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EFFECTS OF FIELD PROPAGATION ON THE PEAK CURRENT ESTIMATES

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Abstract

Accuracy of peak currents inferred from peak magnetic fields is dependent on the attenuation of peak fields due to finite ground conductivity. In our presentation we will show significant differences in signal strength reduction caused by propagation paths of dissimilar conductivity over the Austrian territory. Comparing time correlated data from direct lightning peak current measurements from an instrumented tower at a minimum distance of about 70 km to a DF in the Austrian mountains reveals differences in range normalized signal strength of more than 50%. Attenuation models that are only distance dependent are not applicable to correct this effects observed in our location system. In this case, a distance and angle dependent attenuation model, accounting for the actual propagation path is required.

Based on the sensor data from the LLS we have determined for a grid of 10 km x 10 km an estimate for the ratio signal strength measured by the sensor to the mean of the range normalized signal strength of all sensors reporting a stroke. Contour plots of this ratio clearly show regions of significant differences in field propagation effects.

We also compare parameters from lightning fields (rise time and pulse width) measured with an identical experimental setup in Florida and in Austria. Differences found in this comparison are assumed to be mainly caused by the differences in ground conductivity.

1. Peak current estimates from lightning locating systems

The output of modern multiple-station lightning locating systems includes, besides striking coordinates, estimates of lightning peak current for each stroke in a flash. One of the major advantages of lightning locating systems is that the measurements are usually available for an entire year or even for several years, so that the sample size is large and different seasons and types of thunderstorms are included in the data base. Current peaks are determined from lightning peak fields measured by the system using the following semi-empirical equation.

$$i_p = 0.23 \cdot S_n \tag{1.1}$$

where i_p is the lightning peak current in kA and S_n is the mean of the signal strengths from the Direction Finder's (DF) participating in the location in LLP-units range-normalized to 100 km. LLP-units are directly proportional to the local electromagnetic field strength at the DF site. Signal range normalization assuming a 1/R distance dependency is exact only for propagation over ground of infinite conductivity. The coefficient 0.23 in Eq.(1.1) is the standard setting proposed by the manufacturer GAI for a high-gain network. A similar relationship between i_p and S_n was obtained, using Florida triggered-lightning data by Idone et al. [1993]. A plot of measured peak currents versus mean normalized signal strength S_n (in LLP units) for 56 triggered strokes was fitted by a regression equation

$$i_p = 4.2 + 0.17 \cdot S_n \tag{1.2}$$

with a correlation coefficient r = 0.88 and a standard deviation σ = 4.6 kA. It is important to note that this correlation is not based on any return-stroke model. The only assumption made is sufficient similarity of strokes in triggered lightning and first and subsequent strokes in natural lightning in terms of the relation between peak currents and peak fields.

Comparison of Eq. (1.1) and Eq. (1.2) shows, that the standard setting used by ALDIS gives a 25% higher peak current compared to the equation of Idone et al. [1993], when the intercept of 4.2 kA in Eq.(1.2) is neglected.

2. Location system data versus tower measurement

In 1997 and spring 1998 at an instrumented tower in southern Germany (Peissenberg) 8 flashes with 44 strokes (12 α and 32 β type impulse currents) having peak currents greater than 4 kA have been directly measured. All these discharges have been classified as upward lightning. In Zundl et. al [1996] α-pulses are defined as current pulses superimposed on a continuing current and β-pulses are starting from the zero current level. We found correlated reports from the Austrian Lightning Location System (ALDIS) for 35 of those 44 strokes. Discharges with peak currents of less than 4 kA were not included in this analysis, because these discharges are unlikely to be located by ALDIS due to the distance of the tower to the location network (see Fig. 1).

We found correlated lightning locations for 75% (9 out of 12) of the α-type impulse currents and for 81% (26 out of 32) for the β-type impulse currents. This indicates a better system stroke detection efficiency for β-components than for α components. β components are assumed to be more similar to subsequent strokes.

Details of the experimental setup used for direct peak current measurement at the Peissenberg Tower are described comprehensively in Fuchs [1998]. For this analysis we used the results of peak current measurement from the 200 kHz current transformer. Although the bandwidth is limited these data are available for all the strokes used for this study whereas integrated di/dt-values of current peaks from a high bandwidth di/dt sensor are only available for a small subset of these strokes.

