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# Correlation Between Some Current Parameters and Optical Radiation Generated by 280 mm Long Laboratory Sparks

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## ABSTRACT

In remote sensing of lightning and other discharge phenomena it is of interest to know the relationship between optical radiation and the current parameters. Unfortunately, little information is available in the literature on these relationships. In this paper we have studied, therefore, the optical radiation generated by 280 mm long laboratory discharges and its relationship to the current flowing in the discharge channel. In the experiment the optical radiation generated by the discharges was measured at wavelengths 777 nm (bandwidth 10 nm) due to O I(1), and 500 nm (bandwidth 5 nm) due to N II(19), and the broadband optical radiation between the wavelengths 400 - 1100 nm. The shape of the current waveform, which had a rise time of 0.1 µs and a decay time of 5 µs, remained the same with increasing peak value. The experiment was conducted with peak current amplitudes in the range of 1 - 4 kA. In order to test the effect of current rise time on the optical radiation we have also conducted studies with a current waveform having a 5 µs rise time. The main observations are the following: (a) The peak amplitude of the optical radiation pulse at the wavelengths mentioned above is proportional to the peak amplitude of the current flowing through the discharge channel. (b) The rise time of the optical radiation pulse at a given wavelength does not depend significantly on the peak amplitude of the current waveform. (c) The rise time of the optical radiation pulse decreases with decreasing wavelength. (d) A slight increase in the decay time of the optical pulse, at a given wavelength, is observed with increasing peak amplitude of the current waveform. (e) The results show that the rise time of the optical radiation pulse increases with the increasing rise time of the current waveform. The relationship between peak current, peak optical power and peak electrical power is studied. Also the relationship between peak current, optical energy (400 - 1100 and 777 nm) and electrical energy is discussed.

## INTRODUCTION

The study of optical radiation generated by long sparks is of interest in two respects. First, in the use of geostationary satellites to detect lightning, one of the demands on the space based detector is the ability to detect lightning during full daylight [1]. Goodman et al. [2] suggested that this could be realized by detecting either the spectral line of oxygen (O I(1)) at 777 nm or the spectral line of nitrogen (N I(1)) at 868.3 nm. From various observations, done at ground level and above clouds [2-3], the oxygen line at 777 nm appears to be a strong, narrow and stable spectral line in the spectrum of lightning flashes. By recording a strong and narrow spectral line, the background noise may be suppressed so that the recording can be performed even during the day time. The absorption in clouds, in the near infrared region of the spectra, is negligible which is also one of the reasons that we have chosen the O I(1) spectral line.

Second, in the remote sensing of lightning return stroke through the optical radiation it is important to know the relationship between return stroke current parameters and the characteristics of the optical radiation. For example, if the knowledge is available it is possible to estimate how the characteristics of the lightning current is changing along the return stroke channel by analysing the optical radiation.

A lot of work has been done on the optical radiation from lightning [3-7] but there is very little work done on optical radiation from laboratory sparks under controlled atmospheric conditions. For example by extrapolating the data obtained from laboratory discharges, Krider et al. [6] and Uman et al. [8] have estimated the electric power and electric energy dissipated in lightning flashes. To increase our knowledge of the correlation between the optical and some electrical parameters of the discharge channel, we have started to investigate the appearance of the O I(1) and the N II([illegible]) spectral lines and the broad band optical radiation between the wavelengths 300 and 1100 nm from long laboratory sparks to increase our knowledge of the correlation between the optical and some electrical parameters of the discharge channel.

## EXPERIMENTAL SYSTEM

The light output from the discharge channel was measured with an optical detector, especially designed for this purpose [9] (figure 1). The optical detector consist of a light collecting and a collimating lens system, an optical interference filter and a photodiode with electronics.Some characteristics of the optical detector: rise time < 0.4 µs, fall time < 10 µs, transmission 64%. A typical optical pulse waveshape from a 280 mm long laboratory discharge can be seen together with current in figure 2.

