EFFECT OF PROPAGATION PATH CHARACTERISTICS ON LOW-FREQUENCY CLOUD-TO-GROUND LIGHTNING SIGNAL PARAMETERS.

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ABSTRACT

This work explores the effect of propagation-path characteristics (electrical conductivity of the soil (σ) and propagation distance (d)) on cloud-to-ground (CG) lightning waveform parameters (rise-time and peak amplitude). The ground wave electromagnetic field propagates long distances (100's of km) over finitely-conductivity soil and can be detected by remote ground-based lightning sensors which respond to the vertical electric field (horizontal magnetic field) component of the resulting waveform.

This work has lead to a key insight regarding ground-wave propagation of electromagnetic waves produced by CG lightning. The behavior of waveform parameters (rise-time and amplitude attenuation) as a function of propagation distance (or equivalently, changes in electrical conductivity) is primarily determined by the duration (width) of the initial waveform pulse. This has lead to the inference that the first strokes in CG lightning (which have the widest initial pulse) exhibit the greatest variation in rise-time as a function of distance or conductivity. Conversely, subsequent strokes (which have the narrowest initial pulse) exhibit the greatest attenuation of the field peak as a function of distance or conductivity. Since wider pulses have the greatest dependence of rise-time on the ratio d/σ, focusing on this sub-population should provide the most sensitive indication of changes in electrical conductivity.

Index Terms— electrical conductivity, propagation distance, rise-time, peak amplitude

1. INTRODUCTION

When lightning strikes the ground an electromagnetic field is produced. This field propagates long distances and can be detected by remote ground-based lightning sensors, which respond to the vertical electric field and/or horizontal magnetic field. The ground-wave propagation of electromagnetic fields over finite-conductivity soil serves as a low pass filter whose cutoff frequency is determined by the ratio d/σ. The ground-wave components of electromagnetic fields produced by CG lightning strikes include significant energy in the low-frequency (~30-300 kHz) pass-band range of this "filter." The parameterized waveform shapes of these fields vary with the propagation characteristics of the path.

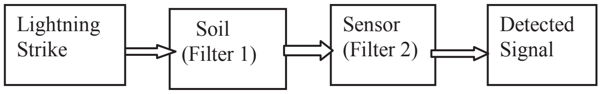

Figure 1. Block Diagram

Much of the work describing the effect of propagation on lightning electromagnetic fields has been summarized by Cooray [2], who found that various approximate theories were close to those of the exact theory put forward by Sommerfeld [11] and Wait [10]. From these approximate theories, Cooray's approximation #2 is used in our work, which computes the propagated electric field at any point above a flat earth (see also Norton [5]). The validity of the approximation in the mathematical model is further described by Cooray [1]. It is shown that the mathematical model predicts the propagation effects accurately. In [3], Cooray et al. evaluated propagation effects on radiation fields for a few types of lightning strokes. It is shown that the width of the initial peak also effects the attenuation of the electromagnetic field due to propagation over a finitely conducting and homogeneous medium. In their work the effect of the sensor was not considered; this effect is included in the analysis presented here (see Figure 1).

The work presented here focuses on the effect of propagation on strokes in negative cloud-to-ground (CG) flashes. Rakov and Uman [4] describe the various types of lightning discharges in great detail. In [8], these same authors provide a statistical analysis of the peak amplitude of electric field for the different types of lightning strokes. Our long-term objective is to employ measured changes in electrical conductivity to infer changes in soil moisture. Archie [9] provides a simple parametric model of the relationship between soil electrical conductivity and soil moisture.