The location of the Peissenberg tower and the sensor sites of the lightning location system in Austria are shown in Fig.1.

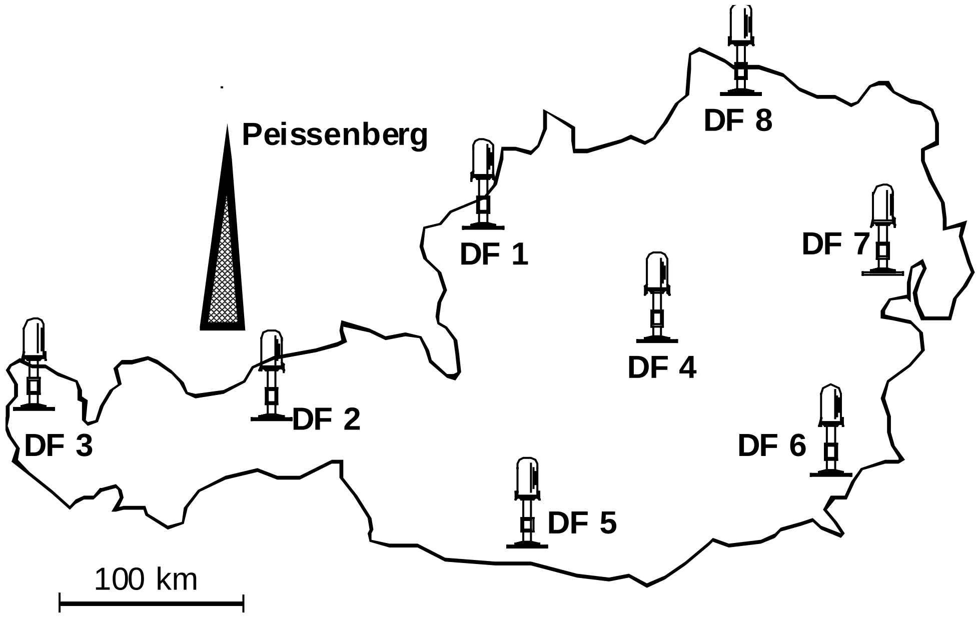


Fig. 1: Sites of IMPACT sensors in Austria and location of the Peissenberg tower

Distances of the three closest sensors to the instrumented tower are 72 km to DF 2, 110 km to DF 3 and 151 km to DF 1, respectively. The main features regarding detection efficiency for the correlated data are summarized in Table 1.

Table 1: Available DF reports for the directly measured strokes

	Directly measured peak current $I_p > 4$ kA for 44 strokes to the tower					
	12 α-type pulses			32 β-type pulses		
number of strokes	9	1	2	26	4	2
reported by	$\geq$2 DF	single DF	no DF	$\geq$ 2 DF	single DF	no DF

In Fig. 2 we have ploted peak current I_{ALDIS} as reported by the LLS versus directly measured stroke peak current I_{TOWER}. For these data, the linear correlation coefficient, r, is 0.974 and the linear regression equation is specified as

$$I_{ALDIS} = 1.13 * I_{TOWER} \tag{2.1}$$

when the regression line is forced to go through the origin.

A slope of 1.13 of the regression line in Fig.2 indicates that the LLS overestimates the peak current by about 13%. This is a somewhat surprising result when we compare the LLS median of peak current in Austria of -15 kA with the -30 kA median given by Berger et al [1975]. This difference was assumed to be more an indication of an underestimation of peak currents by the ALDIS location system than for a 13 % overestimation.

