Review of "Analysis of Lightning-Induced Currents in Supply Cable Shields and Their Impact on LLS Sensor Site Errors " by Kohlmann et al., initial draft Reviewer: Martin Murphy

The authors would like to thank Martin Murphy for his valuable review, positive remarks and constructive feedback. His comments and questions allowed to improve the paper.

The paper presents a very interesting "deep dive" into modeling the sources of angle and amplitude site errors at sensor sites in lightning locating systems. The modeling work here provides useful guidance in planning the layout of sensor sites with the goal of minimizing the errors in the first place. The paper is in good shape overall, although I do have some suggestions about clarifications, as follows:

equation 3 looks like it may have an error – it should have a "d" somewhere in it; otherwise, the exponential term is just a constant.

Indeed, thank you for the hint. The equation was corrected and was formulated more generally in terms of a depth "z".

line 214 vs lines 226-227: Yg is referred to as "impedance" in the first place, and "admittance" farther below.

Yes, it should have read 'admittance'. Corrected!

lines 267-268: "considering a channel-base current typical of subsequent return strokes, as depicted in Fig. 4" - should we assume that all calculations, even as far down as figures 11, 12, etc, are all done using a stroke peak current of 12 kA, given the words here about "as depicted in fig. 4"? Or does the stroke peak current ever vary in the calculations presented farther down?

Due to the linearity of the utilized equations throughout the whole paper, the peak current can be chosen arbitrarily. It could have been normalized to 1 (k)A. We have chosen this waveform because subsequent return stroke currents exhibit higher frequency content compared to first return strokes. The waveform exhibits a short rise time which can be affected by the ground parameters along the propagation path to obtain the fields at the sensor site that exhibit the desired characteristics. Scaling the channel-base current amplitude by a constant factor (for example in order to obtain different current- or field peaks) would not have affected the presented results based on ratios (i.e., angle and amplitude site errors). Figures showing absolute values for results of field and current (i.e., non-ratio values) are associated with the respective fields, as indicated in the figure captions.

The segment around lines 267 and 268 was adapted to point out more clearly that the amplitude was not varied throughout the paper:

This section presents the simulation results of lightning incident electric fields following the procedure described in Section 2.1, considering a channel-base current waveform that exhibits characteristics that are typical of subsequent return strokes (in particular, characterized by a short risetime), as depicted in Fig. 4. All results are obtained for a distance to the lightning discharge of 100 km. Due to the linearity and time-invariance of the equations utilized in this paper, the amplitude of the channel-base current was kept constant throughout all computations. Variations of the E-fields used as input for the coupling analyses were solely the result of the assumed ground parameters along the propagation path (see Fig. 7). The main results of this paper, namely the angle and amplitude site errors, are independent of the selected channel-base current amplitude; that is they are unaffected by any scaling of the waveform.

line 298: "ground conductivity values ranging from σp = 10-1 S/m to σp = 10-4 mS/m" That second unit of measurement should be S/m, I think, rather than mS/m. More generally, it might just make more sense to stick with one unit of measurement, whether mS/m or S/m, throughout the paper.
Thank you for the correction and suggestion. The unit of measurement has been standardized to S/m throughout the paper. To better highlight differences among several orders of magnitude, the values are now expressed using a common factor of 10^{-3}, replacing the previous use of "m". Ground

conductivities are therefore presented as coefficient multiplied by 10^{-3} S/m, for example: $50 \cdot 10^{-3}$ S/m, or $1 \cdot 10^{-3}$ S/m, or $0.01 \cdot 10^{-3}$ S/m.

lines 299-300: "(1) fields with shorter rise times (fast transients) tend to create larger Ex-field peaks, and (2) fast transients are better preserved over propagation path with high conductivity σp" – I think that I may have lost touch a bit: in figure 10a, I assume that the frequency content of the lightning signal is an issue indirectly, via the fact that higher values of σp attenuate the high-frequency content of the original signal less, as shown in figure 7 rather than figure 10a. Is my understanding correct, or have I missed something?

