (13)), which completely removes a decay time constant from the signal (ideal integrator). In this paper we will extend this method by the characteristics of the antenna, which mainly influence the gain of the system. If two systems with different characteristics (antenna diameters and time constants) are considered, there are two possible ways to approach a comparison of the two systems.

One way is to transfer the Laplace-domain system transfer function from the system with the faster time constant to the one with slower time constant (as it is done in Rubinstein et al. [1]). The waveform resulting from the convolution of the time-domain representation of this transfer function with the measured E-field of the fast system then should look similar to the waveform measured with the slow system. That makes the systems comparable. We call this method “E-field Transfer”.

The other method is a compensation, where for the system transfer function $H(s)$ with $u_o(s) = E(s)H(s)$, the time-domain representation of $1/H(s)$ has to be determined and convolved with $u_o(t)$. $E(s)$ is the electric field strength which shall be measured with the antenna and $u_o(s)$ is the output voltage of the amplifier. If applied to both, E-fast and E-slow, the resulting waveforms after the convolution should be identical, representing the unbiased E-field. We call this method “E-field Compensation”.

Lightning electromagnetic fields compensated for time constant are often used to determine the continuing current of a return stroke [2–5]. Normally so called “slow” antennas (antennas with a time constant greater than 1 s) are used and the resulting field is then “compensated” for the time constant by a “graphical” method [6,7].

It is the goal of this paper to show that so called fast E-field data (measured with integrators with a small time constant, e.g., 0.5 ms) can also be used to determine continuing currents as with

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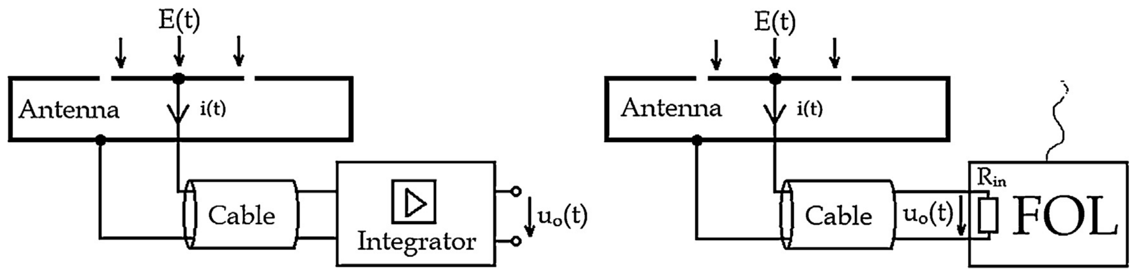
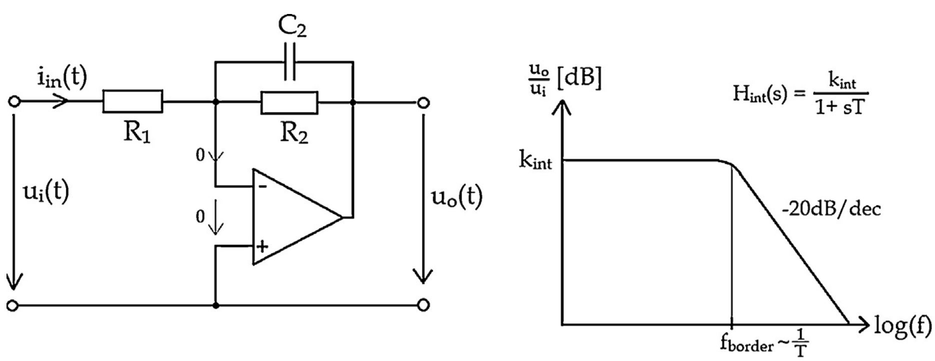


a Plate antenna attached to an active integrator circuit

b Plate antenna directly attached to a fiber optic link (FOL) or oscilloscope with an input impedance (passive integrator)

Fig. 1. Active and passive amplifier configurations.



a first-order-low-pass circuit

b frequency behavior with border frequency f_{border}

Fig. 2. Integrator (first-order-low-pass).

slow E-fields. The compensation of E-fast is faster and continuous compared to the "graphical convolution" [7] of the E-field data measured with "slow" antennas, where a step-by-step correction was performed.