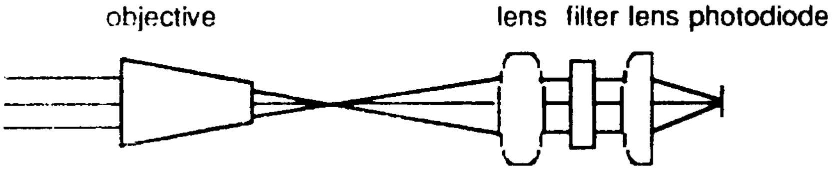

*Figure 1 The optical detector*

The current was measured with a Rogowski coil. The coil used was a Singer Current Probe, model 94456-4, which is designed to measure current pulses with durations up to 500 µs and peak current levels of up to 6000 A. The frequency range of the probe is 10 kHz to 100 MHz. The current probe is placed around the rod to which the discharge takes place, as can be seen in figure 2. The output from the optical detector and the current probe were recorded and displayed on a Hewlett Packard 54111D Digitizing Oscilloscope. The displayed waveforms were then transferred via a HPIB bus to a portable IBM Personal Computer for post processing. The recording system was placed in a screening cage, see figure 3. The electrode configuration is sphere-rod and a negative impulse voltage is applied to the sphere. The shape of the voltage impulse is 1.2;50 µs. The shape of the current waveform generated by the impulse generator has 0.1 µs rise time and 5 µs decay time. The distance between the electrodes in the spark gap is 0.28 m. The distance between the optical detector and the discharge channel was 6 meter. Measurements have shown that for distances larger then 6 meters, the discharge channel can be regarded as a point light source, i.e. the radiated flux density is decaying as $1/r^2$ [9].

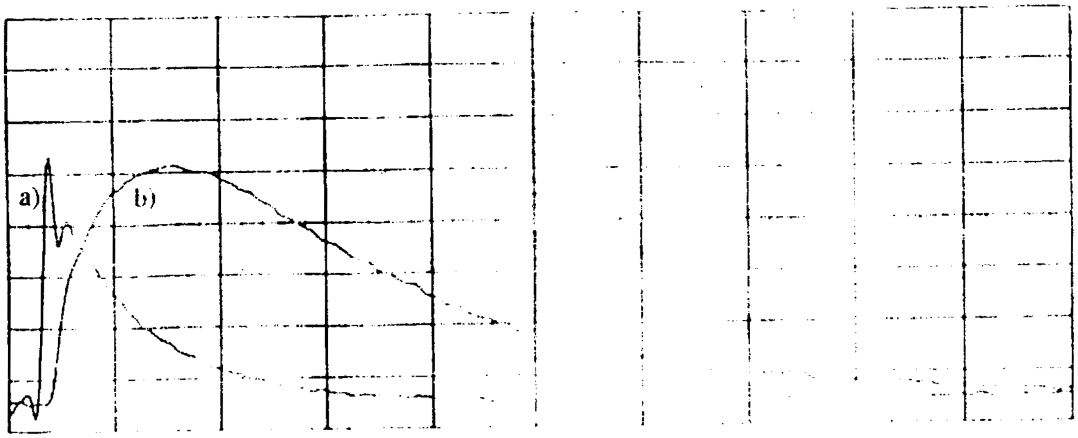

*Figure 2 Typical optical and current wa[illegible] obtained from [illegible] mm long laboratory discharges, a) current waveform, b) optical [illegible] time base [illegible]/div*