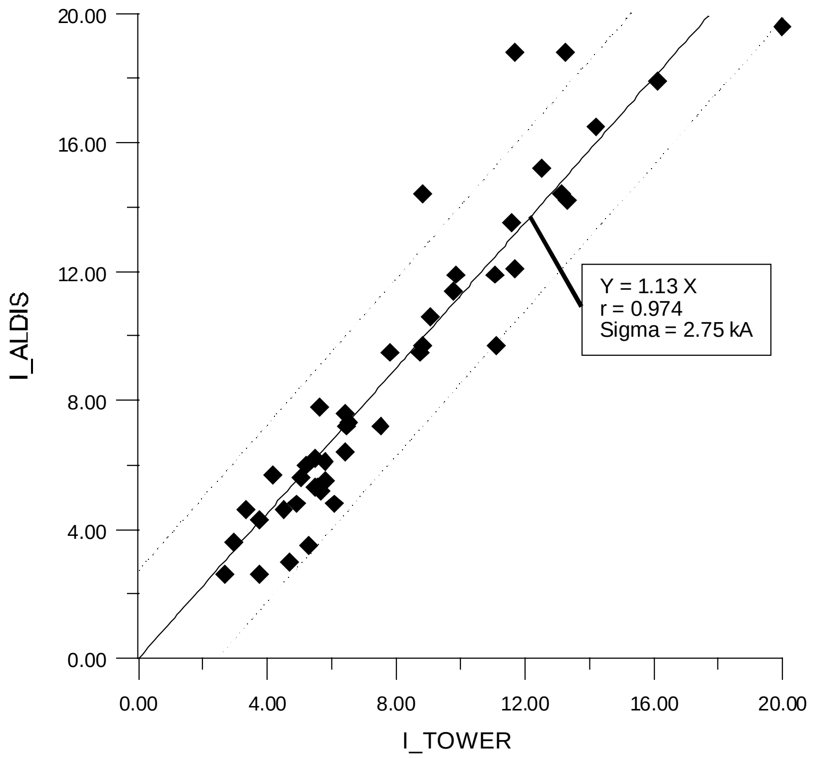


Fig. 2: Scatter plot of measured stroke peak current versus peak current reported by ALDIS (dashed lines represent the plus/minus sigma region)

2.1 Signal attenuation as a function of propagation path

The different steps to estimate a lightning peak current for a given stroke reported by 3 DF's are summarized in Table 3. This located stroke is time correlated to a tower lightning event at 6.Jan.1998, Time: 01:16:19.022, I_p=-11.6 kA (measured by the 200 kHz current transformer).

Table 3: DF reports and range normalized signal strength for a flash to the Peissenberg tower

DF - reports					
DF	Time	Angle	S_i [LLP-units]	$S_{i,100} = S_i * R_i / 100$	I_{DF}= 0,23* $S_{i,100}$ [kA]
2	01:16:19.0218691	313.8	-52.8	-38.0	-8.7
3	01:16:19.0219949	62.2	-71.2	-78.3	-18.0
1	01:16:19.0221335	259.7	-43.3	-65.4	-15.1

The stroke peak current is calculated by the LLS as the mean of all the available I_{DF} values and therefore

$$I_P = (-8.7 - 18.0 - 15.1)/3 = -13.9 \text{ kA} .$$

Although the directly measured peak current at the Peissenberg tower of -11.6kA and the peak current provided by the LLS are in good agreement, obviously signal attenuation causes significant differences in the peak current estimates based on the individual sensor signal strength reports being in the range from -8.7 kA for DF 2 to -18.0 kA for DF 3. Theoretically all I_{DF} values should be the same and equal to the measured peak current. This example clearly demonstrates the necessity to include signal attenuation effects for peak current estimates especially in regions of poor ground conductivity like some mountainous areas in Austria.

Although DF 2 is the sensor closest to the tower the range normalized signal strength with -38 LLP-units is only 58 % of the range normalized signal strength of DF 1 (-65 LLP-units). This result indicates significant attenuation of the lightning field pulses from the tower to DF 2. Propagation path from the tower to DF 2 is mainly over a mountainous area of limestone of low conductivity. Mountain top altitudes in this region are in the range of 2000 m - 2500 m above sea level.

Similar ratios of the DF signal strength have been observed for all the other strokes. In Fig. 3 we have ploted the regression lines for the range normalized signal strength for the three closest DF (DF1, DF2 and DF3 in Fig.1).