You understood it perfectly right! Thank you for pointing out the ambiguity of the sentence, it was indeed presenting the key aspect of Fig. 10 in a confusing way. Some information was added and some other info removed to that paragraph in order to point out the results of Fig. 10(a) more clearly:

As previously shown in Fig. 7, propagation over a highly conducting ground (ideally PEC) preserves the high-frequency content of the propagating fields. This results in incident fields exhibiting fast transients and corresponding short risetimes. In contrast, propagation over less conductive ground attenuates the high-frequency content and causes dispersion, leading to incident fields with slower transients and longer risetimes. Examination of Fig. 10a now reveals two key aspects. (1) fields with shorter rise times (fast transients) produce larger E_x-field peaks (as evidenced by the bold blue curve with the thin red curve at a given local ground conductivity σ_{loc}) and (2) low local ground conductivity produces large E_x-field peaks, whereas highly conductive local ground reduces the E_x-field peak significantly that eventually reaches zero for infinite ground conductivity σ_{loc} (PEC ground). A realistic scenario for a lightning EM field involves propagation over lossy ground with conductivity values σ_p between $0.1 \cdot 10^{-3}$ S/m and $10 \cdot 10^{-3}$ S/m over 100 km, resulting in incident fields similar to those shown in Fig. 7.

lines 365-368: it is worth pointing out that the sampling instant in question here applies only to the measurement of angle of arrival and peak amplitude, but the sampling of the arrival time is hardly affected because times of arrival are measured as close as possible to the start of the rising edge of the waveform, precisely to avoid the significant delay of the peak due to propagation effects.

Thank you for that comment. The following note was inserted between lines 366 and 367:

Note that the estimated time of arrival is not significantly affected by the addition of the $\vec{H}_{err}$ field, as it is determined as close as possible to the onset of the waveform's rising edge. Thus, the LLS location results obtained using the ToA technique remain unaffected by the phenomena illustrated in Fig. 13.

lines 404-414: discussion surrounding figure 15 appears to be on solid ground, but slightly confusing. In lines 407-408, "For a burial depth of 1.5 m, the angle site errors αerr decrease by only -8.5%, while the total reduction reaches -46%" you may want to clarify that the decrease of 8.5% addresses only the cable depth component, whereas the term "total reduction" is the combination of cable depth plus increased distance to the sensing antenna when the antenna is kept at 2 m above ground. It is also not exactly clear what is meant by "Thus, the contribution of the cable distance to the sensor remained practically the same, as expected" at the end of that section: In figure 15a, the combined total reduction actually appears to be about 3 degrees zero to peak, as opposed to the 1.3-degree reduction (3.07 vs 1.78) stated in the high-conductivity case.

Thank you for the comment. The paragraph was now split up into two parts, giving more explanation and reasoning behind the idea of recalculating the impact of the burial depth for a higher ground conductivity. Further, Scenario 1 (combined effect of ground attenuation + distance between the cable and the sensor) and Scenario 2 (accounting merely for the ground attenuation) are more explicitly described further above. The whole segment, including the bullet points of scenarios 1 and 2, now reads as follows, should now allow for a better reading flow and be much better interpretable:

We begin by examining the impact of the burial depth of the power supply cable on the site errors. The simulation results are presented in Fig. 15 and cover two distinct scenarios:

- *Scenario 1: As the burial depth increases, the distance between the cable to the sensor head also increases, reflecting the most realistic scenario. In this case, the site error reduction is influenced by a combined effect of increasing distance between the cable to the H-field sensor and the field attenuation by the ground (solid lines in Fig. 15).*
- *Scenario 2: The cable is buried at different depths, but the relative distance between the cable and the H-field sensor is kept constant at 2 meters. This scenario isolates the effect of ground attenuation from the distance effect, highlighting their distinct contribution. The impact of ground attenuation alone is shown in dashed lines in Fig. 15.*

