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CORRELATED CURRENT AND FAR FIELD RECORDS FROM LIGHTNING DISCHARGES TO THE GAISBERG TOWER

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Abstract - Simultaneous measurements of lightning current and associated radiated fields from tower lightning are of fundamental interest for various reasons in lightning research. These data can be used for the evaluation of return stroke models or to investigate the so called tower effect when lightning hits an elevated object [1].

In this paper we show first results of simultaneously measured far-field waveforms at a distance of 78.8 km together with the corresponding current pulses measured at the top of the instrumented Gaisberg tower in Austria. We have analyzed the E_p/I_p ratios separately for two distinct groups of current pulses observed at the tower, the so called α-pulses, which are superimposed on the initial continuing current and the β-pulses, which occur after the initial continuing current. It is generally accepted, that β-pulses are assumed to be most comparable to subsequent strokes in flashes to ground.

Based on the available experimental data we determined a field enhancement factor of 1.6 compared to the predicted transmission line model E_p/I_p ratio. This observation is comparable to results with triggered lightning data [2] and agrees with a calculated enhancement factor for an "electrically short tower" in [1]

1 INTRODUCTION

Lightning locating systems (LLS) infer the stroke peak currents from remotely measured peak fields. Model simulations predict enhancement of the radiated fields when lightning strikes elevated objects and the calculated enhancement is depending on tower height and current risetime [1].

The "Transmission Line Model" (TLM) proposed by Uman and McLain [3] is often used to infer peak currents from remote peak fields. First experimental evaluation of the TLM was done by Willett et al. [2] based on measured currents in rocket-triggered lightning, correlated two-dimensional return stroke speeds and electric field waveforms (at a distance of 5.15 km). Based on the TLM they calculated a stroke propagation speed significantly less than the speed of light but grater than the optically measured velocity and a modification of the TLM involving two return-stroke wave fronts and resulting in better agreement of the experimental data was suggested.

It is typically assumed that the current pulse injected at the tower top and the associated current pulses reflected at ground level propagate along the tower with speed of light c. For the Gaisberg tower with a height of 100 m the round-trip time is about 0.7 µs. In the case when this time is in the range of zero-to-peak rise time t_f of fast rising pulses we have to consider the Gaisberg tower as an "electrically tall" strike object ($t_f < h/c$). For current pulses with zero-to-peak rise time $t_f \gg h/c$, the Gaisberg tower is an electrically short strike object [1].

2 EXPERIMENT

On average about 50 lightning discharges are recorded at the Gaisberg tower annually and lightning currents are measured at the tower top since 1998 [4]. The overall current waveforms are measured at the base of the air terminals installed on the top of the tower with a current viewing resistor of 0.25 mΩ having a bandwidth of 0 Hz to 3.2 MHz. Digital filtering (Butterworth lowpass filter, 2nd order) with an upper frequency of 250 kHz and offset correction is applied to the current records before the lightning parameters (peak current, charge transfer, action integral) are determined. As typical for elevated objects, more than 90% of the flashes to the tower are upward initiated. The upward discharge starts with a so called initial continuing current (ICC), often superimposed by a number of more or less pronounced current pulses, called α-pulses. After the cessations of the ICC, one or more downward leader/upward return stroke sequences may occur – the associated current pulses are called β-pulses. Typically amplitudes of α-pulses are relatively small, a few kA only, while β-pulses have peaks mostly in the range above 5 kA and most comparable to subsequent strokes in natural downward lightning [5].

Recently we have installed a field measuring station for simultaneous recording of fast E-fields at a distance of about 80 km (far-field) from the Gaisberg tower (see Fig. 1). The vertical E-field is continuously measured with a flat plate antenna and a sampling rate of 5 MS/s. Data are temporary stored in a circular buffer for a period of several seconds and whenever a lightning current is measured at the top of the Gaisberg tower a trigger signal is sent to the E-field measurement site via the internet and the buffered data are transferred to the hard disk of the local PC. This method allows to capture and store only the short duration data sequences including the tower events, without overloading the recording system by the overall lightning activity. GPS time stamping of both records (tower current and E-field) assures straight forward correlation of the individual pulses from both data sets.