2. PROPAGATION MODEL

The CG lightning flash injects charge along a channel between the cloud and ground. The removal of this charge after connection to the ground produces a rapidly changing current in the channel that creates an electromagnetic field. The radiation field, which consists of several frequency components, can propagate long distances along the ground. In this section, the ground-wave propagation model is discussed. The mathematical equations used to model the propagation effects, represented as the frequency response of the ground-wave propagation path, are provided in [1]. This frequency response $G(\omega,\sigma,d)$, is a function of the propagation (d) and the electrical conductivity (σ) of the propagation path., given by :

$$G(\omega,\sigma,d)=1+i\cdot\left[\left[\sqrt{\frac{4\pi\cdot\xi(\omega,d,\sigma)}{\left(1-\lambda(\omega,d,\sigma)\right)^2}}\right]\exp\left[\frac{-4\cdot\xi(\omega,d,\sigma)}{\left(1-\lambda(\omega,d,\sigma)\right)^2}\right]\right]\cdot erfc\left[-i\cdot\sqrt{\frac{4\cdot\xi(\omega,d,\sigma)}{\left(1-\lambda(\omega,d,\sigma)\right)^2}}\right] \quad [2.1]$$

$$\xi(\omega,d,\sigma)=\frac{\omega\cdot d\cdot U^2(\omega,\sigma)\cdot i}{2c} \quad [2.2]$$

$$U^2(\omega,\sigma)=\frac{i\omega}{i\omega\varepsilon-\mu_0\sigma c^2} \quad [2.3]$$

$$\lambda(\omega,d,\sigma)=\frac{U(\omega,\sigma)-\frac{z}{d}}{U(\omega,\sigma)+\frac{z}{d}}\,. \quad [2.4]$$

In the above equations *erfc* stands for the complementary error function, σ is the electrical conductivity of soil, *d* is the distance from the lightning strike to the sensor or the distance of propagation, *z* is the length of the channel that contributes to the radiation field, $c=2.998\times10^8$ m/s is the speed of light in free space, $\mu_0=4\cdot\pi\cdot10^{-7}$ H/m is the magnetic permeability of the soil, and $\varepsilon=k\cdot8.854\cdot10^{-12}$ is the permittivity of the soil , where k is the dielectric constant (set to 8 in our studies).

As explained in [3] the channel length (z) that contributes to the radiation field is less than a few hundred meters. The distance from the lightning strike to the sensor is on the order of tens to hundreds of kilometers, and is much greater than the channel length. As shown by Cooray [1] approximating the length of the channel to be zero in [2.4] does not introduce significant errors in the model. Using the above approximation and the results derived by Wait [10], Cooray's approximation #2 in [2] predicts that the propagation effects depend on the parameter *d*/σ.

As seen in Section 1, the "total" system is comprised of the ground propagation path and the sensor. In our case, the sensor includes a four-pole Bessel low-pass filter. To understand the interaction between the signal and the system, the frequency response of the "total" system is studied. Figure 2 shows the frequency response of the entire system for various propagation path characteristics. There is very litter difference in frequency response for the higher conductivities because the behavior of the system is dominated by the band-limited sensor response.

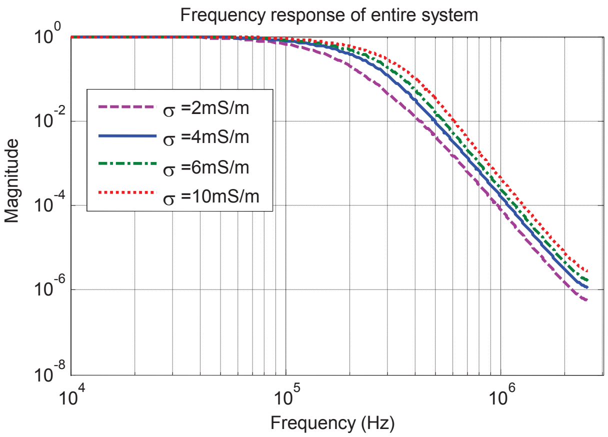

Figure 2. Magnitude of the frequency response of the entire system for a propagation distance of 100 km.

3. PROPAGATION OF LIGHTNING SIGNALS

The propagation effects on rise-time and peak amplitude for the different observed lightning strokes types are studied in this section. The lightning waveforms were measured using a research sensor that recorded the signals over a short distance to minimize propagation effects. These waveforms were then passed through the propagation model described in Section 2 to obtain the propagated signals for the different propagation distances and conductivities. Rise-time is defined as the time taken by the CG lightning stroke waveform to increase from 10% to 95% of its peak amplitude.