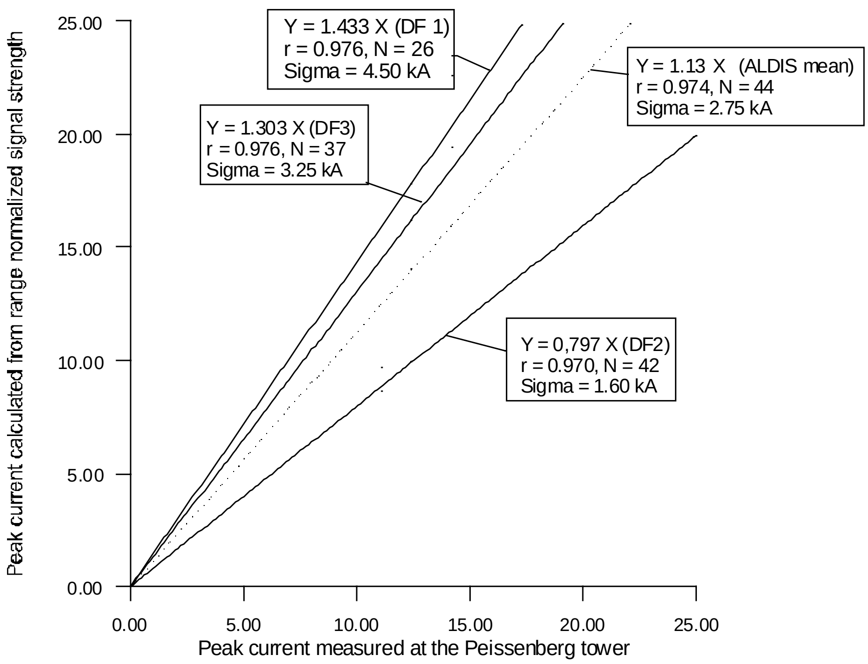


Fig. 3: Regression lines fitted to the range normalized data of the three closest DF of the Austrian network to the Peissenberg tower

With a slope of 0.797 signal peaks at DF2 are about 45 % lower than the normalized signals of DF1 with a slope of 1,43 in Fig 3. This indicates major differences in the field attenuation to the different sensors. Although the distance to DF1 is about twice the distance to DF 2 signals are much less attenuated than at DF2. These results also show that attenuation models for lightning location systems of the from of Eq.(2.2) that are only distance dependant [e.g. Idone et al., 1993] are not applicable in regions of inhomogenous ground conductivity like in Austria.

$$E_{100} = E_D \cdot \left(\frac{D}{100} \right)^{\beta} \tag{2.2}$$

2.2 Measured $(di/dt)_{max}$ values versus LLS-data

Values of $(di/dt)_{max}$ are available for 26 out of the 44 directly measured strokes. In Fig. 4 we have plotted $(di/dt)_{max}$ versus I_{max}. We determined a relatively strong linear correlation between these two parameters (r =0.79). FISHER et al. 1993 reported a similar correlation between S_{30} (30 % – 90 % average slope) and the peak current for triggered lightning.