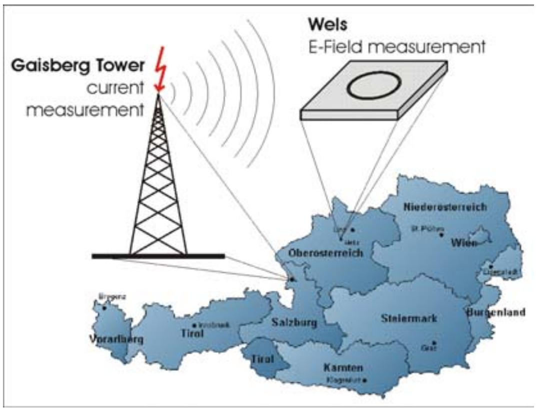

Fig. 1: Austria Map with Gaisberg location and E-field station in Wels (distance between Gaisberg tower and field measurement site is 78,8 km)

2.1 Enhancement factor of E-field measurement

As the fast antenna for the E-field measurement is placed on the flat roof of a multi-story office building the E-field records are suffering from local field enhancement due to the surrounding structure. Hence the measured fields from the tower strikes might be enhanced for two completely separate reasons:

(1) enhancement of the radiated field due to the presence of the elevated tower and

(2) enhancement of the measured field due to the location of the antenna on the roof of a building instead on the ground level.

In order to separate those two effects and to determine the enhancement factor of the E-field antenna without any influence of the tower effect we have recorded continuously lightning fields during storm activity at various distances from the fast antenna on June, 22nd, 2007. We assume that basically all these fields are from lightning striking ground level and therefore without any tower effects involved.

Based on data from the lightning location system ALDIS we have selected a set of 43 lightning strokes to ground that occurred at about the same distance from two of the sensors in the ALDIS network (sensor #1 and sensor #8) and from the E-field recording site in Wels (see Fig. 2). Both sensors used in this analysis are LS7000 type sensors that actually measure the peak magnetic fields which are directly related to the peak electric field for far field conditions.

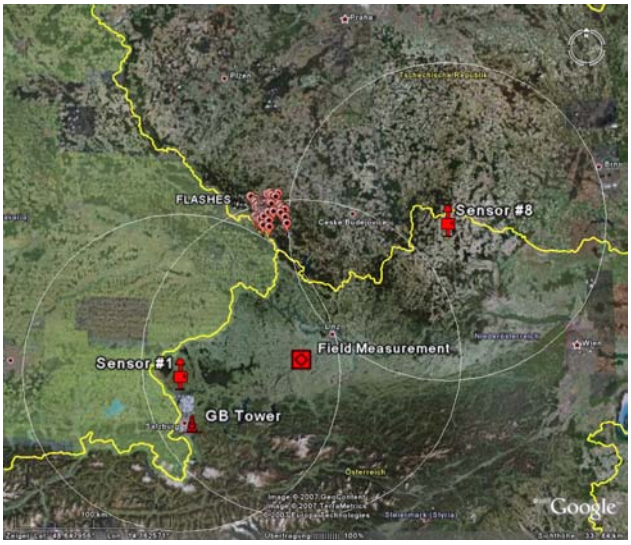

Fig. 2: Location of selected lightning flashes relative to ALDIS sensor #1 and sensor #8 and to the Field measurement site in Wels. Circles show 100 km distance range around the sensors and the field antenna.

Peak E-fields at ground level at the sensor sites are calculated from the sensor reported LLP Unites based on the correspondence between the LLP Units and the electric field given by the manufacturer in the form of

$$1158 \text{ LLP Units} \triangleq 52 \text{ V/m} \qquad (1)$$

By selecting this subset of strokes we tried to minimize the effect of peak attenuation due to field propagation over ground of finite conductivity, as all three peak measurements (2 sensors plus fast antenna) are done at

about the same distance from the source. When we assume similar attenuation of the field peaks to all three recording sites the ratio of range normalized field E_{Wels} (measured on the roof and enhanced by the building) divided by the sensor reported field peak should be independent of field attenuation and represent the building enhancement factor.

After range normalizing peak measurements of all three data sources (2 sensors plus fast antenna) to a distance of 100 km we determined for each stroke the enhancement factor of the fast antenna relative to sensor #1 and sensor #8, respectively, and results are plotted in Fig. 3.