In this paper we will first describe the different systems (with their corresponding differential equations, Section 2) that are used to measure the electric field of the lightning discharge and we will introduce the system compensation functions (Section 3). We further show some results and present our conclusions (Sections 4 and 5). Especially the compensation method considering the antenna characteristics and offset error treatment could improve and simplify future lightning measurements with plate antennas.

2. System transfer functions

As already mentioned in the introduction it is possible to integrate the measured $\mathrm{d}E(t)/\mathrm{d}t$ of the antenna output with an active or passive circuit.

The main characteristics of the active integrating circuit are an amplifier-specific gain k and a time constant τ which makes it stable (in the literature known as a first-order-low-pass). As for the passive integrator the time constant is given naturally, defined by the antenna capacity (including the cable capacity) and input impedance of the connected device, which can be a fiber optic link or an oscilloscope for example. Fig. 1a and b shows the schematics of these two measurement arrangements.

In the following considerations, we use parameters that are described in more detail in Appendix A. These parameters are the antenna capacity C_{ant} (which includes the cable capacity C_{cable}), the antenna plate surface A (see Fig. 9 and Eq. (A-1)) and the vacuum permittivity ε_0. For the active integrator, the additional parameters are depicted in Fig. 2a. While C_{ant} is quite unimportant for the frequency behavior in the bandwidth of interest (upper frequency limit of about 1–2 MHz) when measuring with the active amplifier, it is dominant for the frequency characteristic and amplification of the passive system. Hence, in that case, precise knowledge of C_{ant} (especially C_{cable}) and R_{in} is of utmost importance.

Eq. (II-1) is the corresponding Laplace-domain transfer function from the E-field $E(s)$ to the output voltage $u_{\mathrm{o}}(s)$ of the active integrator, shown in Fig. 2. The detailed derivation of this system equation is shown in Appendix A.

$$H_{\mathrm{int}}(s) = \frac{u_{\mathrm{o}}(s)}{E(s)} = s\frac{k_{\mathrm{ant}}}{1+s\,\tau_{\mathrm{ant}}}\,\frac{-k_{\mathrm{int}}}{(1/\tau_{\mathrm{int}})+s} \tag{II-1}$$

where $k_{\mathrm{ant}} = R_1\,\varepsilon_0\,A$, $k_{\mathrm{int}} = 1/(R_1\,C_2)$, $\tau_{\mathrm{ant}} = R_1\,C_{\mathrm{ant}}$ and $\tau_{\mathrm{int}} = R_2\,C_2$.

The subindices 'int' and 'ant' denote 'integrator' and 'antenna'.

Within a certain frequency range, $H_{\mathrm{int}}(s)$ is not frequency-dependent.

$$H_{\mathrm{int}}(s) = \mathrm{cf} = -\frac{\varepsilon_0 A}{C_2} = \mathrm{const.},\ \text{when}\ f_{\mathrm{low}} < f < f_{\mathrm{high}} \tag{II-2}$$

'cf' means 'calibration factor', which can be seen in the bode plot in Appendix A.

For the passive integrator (Fig. 1b) the corresponding transfer function is given in Eq. (II-3) and the derivation of that system equation is also given in the Appendix A.

$$H_{\mathrm{pi}}(s) = \frac{E(s)}{u_{\mathrm{o}}(s)} = s\frac{k_{\mathrm{pi}}}{(1/\tau_{\mathrm{pi}})+s} \tag{II-3}$$

where $k_{\mathrm{pi}} = \varepsilon_0 A/C_{\mathrm{ant}}$ and $\tau_{\mathrm{pi}} = R_{\mathrm{in}} C_{\mathrm{ant}}$.

The subindex 'pi' stands for 'passive integrator'.

The next section (3) presents a method, how the recorded E-field waveforms (that are distorted due to Eqs. (II-1) and (II-3) with their time constants τ_{int} and τ_{pi}) can be corrected in the time-domain. This method is called 'compensation', as already mentioned in Section 1.