3.1. Negative first stroke

The negative first stroke is the first in a series of lightning strokes that comprise a negative flash. This stroke is typically characterized by a large duration, usually several microseconds, near the peak of the signal. It is also characterized by a rise-time of 3-8 microseconds.

Ground wave propagation significantly affects the rapidly varying part of the waveform (first few microseconds of the waveform). The negative first stroke waveform is passed through the propagation model described in Section 2 to obtain the propagated signal. The procedure is repeated for various distances with a ground conductivity of 10 mS/m to obtain the propagated signal as shown in Figure 3. The wide width of the signal after the peak allows the signal to rise to an amplitude close to its peak value, thereby allowing the rise-time to be strongly dependent on the propagation path.

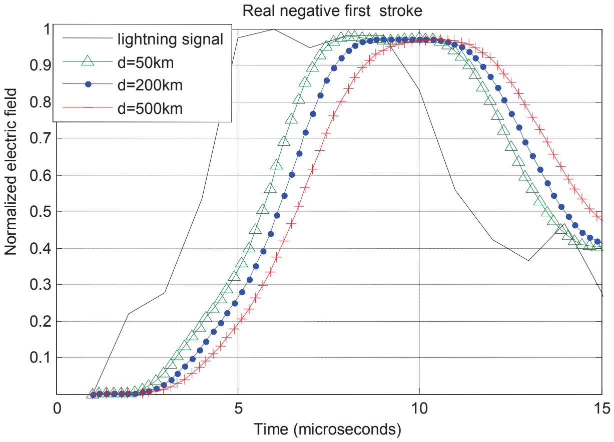

Figure 3. Real negative first stroke and its modeled propagated signals for various distances with a ground conductivity of 10mS/m.

As the distance of propagation increases (or equivalently, the conductivity of the propagation path decreases) the signal is also delayed in time.

3.2. Negative subsequent stroke

Negative subsequent strokes are strokes subsequent to the negative first stroke in a series of lightning strokes that comprise a negative flash. These strokes are typically characterized by a fast rising edge and narrow duration. Figure 4 clearly depicts the effect of propagation distance on peak amplitude for an observed negative subsequent stroke for a ground conductivity of 10 mS/m. It is clear negative subsequent strokes show a significant decrease of peak amplitude with increasing propagation distances. This is because negative subsequent stroke waveforms have a narrow duration, thus they have significant energy in the high frequencies. The propagation results in an increased attenuation of these high frequency components that causes a reduction of peak amplitude for the negative subsequent strokes. Regarding rise-time, the narrow duration of negative subsequent strokes causes these signals to fall before the rising edge of the propagated signals have manifested themselves completely. Hence for negative subsequent strokes, the increase in rise-time due to increase in propagation distance is not as significant as the decrease in peak amplitude.

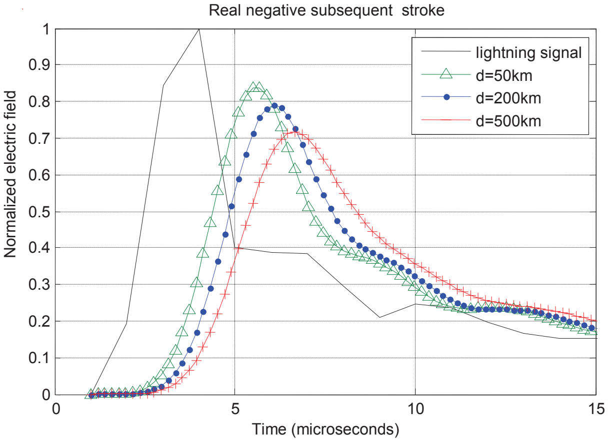

Figure 4. Real negative subsequent stroke and its modeled propagated signals for various distances with a ground conductivity of 10mS/m.

In Figure 5 the ratio *d*/σ is swept (from 5 km^2/S to150 km^2/S) and the corresponding rise-times are plotted for the two types of negative lightning strokes. It shows that negative first strokes (or long duration lightning signals) exhibit a more prominent rise-time variation as a function of *d*/σ.