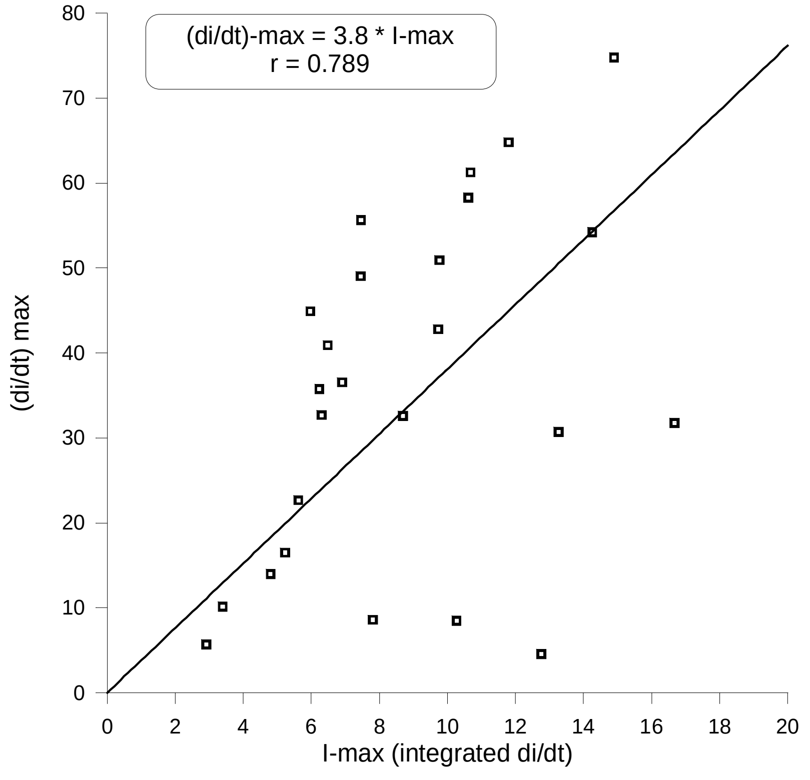


Fig. 4: Scatter plot and regression line for the peak current I_{max} in kA integrated from (di/dt) versus the maximum current derivative $(di/dt)_{max}$ in kA/µs.

2.3 DF reported rise times

In addition to the time and angle of incidence the Impact DF reports also a risetime value measured from threshold crossing to the peak. In Fig. 5 we have plotted the DF reported risetimes for the above mentioned 26 events.

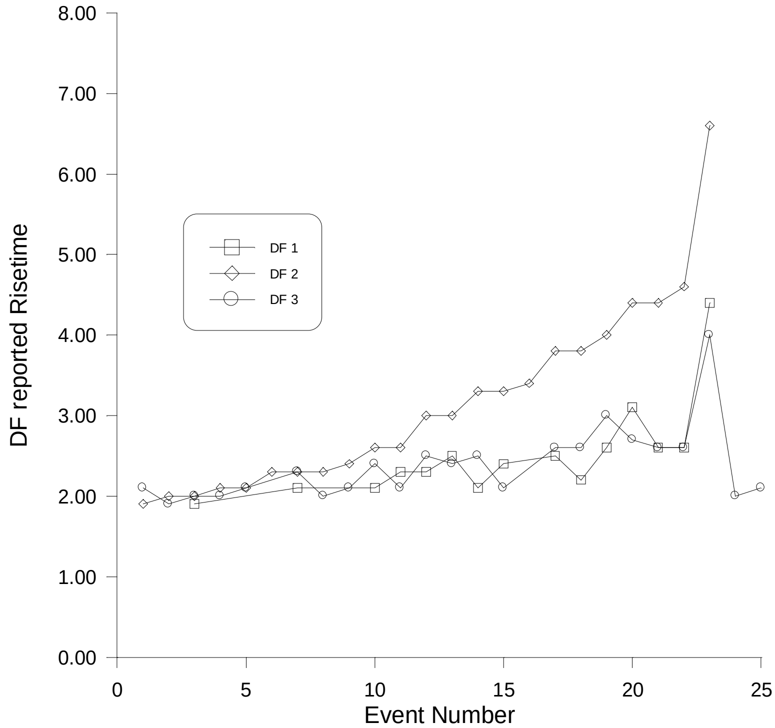


Fig. 5: Rise times reported by the DF close to the Peissenberg tower for 26 correlated events

Obviously DF2 reports significant higher risetimes than DF1 and DF3 due to a more pronounced attenuation of the field pulses.

3. Estimate of propagation effects over the Austrian territory

In Austria attenuation varies significantly depending on regional conditions and needs to be specified as a function of distance and angle. A first approach to estimate distance and angle dependent field attenuation is shown in Fig. 6. For a geographical grid of 10 km x 10 km we have calculated for each DF i the ratio

$$\gamma_i = \frac{E_{100,i}}{\overline{E_{100}}} \tag{1.3}$$

where $E_{100,i}$ is the range normalized field reported by the i-th sensor and $\overline{E_{100}}$ is the mean of all sensors reporting a stroke [Mair et al. 1998].

As an example a contour plot of this ratio γ_i for DF7 in the Austrian network is given in Fig. 6.