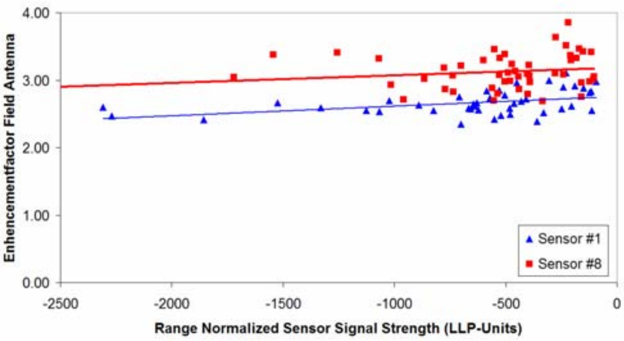

Fig. 3: Fast Antenna enhancement factor as a function of Range Normalized Signal Strength (RNSS) of 2 ALDIS sensors

The trend lines shown in Fig. 3 for the data of the two sensors indicate no dependency of the enhancement factor from the RNSS, but we observe a somewhat smaller enhancement factor (mean 2.7) from sensor #1 data than from sensor #8 data (mean 3.1).

The discrepancy in these two values is assumed to be the result of unequal signal attenuation along the propagation paths to sensor #1 and sensor #8 caused by differences in ground conductivity [6]. This observation contradicts to some extent our assumption of equal attenuation when selecting the stroke data. For the following analyses of measured fields at 80 km versus measured peak currents at the Gaisberg tower we assume an average antenna enhancement factor of 2.9.

In addition to the above discussed antenna enhancement we have to consider the effect of limited bandwidth of the ALDIS sensor. The sensor can be modeled as a Butterworth bandpass filter of 2nd order with a lower cutoff frequency of f_l=1 kHz and an upper cutoff frequency of f_u=350 kHz [7]. In a different project we have applyed such a 350 kHz bandpass filter to a set of field records measured with a fast antenna of the same type as used in Wels and this resulted in an average 30% reduction of the signal peaks of typical return stroke fields. Consequently the sensors actually report about 30% reduced field peaks compared to the fast antenna peaks and therefore the overall field enhacement factor of the fast E-field antenna in Wels reduces to 2.9*0.7=2.0.

3 DATA

Correlated current and field waveforms for a typical α-type current and a β-type current at the tower are shown in Fig. 4 and Fig. 5. In both records we can see the constant propagation time of 263 µs between the tower and the fast antenna site corresponding to the distance of 78.8 km and the speed of light.

In Fig. 6 we show the correlated current – field record of a very slow rising α-pulse (current waveform is similar to M-component currents in downward lightning). It is interesting to note that the ratio of I_p/E_p is close to 1 for the fast raising pulses in Fig. 4 (4.9 kA / 4.9 V/m) and Fig. 5 (13.8 kA / 14.4 V/m), whereas for the slow raising current pulse in Fig. 6 this ratio is 2.3 (1.4 kA / 0.6 V/m) and the time delay between current peak and field peak is 250 µs, about 10 µs smaller than in Fig. 4 and Fig. 5.

For the following analysis we have used correlated current – field record from 61 α-pulses (current was superimposed on the initial continuing current) and 16 β-pulses measured at the Gaisberg tower top.

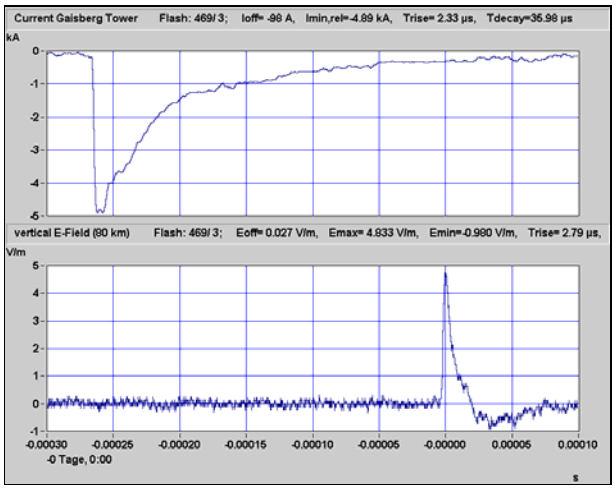

Fig. 4: Current and correlated E-field of a typical α-pulse (stroke #469-3) I_p = 4.9 kA, E_p=4.9 V/m

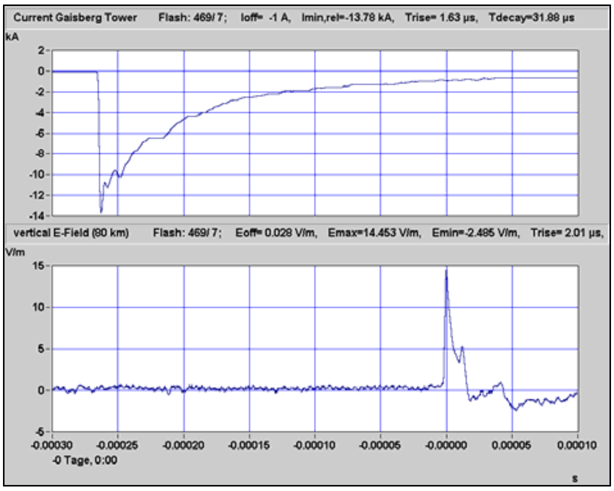

Fig. 5: Current and correlated E-field of a typical β-pulse (stroke #469-7) I_p= 13.8 kA, E_p=14.4 V/m