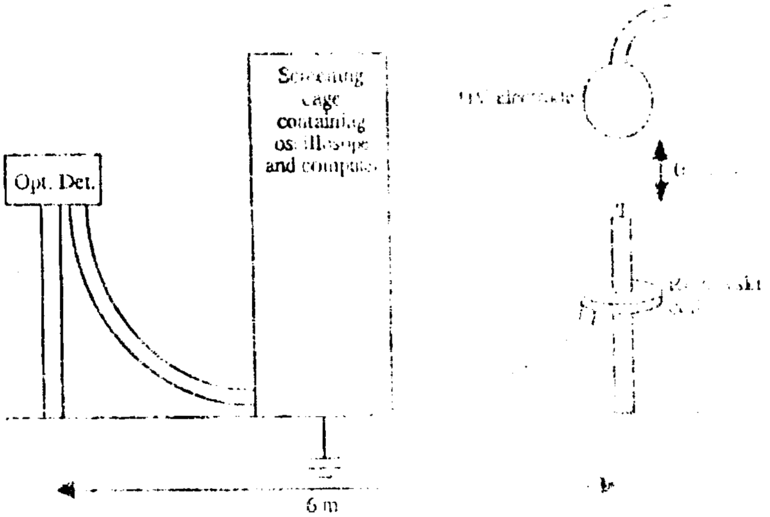

*Figure 3 Experimental set-up in high volta[illegible]*

The O I(1) spectral line is a triplet with [illegible] of almost equal intensity, separated 0.34 nm, and the N II(19) spectral line is a doublet [illegible] lines separated [illegible] 0.03 nm. Therefore the light detected from the discharge channel [illegible] wavelengths is due to the [illegible] sum all the components in the spectral line. The light signal [illegible] by the optical detector is basically a superposition of the geometrical growth of the [illegible] channel and other luminous effects happening when a discharge takes place.

## RE[illegible]S

### PEAK LIGHT OUTPUT VERSUS P[illegible] CURRENT

Measurements [illegible] that there is a [illegible] relationship between the peak output of the optical radiation at 777 nm, 500 nm, 4[illegible] [illegible] peak current. The results for the 777 nm spectral line [illegible] shown in figure 4. [illegible] the data to a high [illegible] correlation coefficient [illegible]

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$$P_{o,777} = 1.76 \times I_p^{1.37} \qquad (1)$$

where $P_o$ is in $10^3$ W/m and $I_p$ in kA. The peak power generated by 3 kA peak current is $7.92 \times 10^3$ W/m.

The results for the broad band optical radiation is shown in figure 5. The following curve can approximate the data to a high accuracy (correlation coefficient 0.988):

$$P_{o,400-1100} = 0.68 \times I_p^{1.40} \qquad (2)$$

where $P_o$ is in $10^5$ W/m and $I_p$ in kA. The peak power generated by 3 kA peak current is $3.16 \times 10^5$ W/m.