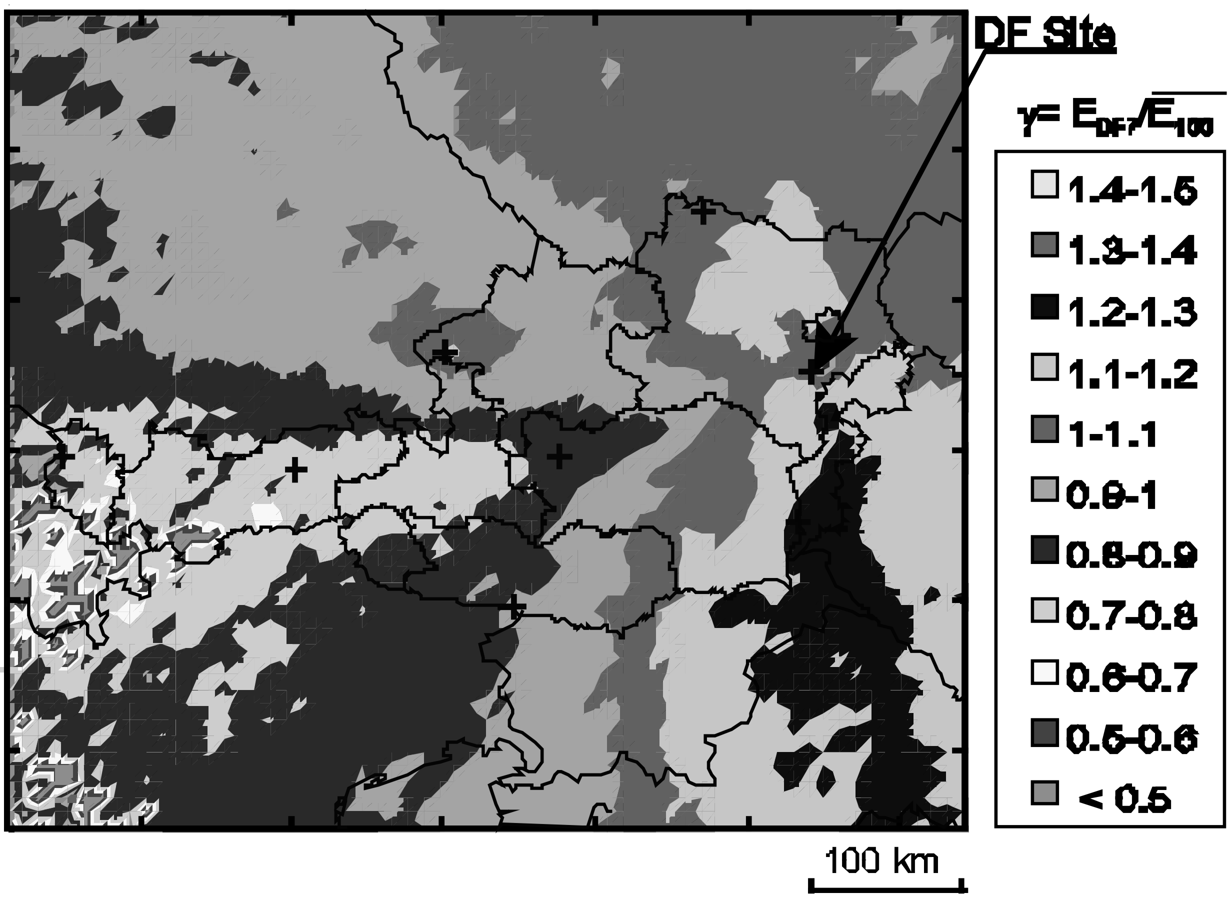


Fig. 6: Contour plot of the ratios γ_7 for DF 7 in the Austrian lightning location network ALDIS

In case of a purely distance dependent attenuation we would expect a pattern of more or less concentric circles. This is obviously not the case in Fig. 6 where we observe much lower ratios γ_i in the western direction than in all other directions. West direction correlates with the mountainous region in Austria.

4. Comparison of lightning field parameters in Austria and Florida

In summer 1996 we have measured lightning electric fields in Austria and Florida using a flat plate antenna. An overview of the experimental setup is shown in Fig. 7 and described in detail in Mair et al. 1996.