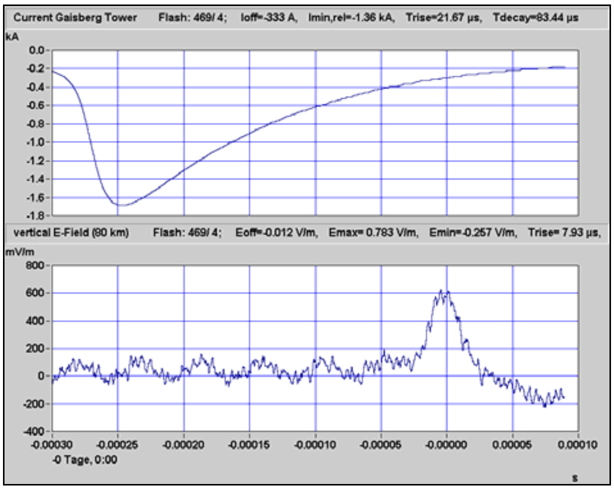

Fig. 6: Current and E-field of very low rising α-pulse (#469-4) I_p = 1.4 kA, E_p = 0.6 V/m

4 RESULTS

According to the transmission line (TL) model [8] the current peak I_p is related to the far-field peak E_p and to the return-stroke speed (assuming that v=const, the ground is perfectly conducting and no elevated strike object is involved) in the form of

$$I_p = \frac{2.\pi.\varepsilon_0.c^2.D}{v_{TL}}.E_p \qquad (2)$$

Considering the antenna enhancement factor of 2.0 for the measured peak fields at the remote site in Wels, we can determine from the measured fields the radiated peak electric field in V/m for the tower strokes at a distance of 78.8 km from the tower.

Assuming validity of the TL model for the first few microseconds the experimentally measured E-field peaks are basically affected by two unknown parameters, (1) the return stroke velocity v_{TL} being typically in the range from $1x10^8$ to $1.5x10^8$ m/s [9] and (2) the tower enhancement effect, which itself depends on the rise time t_f of the current pulse.

Assuming in a first step a negligible tower effect and no peak attenuation due to finite ground conductivity (results in a pure 1/R distance dependency of the radiated field) we have calculated the transmission line return stroke velocity v_{TL} from the measured E_p and I_p for the correlated tower current pulses using Eq.(2). In Fig. 7 we have plotted the resulting v_{TL} as a function of measured peak current for α- and β-pulses, respectively. We determine a mean value for $v_{TL} = 2.4x10^8$ m/s for α-pulses and $v_{TL} = 2.3x10^8$ m/s for β-pulses, respectively. Obviously there is no significant difference between α- and β-pulses, although some of the α-pulses have significantly longer current rise times than β-pulses and hence we would expect to see more likely any tower enhancement effect for the faster raising β-pulses. On the other hand these calculated values of v_{TL} are significantly higher then typically measured return stroke velocities in natural and triggered lightning [9]. We have to note that for some pulses, mostly α-pulses with small peak current, the calculated v_{TL} even exceeds 3.10^8 m/s, the speed of light, which is physically unrealistic.

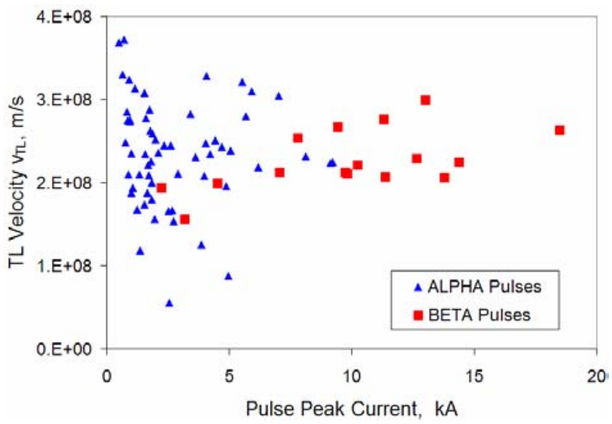

Fig. 7: Calculated transmission line velocity V_{TL} as a function of peak current

These results are indicating that there is also some field enhancement effect involved in the measured electric field peaks, which is caused by the tower effect. We can estimate a first approximation of the mean enhancement factor of the tower as the ratio of v_{TL} = 2.4x10^8 m/s to an average return stroke velocity in the range of 1x10^8 to 1.5x10^8 m/s resulting in a tower enhancement factor in the range of 1.6 to 2.4.

