On the Frequency of Lightning Flashes to High Objects
A Study on the Gulf of Bothnia

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Abstract

The space-charge calculation of a lightning stroke according to Golde results in a simple geometrical relation between the area within which a flash strikes an object and its height. A comparison between the number of lightning strokes to chimneys and the number of lightning downstrokes per km^2 shows, that the statistical attraction distance of a 70 m high chimney is more than 250 m and thereby more than the leader's step-length after Schonland. An explanation may be the space-charge plume, which leaves the lightning rod in a thunderstormfield and may conduct a lightning discharge to the chimney from some hundreds of meters' distance.

High objects and leader "head"

In 1933 B. WALTER in a report which attracted much attention at the time pointed out that the lightning flash in its approach to the earth's surface does not fix on its downstroke point until the final phase at a distance of less than 150 m from the ground. Walter's statistical work was based on 438 cases of lightning damage in Hamburg during 27 years. The average number of cases of lightning damage annually is calculated at 0.57 per km^2 in Hamburg with ca 19 thunderstorm days a year. The area A, within which the flash strikes an object with a height h above its surroundings, is calculated from geometrical ratios as

$$A = h^2\pi\left(\frac{2d}{h} - 1\right) \qquad (d > h) \qquad (1)$$

$$A = 2\pi h \cdot d \qquad (d \gg h) \qquad (1\,a)$$

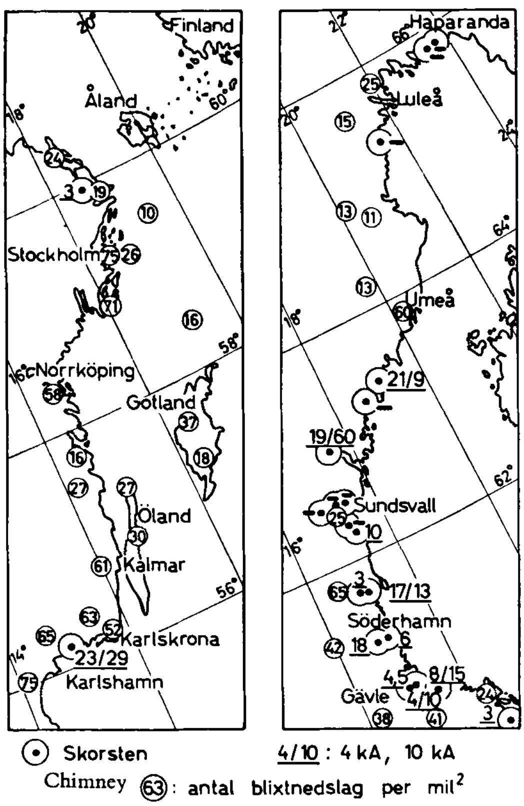
$$A = d^2\pi \qquad (d \leqq h) \qquad (1\,b)$$

with d as attraction distance. The area and in consequence the probability of attracting a lightning stroke increases *linearly* with the height of a lower object and is independent of the height of full objects. This simple relation has been the basis of many investigations. R. H. GOLDE (1945) has presented a plausible opinion that the attraction distance is dependent on the size of the electric charge in a stepwise projecting space-charge channel, which prepares the lightning path. The distance is greatest for large electric space-charges and consequently also for high lightning current-strengths (Schonlandprocess, step process of the initial leader).

Golde's pre-requisite condition for the calculation is the assumption that the space-charges are distributed in a kind of "pipe" with a charge density which decreases exponentially with the height. S. B. GRISCOM (1958) puts forward views which lead to the assumption that the charges at the "leaderhead" are chiefly hemispherically distributed. The form of the corona envelope earthward of the leader is like an onion. This leaderhead contains a very large concentration of immediately available energy. The leader grows by fits and starts in the direction of the ground, when a transformation takes place from the hemisphere to a channel and from the channel to a hemisphere. The distance from which a flash-over takes place between the leaderhead and a high object is assumed to be 50 m. According to R. H. Golde, the smallest distance from which the flash starts its last step to the ground or from which a discharge from the ground to the space-charge of the flash starts is less than 17 m. Practical observations have confirmed this. At a distance of less than 15 m from the ground the flash has altered its path and struck an object from the side (4, 5). In calculations of the area of attraction a distance of 40—60 metres from the ground is often assumed.