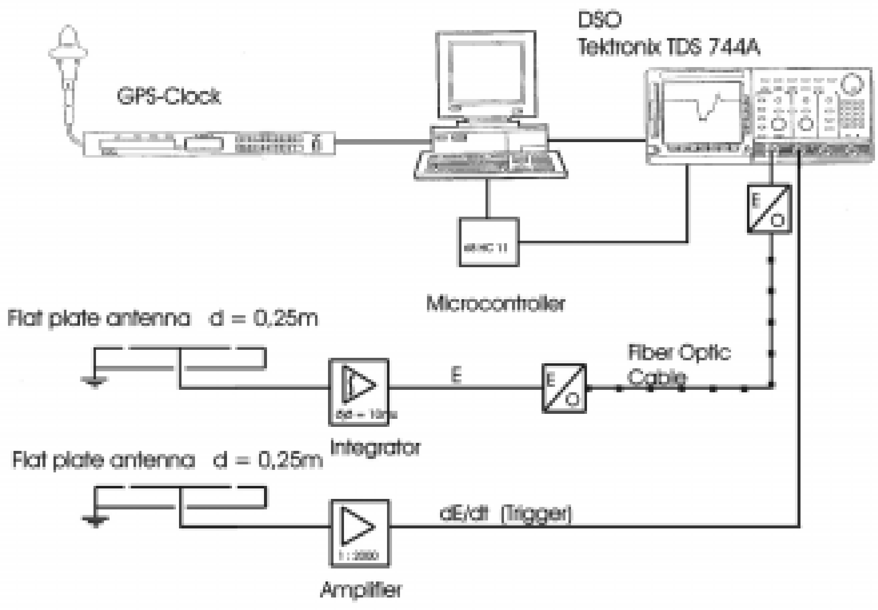


Fig. 7: Experimental setup used for field measurements in Austria and Florida

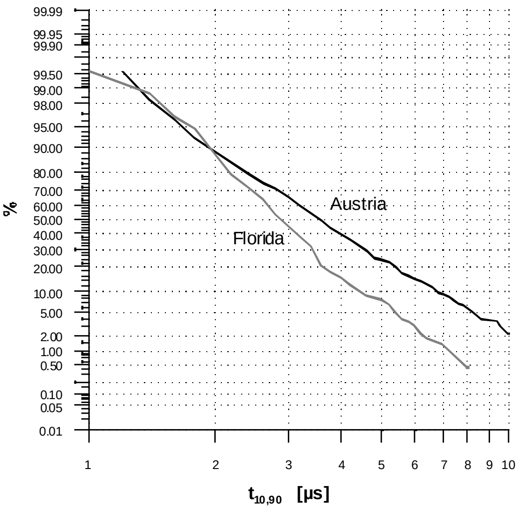
The overall bandwidth of the measuring system was increased to about 1 MHz compared to the system described in [Mair et al., 1996].

By correlating data from the NLDN in Florida and from ALDIS in Austria with the field measurements we have created a subsets of data for Austria and Florida specified as follows:

- only negative strokes are used
- GPS time correlated reports of the location system are available for the recorded lightning field pulses
- distinction between first and subsequent strokes is based on LLS reports.

Out of these data sets we have selected pairs of similar stroke data in Austria and Florida of the same distance (± 3 %) to the flat plate antenna and with the same peak current reported by the LLS (± 3 %). The following analysis are based on N = 233 pairs of first strokes and N = 233 pairs of subsequent strokes as specified above.

In Fig.8 and Fig.9 we show a comparison of the 10 – 90 % rise time of lightning field pulses in Austria and Florida for first strokes.