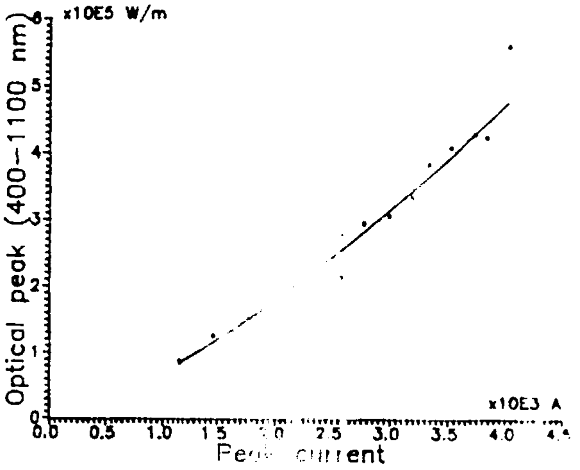

*Figure 4 Peak light (400 - 1100 nm) peak current*

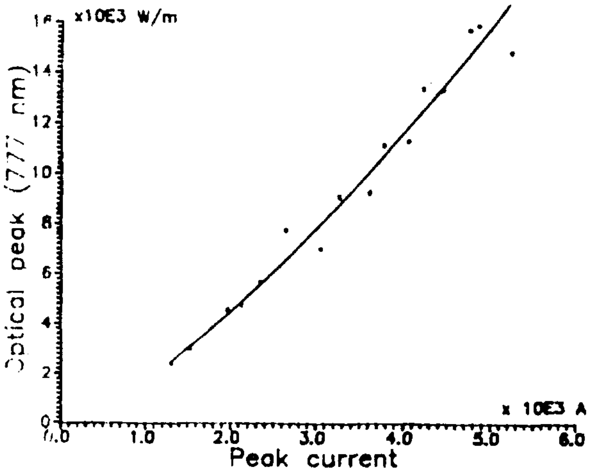

*Figure 5 Peak light (777 nm) versus versus peak current*

It is of interest for us to compare our results with those obtained from lightning. Recently, Idone and Orville [10] measured the optical radiation (spectral range 300 - 670 nm) generated by a short segment of lightning channel situated at 50 meters from ground level and the peak current in the return stroke channel. They found that there is a linear relationship between the peak light intensity and the peak current for subsequent strokes in triggered lightning. Unfortunately, Idone and Orville did not give the optical power in absolute units so that we can investigate whether the laboratory results can be extrapolated to lightning conditions. Baker et al. [7] have measured the peak optical power and the peak current from triggered lightning. For a 17 kA current they have measured a peak optical power of $3.7 \times 10^6$ W/m. They have also calculated the peak optical power for a 17 kA current to be $10.9 \times 10^6$ W/m. If we assume that our measurements can be extended to lightning we get for a 17 kA current a peak optical power of $3.5 \times 10^6$ W/m which is in good agreement with the measured results.

## THE RISE AND DECAY TIME OF THE OPTICAL PULSE

The results shows that the rise time of the optical radiation pulse at a given wavelength does not depend significantly on the peak amplitude of the current waveform (figure 6). We have also found that the rise time of the optical radiation pulse decreases with decreasing wavelength. We measured the mean rise time $\tau_{mean}$ to be 2.32 µs for the O I(1) (777 nm) spectral line and 0.48 µs for the N II(19) (500 nm) spectral line. This result is, in principal, in good agreement with measurements done by Lundquist and Scuka [11]. They have measured the time characteristics of the spectral line $H_\alpha$ (655.5 nm) and the channel continuum at wavelength 390.5 nm from lightning discharges and have found that there is an decrease in rise time with decreasing wavelength as in our case.

There is a slight increase in the decay time (the time it takes for the peak light output, $I_p$ to fall to half the peak light, $0.5I_p$) of the optical pulse at a given wavelength with increasing peak current (figure 7).