Lightning flashes to chimneys

For a period of 17 years from 1943 to 1959 we have had under observation about 37 chimneys at 27 different places. Twenty chimneys (height 60—106 m) are situated on the coast of the Gulf of Bothnia (Fig. 1); 15 north



Number of lightingflashes per 100 km²

Fig. 1. Lightning strokes to 16 chimneys on the coast of the Gulf of Bothnia and number of lightning downstrokes per 100 km².

of Gävle (60°40′ lat., 17°02′ long.) to Haparanda (65°50′ lat., 24°09′ long.) and 4 in the Gävle district. One was situated to the south at Karlskrona (56°10′ lat., 15°30′ long.). The remaining 17 chimneys are situated inland. The observation was carried out by means of steel rods. Through the courtesy and assistance, continued for many years, of the managements of the respective factories, we have obtained information on the annual mounting of the steel rods from inspection cards. The average number of observation years is more than 12 and the number of measured flashes with more than 5 kA current is 28. The risk, of chimneys of an average height of ca 70 m being struck by a flash with a current strength of more than 5000 A, is 5.85 % (see Table I). This is an average value for all observation years together (7.4 % for the years 1943—1949, richer in thunderstorms, and 4.7 % for the years 1950—1958, poorer in thunderstorms). In Fig. 2 the results are reproduced graphically. The probability of the downstroke of a flash having a current strength of 20 kA and more is ca 2.7 %. A powerful flash with a current strength of 50

Table I. Comparison of the measurements on chimneys.

	Chimneys situated	
	on the coast	inland
Average number of thunderstorm days per year	5	12
Number of chimneys	20	18
Average height, m	70	60
Number of observation years	12.4	12.8
Number of flashes measured		
Total	18	16
Over 5 kA current	13	15
Strike probability, %		
For flashes with at least 5 kA current	5.25	6.5
Area of attraction, km²		
Path of the flash influenced with a distance of $d = 100$ m	0.026	0.024
$d = 250$ m	0.084	0.071
Lightning downstroke per km² per year		
For $d = 100$ m	2.02	2.70
$d = 250$ m	0.625	0.915

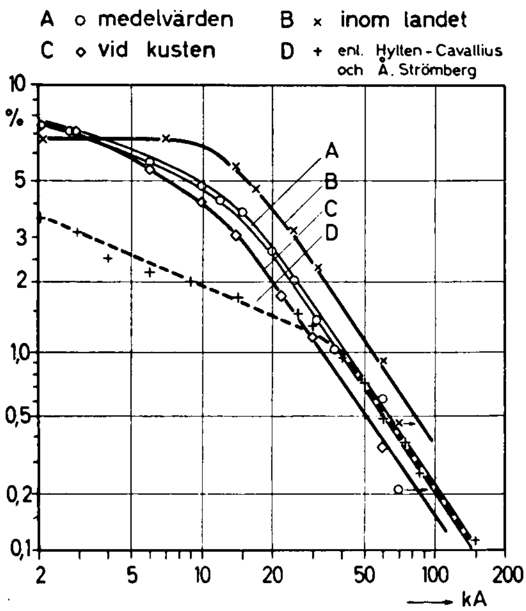


Fig. 2. Probability of currents with lightning strokes to chimneys.

A Mean value B In the country
C On shore D According to Hylthén-Cavallius and Strömberg (1959)

kA and more will strike a 70-metre-high chimney annually with ca 0.75 % probability.

If the area of attraction is calculated from formula (1) with the proportionately high value for the attraction distance $d = 100$ m, the area of attraction is therefore 0.0263 km² large for a chimney with 60 m effective height. Here it has consequently been assumed that the lightning path is influenced at a height of 60 m and at a distance of 100 m from the tip of the lightning leader. It was assumed in the calculation that the effective height of the chimney was reduced by 10 m by surrounding buildings.

With $A = 0.0263$ and with a probability 0.0525 (Table I) the average value of the annual number of lightning downstrokes per km² $\frac{0.0525}{0.0263} = 1.99$ at the coast. The corresponding value inland is 2.75. This is not likely. The number of years of observation with lightning counters is certainly not sufficient for drawing definitive conclusions (6). However, the following can be asserted.