The results presented in Fig. 15 were obtained for a local ground conductivity $\sigma_{loc} = 10 \cdot 10^{-3}$ S/m. They reveal a significant finding: The site errors are very strongly impacted by the (vertical) distance of the cable to the H-field sensor, as indicated by the solid-line curves. In contrast, the dashed-line curves, representing the scenario with a fixed 2-m distance, exhibit only a minor reduction in site errors with increasing burial depth. Specifically, at a burial depth of 1.5 m in Scenario 2, the angle site error α_{err} is reduced by only 8.5%. However, in Scenario 1, where the cable-to-sensor distance increases with burial depth, the reduction reaches 46%. This finding is consistent with results presented in Fig. 10b which suggests the same effect based on the attenuation caused by the ground penetration of the E_x-field for the assumed parameters. The amplitude site errors s_{err} exhibit a similar trend, decreasing by comparable amounts.

Next, the impact of a significantly higher local ground conductivity σ_{loc} is investigated. As shown previously in Fig. 10b, higher conductivity increases the attenuation of the illuminating Ex-field as it penetrates to ground. Additionally, Fig. 10a demonstrated that higher σ_{loc} leads to smaller site errors due to the reduced horizontal Ex-field illuminating the cable shield. To account for this effect, a new baseline angle site error was calculated for a cable placed at ground level (d = 0 m) and a sensor located 2 m above, assuming a value for the local ground conductivity of $\sigma_{loc} = 50 \cdot 10^{-3}$ S/m. The angle site error in this case drops to 3.86°, compared to 7.5° for $\sigma_{loc} = 10 \cdot 10^{-3}$ S/m at an azimuth of 130°, for example. Using this new baseline angle site error, the impact of ground attenuation for a buried cable is re-evaluated. For Scenario 2 (only the effect of ground attenuation), the angle site error is reduced by 20% at a burial depth of d = 1.5 m, compared to just 8.5% for the lower conductivity case $\sigma_{loc} = 10 \cdot 10^{-3}$ S/m. In Scenario 1 (which includes both ground attenuation and increased distance to the sensor), the reduction reaches 54%, compared to 46% for $\sigma_{loc} = 10 \cdot 10^{-3}$ S/m.

Thus, while the attenuation-caused reduction is greater for higher σ_{loc} (20% vs. 8.5%), the dominant factor contributing to the total site error reduction in Scenario 1 remains the increased vertical distance between the sensor and the cable. It is important to note that these findings are independent of the significant overall decrease in site error of almost 50% (for $\sigma_{loc} = 50 \cdot 10^{-3}$ S/m in contrast to $\sigma_{loc} = 10 \cdot 10^{-3}$ S/m) that results directly from the reduced Ex-field strength at high local ground conductivity.

lines 470-489 make reference to “wave propagation effects” several times. This may be another place where I've lost touch with earlier sections of the paper. I see “wave propagation” in line 163, where it clearly appears to refer to the effects on the overall signal as it propagates long distances over lossy ground. Then again “wave propagation” appears in line 373, which is a reference to the vertical penetration of the Ex component and thus the induction of current on the cable. In lines 470-483, I think that the “wave propagation effects” refer to the vertical penetration part, but it's not entirely clear, at least not to me.

Thank you for the input. Indeed, the wave propagation effects mentioned in 163 with regard to Wait’s work is related to the propagation of electromagnetic fields (of arbitrary kind & polarization). The “wave propagation effects” appearing in line 373, in turn, relate to the *”propagation effects of the* *induced cable shield current wave" (*which result to pronounced reflections and resonances along long lines). *The whole sentence was now extended to highlight that fact:*

However, for very low ground conductivities (0.1·10^{-3} S/m and below, see Fig. 13c Fig. 13d), the induced current wave on the cable shield experiences minimal attenuation as it propagates along the shield. This leads to pronounced reflections and resonances along long lines.

The "wave propagation" occurring between lines 470 and 483 towards the end of the paper again relate to the coupled shield currents that propagate along the line as a travelling wave. This lack of information was addressed by adding the information to "wave propagation": *" propagation of the induced current wave on the cable shield".*