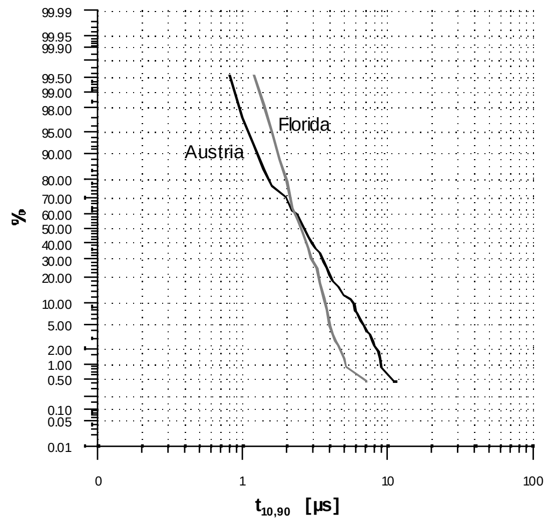
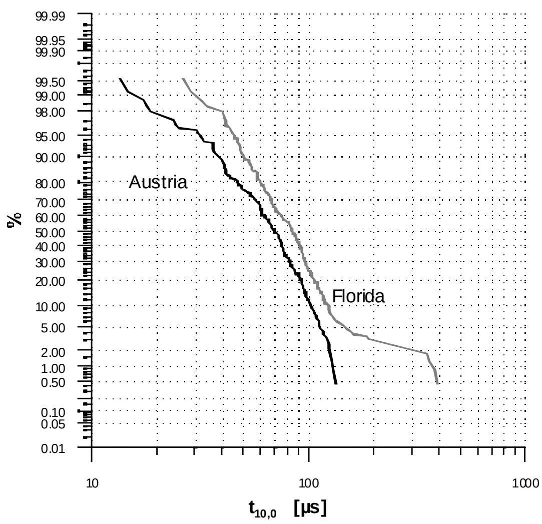


Fig.8: Rise times of first strokes in Austria and Florida

Fig.9: Rise times of subsequent strokes in Austria and Florida

The median of the ratio of rise-time of the first stroke data pairs is 1,2 indicating 20 % higher rise times in Austria than in Florida. The same analysis for subsequent strokes (Fig. 9) does not show any significant difference in the rise time ratio. Again this higher rise times in Austria are assumed to be mostly an effect of lower ground conductivity compared to Florida (see also Fig.5).

A similar analysis of the pulse width (10 % front value to zero crossing) is shown in Fig. 10 and Fig. 11 for first and subsequent strokes, respectively.



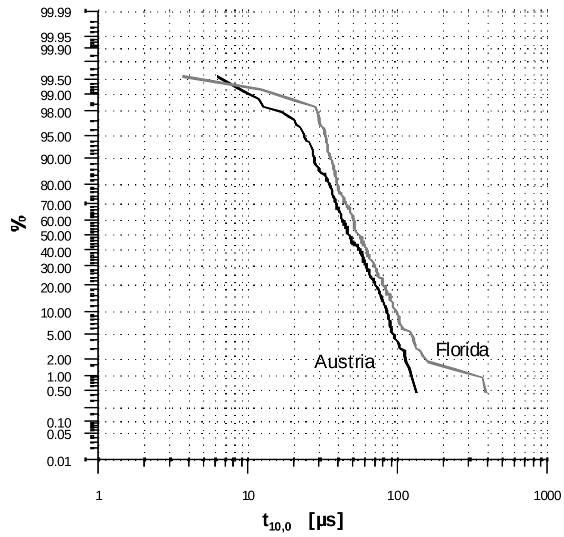


Fig.10: Pulse width of first strokes in Austria and Florida

Fig.11: Pulse width of subsequent strokes in Austria and Florida

Median of ratios of pulse width is 0,82 for first strokes and 0,88 for subsequent strokes indicating shorter pulse width in Austria than in Florida.

Detailed explanations of whether this differences in the characteristics of lightning fields in Austria and Florida are caused by differences in attenuation and/or by different physical conditions of the discharge (e.g. channel-length) are outside of the scope of this paper.

Summary and discussion

Comparison of directly measured peak currents at the Peissenberg tower with peak currents provided by the Austrian Lightning Detection System (ALDIS) revealed significant effects of signal attenuation. Because the most closest sensor shows the most pronounced signal attenuation these effect can not be corrected by a simple distance dependent attenuation model as proposed recently in literature and by the system manufacturer. In regions of inhomogeneous ground conductivity a more sophisticated model - distance and angle dependant is required.

Assuming insignificant attenuation for the field propagating from Peissenberg tower to DF 1 the data reveal an overestimate of peak current by about 40 % in regions of good ground conductivity when the default setup proposed by the manufacturer is used for the calculation of peak currents from the range normalized signal strength.

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