In 1959 the number of thunderstorm days on the east coast (Karlshamn to Haparanda) was 7 to 3. The average value for 10 years is 7 in the south and ca 4 in the north, and the average value for 37 years is 8 and 5 respectively. During 1959 the number of lightning days correspond to a medium value. In 1959 there was recorded an average value of 38 lightning strokes to ground per 100 km² with 14 lightning counters placed on the east coast (Karlshamn to Luleå). The highest number of flashes for 100 km² was 75 (the Stockholm archipelago) and the smallest number was 7 (Umeå). If we count on an average annual value of 60 flashes per 100 km² on the east coast, then this will presumably be a high amount. Thus the attraction distance for 70-metre-high chimneys at the coast will be 309 m.

The chimneys inland are situated north of a line from Gothenburg (57°40′ lat. 11°55′ long.) to Norrköping (58°35′ lat. 16°10′ long.) in areas with 8-12 thunderstorm days as an average value for 10 years and 8-13 thunderstorm days as an average value for 37 years. The lightning counters set up in the neighbourhood of the factories recorded in 1959 50 flashes to the ground for 100 km². The highest number was 110 flashes per 100 km². This is comparable with the average value of 0.915 reproduced in Table I, when an attraction distance of 250 m is used as a basis.

The values reproduced in curve D in Fig. 2 have been taken from a nine-year investigation (1950 to 1958) by N. HYLTHÉN-CAVALLIUS and A. STRÖMBERG (1959), which comprises 1125 observation years and 19 current values more than 5 kA. In the transfer of their results we calculated with 75 % of the number of station years (845), partly with regard to a 6 % loss of measuring rods and partly (after consultation with the authors) with regard to the possibility that not all magnetic rods were mounted during the whole thunderstorm season. After the reduction the probability values agree for flash currents over 35 kA (curve D and curve A). On the other hand, the probability of a flash downstroke with a current strength of at least 5 kA is 2.75 % according to curve D (5.7 % curve A). The average height of chimneys struck by a lightning was 55 m and the effective height probably 45 m. The medium value of lightning strokes to earth is estimated at

$0.5/\text{km}^2$ in the region with the majority of chimneys. The attraction area becomes accordingly $\frac{0.0275}{0.5} = 0.055\ \text{km}^2$ and the attraction distance 212 m with $h = 45$ m.

The result of the simple calculation is: the distance of attraction is about 200 to 300 m and consequently not in agreement with the Schonlandprocess in the interpretation of Golde.

Corona discharges and space-charge

For the regions of the U.S.A. rich in thunderstorms (30—40 thunderstorm days per year) McCann (1944) has reported the strike probability for fire-watch towers ($h_m = 28$ m), for high radio masts ($h_m = 107$ m) and for chimneys and high buildings (171 m). These values and the ones measured on the Empire State Building in New York have been reduced to 10 thunderstorm days (for lack of knowledge of lightning downstrokes for one km^2) and reproduced in Fig. 3, together with our measurements. The probability increases approximately with the *square* of the height of the object.

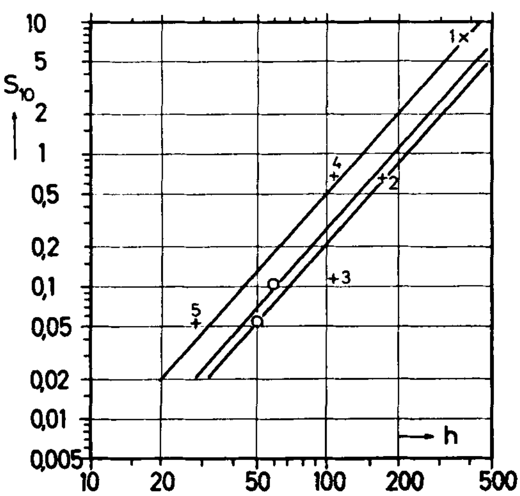


Fig. 3. Strike probability for towers and chimneys.