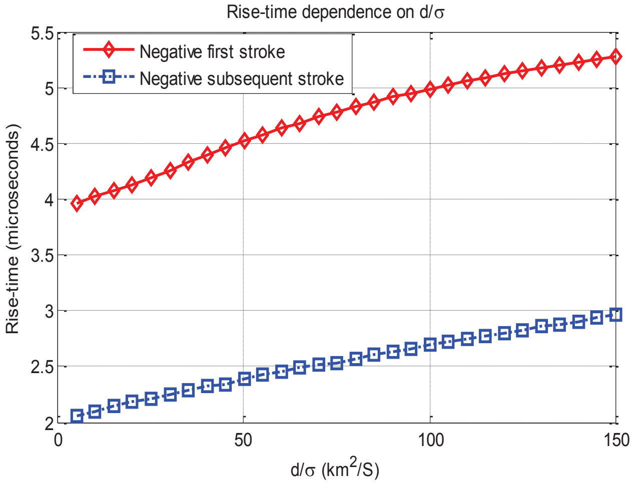

Figure 5. Rise-time variations with d/σ for a real negative first stroke and negative subsequent stroke.

In Figure 6 the ratio *d*/σ is swept (from 5 km^2/S to150 km^2/S) and the corresponding peak amplitudes are plotted for the two types of negative lightning strokes. It shows that negative subsequent strokes (or short duration lightning signals) exhibit a more prominent variation in peak amplitude as a function of *d*/σ.

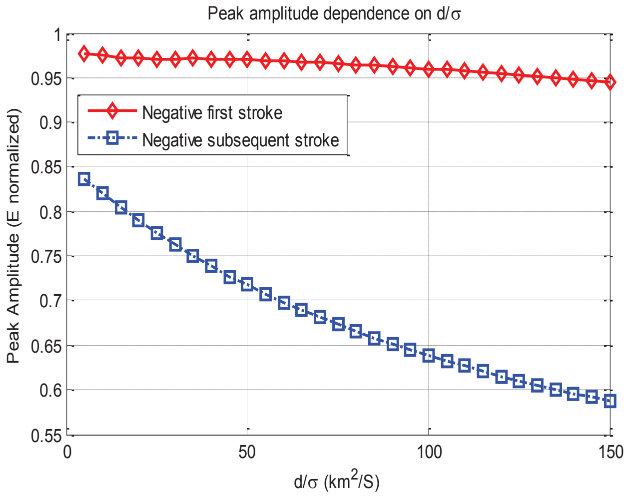

Figure 6. Peak Amplitude variations with d/σ for a real negative first stroke and negative subsequent stroke.

4. SUMMARY AND CONCLUSIONS

The effect of propagation on lightning waveform parameters was studied. The propagation model was briefly described. The low-pass filtering effect of the propagation path is characterized by the ratio of the distance of propagation to the electrical conductivity of the soil. As shown in Section 2 an increase in electrical conductivity of the soil or a decrease in propagation distance results in less attenuation of higher frequency components.

The waveform parameters – rise-time and peak amplitude – are a function of propagation path characteristics (distance of propagation, conductivity of ground) and are determined by the duration (width) of the initial portion of the waveform. Hence the waveform shapes must be carefully chosen for the analysis. As shown in Section 3.1 the wide width of the waveform after the peak for negative first strokes allows the waveform to rise to an amplitude close to its peak value, thereby allowing the rise-time to be strongly dependent on the propagation path. As shown in Section 3.2 negative subsequent stroke waveforms have a narrow duration, thus they have significant energy in the high frequencies. The propagation results in an increased attenuation of these high frequency components that causes a reduction of peak amplitude for the negative subsequent strokes. However, the increase in rise-time due to increase in propagation distance is not as significant because the narrow duration of negative subsequent strokes causes these signals to fall before the rising edge of the propagated signals have manifested themselves completely. This finding explains why in practice, negative first strokes have been shown to provide a better correlation between rise-time and conductivity than negative subsequent strokes.

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