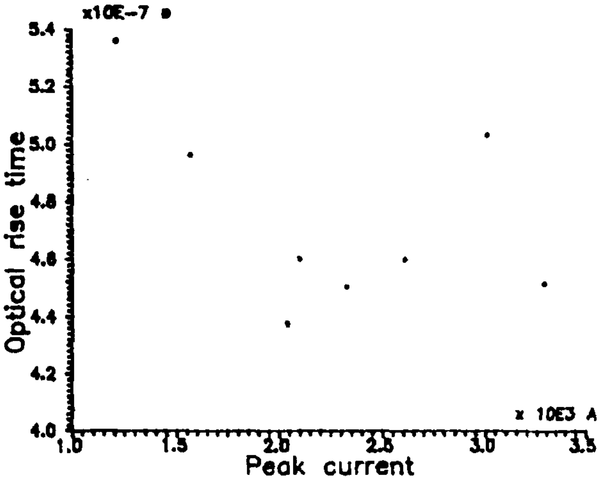

*Figure 6 Optical rise time (400 - nm) versus peak current*

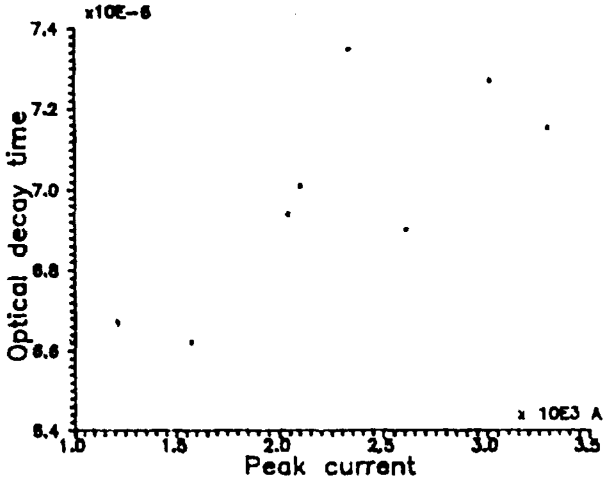

*Figure 7 Optical decay time (400 -1100 1100 nm) versus peak current*

In order to test the effect of the current rise time on the optical radiation we have conducted studies with a current waveform having 5 µs rise time and 25 µs decay time. The result is that the rise time of the optical radiation pulse increases with increasing rise time of the current waveform (figure 8).

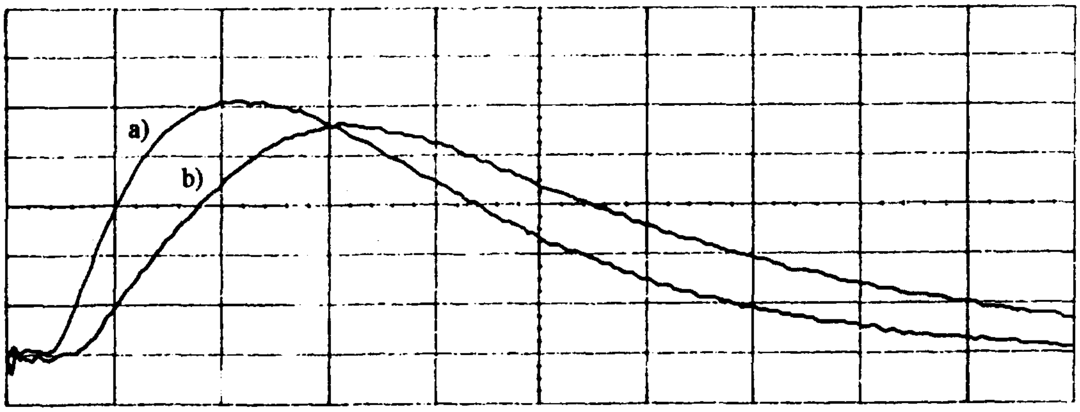

*Figure 8 The effect of increasing current rise time on the optical pulse, a) current waveform, b) optical waveform, time base 5 µs/div*

For lightning it has been observed that the rise time of the optical radiation is increasing with increasing height. This indicates, according to our results, that the current rise time is increasing with increasing height. A similar result is predicted by a new return stroke model introduced by Cooray [12-13]. A thorough investigation of the relationship between the current rise time and the optical rise time will be carried out in the near future at the Institute of High Voltage Research.

## POWER MEASUREMENTS

We have measured the electrical power dissipated in the discharge channel by measuring voltage V and the current I. The results of this investigation together with peak optical power given in table I.

*Table I Results of the power measurements*

| Current<br>(A) | Peak electrical power $P_{el}$<br>($10^9$ W/m) | Peak optical power $P_o$<br>($10^5$ W/m) |
|---|---|---|
| -1157 | 0.87 | 0.83 |
| -1564 | 1.33 | 1.27 |
| -1919 | 2.05 | 1.69 |
| -2214 | 2.66 | 2.07 |

According to this results the relationship between the peak electrical power $P_{el}$ and the peak current $I_p$ can be represented by

$$P_{el} = 0.65 \times I_p^{1.75} \qquad (3)$$

where $P_{el}$ is in $10^9$ W/m and $I_p$ in kA. This agrees very well with calculations done by Cooray [14] for the lightning return stroke. According to these calculations the relationship between the peak electrical power $P_{el}$ and the peak current $I_p$ is given by $P_{el} = k \times I_p^{1.7}$ where k is a constant.