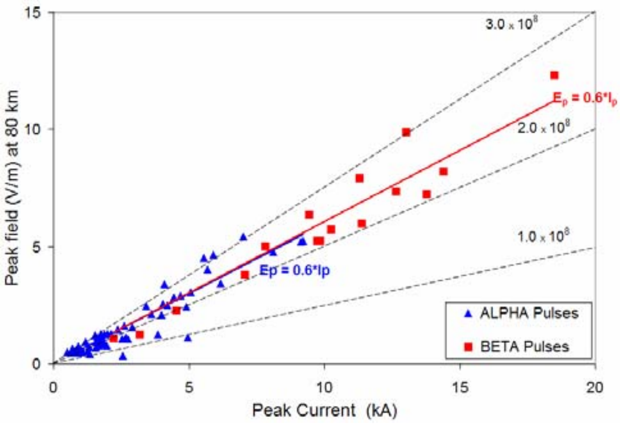

Fig. 8: E_p versus I_p for α- and β pulses with linear regression fit (fits are forced to go through origin). Dashed lines are TL model predictions for three different velocities

In Fig. 8 we have plotted the E_p values against I_p. Similar to Willett et al. [2] we have also drawn as dashed lines TL predictions for three velocities: 1.0x10^8 m/s, 2.0x10^8 m/s as upper bound of measured velocities and 3.0x10^8 m/s (the speed of light). Linear regression fit to the data has a slope of E_p = 0.6*I_p corresponding to a TL velocity of 2.4x10^8 m/s (see above) and a correlation coefficient R = 0.94 for α-pulses and R = 0.95 for β-pulses.

5 DISCUSSION

In case of an elevated strike object considering the tower effect, the peak radiated field is given by

$$E_p = \frac{v}{2.\pi.\varepsilon_0.c^2.D}.I_p.k \tag{3}$$

where k is the field enhancement factor of the tower. Bermudez et al. [1] derived for the factor k for "Tall strike objects" and electrically "Short strike objects" in the form of

$$k_{tall} = \frac{1+(1-2\rho_t).\frac{c}{v}}{1-\rho_t} \tag{4}$$

$$k_{short} = \frac{1+\frac{c}{v}.\rho_{ch-g}}{1+\rho_{ch-g}}\ , \tag{5}$$

$$\text{where} \quad \rho_{ch-g} = \frac{(Z_{ch}-Z_g)}{(Z_{ch}+Z_g)} \tag{6}$$

and where ρ_t is the reflection coefficient at the tower top (impedance discontinuity between tower and lightning channel) and ρ_{ch-g} is the reflection coefficient at ground without any tower (impedance discontinuity between ground and lightning channel).

We can assume for the Gaisberg tower a very low grounding impedance ($Z_g \simeq 0$), as over the years of operation of this radio tower extensive grounding measures were taken all over the area of the tower fundaments and the adjacent building. In this case $\rho_{ch-g} \simeq 1$ and k_{short} becomes equal to (1+c/v)/2. For a return stroke speed v=c/2, the enhancement factor k_{short} becomes equal to 1.5 and is very close to the ratio of 1.6 when we divide the above estimated return stroke velocity of 2.4x10^8 m/s (Fig. 8) by an average of optically measured velocities of 1.5x10^8 m/s.

Our results are similar to the observations by Willett et al. [2]. Their calculated v_{TLM} based on the E_p versus I_p ratio is higher than the average of streak camera measured return stroke velocities. As we do not see any significant differences in the E_p/I_p ratios for the α- and β-pulses, we conclude that we can consider the Gaisberg tower in any case as an electrical short object.

As there is some uncertainty in the way we had to determine the field enhancement factor of the fast antenna located at the roof of the building, more sophisticated calibration procedures of the remote field measurement seems appropriate to be done in the near future. On the other hand as we are dealing with sub microsecond effects (round trip propagation time along the 100 m tower is 0.7 µs) the effects of limited bandwidth of current records need a critical evaluation before drawing any final conclusions.

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