According to table I, the relationship between the peak optical power $P_o$ and the peak electrical power $P_{el}$ can be represented by

$$P_o = 0.96 \times P_{el}^{0.80} \qquad (4)$$

where $P_o$ is in $10^5$ W/m and $P_{el}$ is in $10^9$ W/m. Jordan et al. [15] have measured that the optical radiation generated by lightning decreases with a factor of two within the first 100 meters of the return stroke. On the other hand, Cooray [14] have calculated that over this length the electrical power in the channel decreases with a factor of three. If we assume that relationship 3 is also valid for lightning then the results obtained by Cooray indicate that the peak optical power decreases by a factor of two over the first 100 meters. This is in agreement with the results obtained by Jordan et al.

## ENERGY MEASUREMENTS

By integrating the power curve obtained in the measurements mentioned above we get the electrical energy in the channel and the energy emitted as optical radiation (400 - 1100 nm and 777 nm). The results of this investigation is given in table II.

*Table II Results of the energy measurements*

| Current<br>(A) | Electrical energy $E_{el}$<br>(J/m) | Optical energy $E_{o,400-1100\ nm}$<br>(J/m) | Optical energy $E_{o,777\ nm}$<br>(J/m) |
|---|---|---|---|
| -1157 | 35 | 0.68 | 0.03 |
| -1564 | 53 | 1.74 | 0.12 |
| 1919 | 78 | 2.99 | 0.21 |
| -2214 | 92 | 4.52 | 0.34 |

The ratio between the electrical energy and the energy going into optical radiation (400 - 1100 nm) is varying from 1.9% to 4.8%. The relationship between the electrical energy and the energy emitted as optical radiation (400 - 1100 nm) is

$$E_o = 9.34\times10^{-4} \times E_{el}^{1.87} \qquad (5)$$

where $E_o$ and $E_{el}$ is in J/m.

According to table II, the relationship between the electrical energy $E_{el}$ and the peak cur $I_p$ can be represented by

$$E_{el} = 27 \times I_p^{1.6} \qquad (6)$$

where $E_{el}$ is in J/m and $I_p$ is in kA. This agrees well with calculations done by Cooray [14 the lightning return stroke. According to these calculations the relationship between the elec energy $E_{el}$ and the peak current $I_p$ is given by $E_{el} = k \times I_p^{1.9}$ where k is a constant.

The ratio between the amount of energy going into optical radiation (400 - 1100 nm) I(1) is measured to be 7%. In case of lightning, Goodman et al. [2] and Wolfe et al. [16] observed that 5 - 15% of the total optical energy goes into the O I(1) spectral line. Of cour percentages may be influenced by the spectral sensitivity of the photodiode.

## CONCLUSIONS

The results obtained show that the relationship between peak optical output (at 5 777 nm, 400 - 1100 nm) and the peak current can be represented by $P_o = k \times I_p^{1.40}$. Th time of the optical pulse is increasing with increasing peak current. An increase in the rise the current leads to an increase in the rise time of the optical radiation. The relationship these two parameters will be investigated in the near future. The ratio between the am electrical energy in the discharge and the energy emitted as optical radiation (400 - 110 measured to be between 1.9 - 4.8%. This ratio have a tendency to increase with inc electrical energy. The energy associated with the O I(1) spectral line is approximately 7 total optical energy (400 - 1100 nm). The relationships between the electrical energy $E_{el}$ peak current $I_p$, the peak electrical power $P_{el}$ and the peak current $I_p$ can be repres $E_{el} = 27 \times I_p^{1.6}$ and $P_{el} = 0.65 \times I_p^{1.75}$

## ACKNOWLEDGEMENTS

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