1. Empire State Building, New York (10 yrs)
2. Cathedral of Learning, Pittsburgh (5 yrs)
3. Lexington Building, Baltimore (8 yrs)
4. Radio Tower of WADC, Akron (5 yrs)
5. North Wales substation, Philadelphia El. Co. (5 yrs)

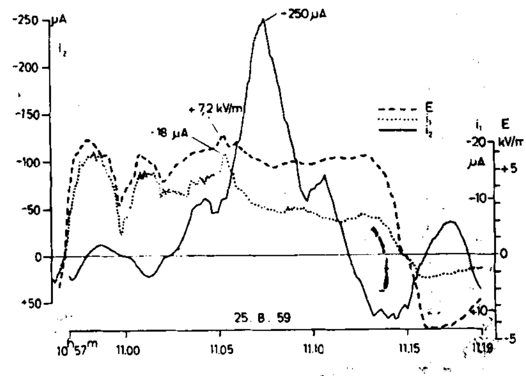


Fig. 4. Electric field strength and corona current on a 70-m-high chimney and a 15-m-high point.

The higher a chimney is, the greater is the corona current which is generated from the lightning rod interceptor in the electrical thunderstorm field of some thousands of volts per metre with a thunderstorm. Fig. 4 reproduces as an example the electrical field strength which was measured in Uppsala on 25 August, 1959, in a widespread cumulo-nimbus without discharges. Some twenty metres from the field-measuring instrument there was a 15-metre-high point, the corona current of which was simultaneously recorded. At a distance of 5.85 km there was measured the current through the lightning rod on an 70-metre-high chimney. The current generates a positive space charge at positive electric field strength. The current strength has a peak value of 250 μA; the charge generated for 10 minutes is 52 m Coul. A positive current of 250 μA leaves the rod and flows upwards or a negative current from the direction of the cloud to the interceptor flows to the ground.

R. Davis and W. G. Standring (1947) have measured the discharge currents in the flying cable of a balloon, flown at 600 m height. In thundery weather they got currents of about 25 mA max. value during several minutes. The recorded currents indicate the passage to earth of a large quantity of charge, 3 to 4.5 Coul. The voltage gradient was also measured, but on the approach of a charged cloud difficulties occurred and no records could be obtained. The order of magnitude of the potential gradient may have been the same as with our measurements, and we can see that currents and charges increase approxi-

Fig. 5. Lightning stroke to a 45-m-high chimney (taken by R. Kinnunen at Thomajärvi in Finland).

mately with (height)^2, equal to $\left(\frac{600}{70}\right)^2 = 74$ times the current of 250 μA = 18.5 mA, and a charge of 52 m Coul. = 3.85 Coul. Theoretically it is well known that the field strength of a point in a homogeneous electric field (long ellipsoid homogeneously polarized) increases with the square of the height. We get the conclusion that the space-charges of these high objects affect the probability of a lightning stroke and that the probability increases with the *square* and not *linearly* with the height according to McCann (1944).

Fig. 5 reproduces a lightning stroke to a 45-m-high chimney, taken by R. Kinnunen at Thomajärvi on 5. 7. 1954 at 8—9 p.m. (62°13′ lat., 30°15′ long.). The lightning channel goes obliquely over a length of at least 145 m, possibly essentially more. The following explanation seems to be plausible. A space-charge plume leaves the chimney. The space-charges are spread rapidly due to their own electric field and as a consequence of the eddydiffusion in the atmosphere. It is well known that the dispersal of pollution from chimneys depends in a high degree on the micrometeorological conditions. With a low turbulence the smoke of a chimney drifts away as a narrow cone which does not diffuse until it has reached a considerable distance from the site (10). If a large number of condensation nuclei or fogdroplets is present, the mobility of the ions decreases, and the electric field strength on the edges of the space-charge may achieve values of a hundred kV/m. This changes the original electric field drastically: a lightning discharge may be conducted to the "plume" and thereby lead discharges from some hundreds of metres' distance to the chimney. Presumptions for this are seldom: the probability of a stroke for a 70-m-high chimney may be about one in 100 lightning days on the coast and one in 130 to 150 lightning days inland.

The pre-requisite conditions are obviously not always present and are more easily fulfilled the higher the chimney. The existence of this positive space-charge at negative field strength is evident when the primary electric field between a thunder-cloud and earth disappears through a lightning discharge between the clouds, and the space-charge field alone is effective. A "rebound" discharge between the positive space-charge cloud and the lightning conductor may occur. Positive currents of 0.5 to 1.5 kA in magnitude were recorded by N. Hylthén-Cavallius and Å. Strömberg (1959) approximately as often as the number of lightning currents over 5 kA. Similarly McCann (1944) has several times measured currents of the same order of magnitude (100-800 A, 50-150 μsec duration) and their origin is explained as induced currents. However, it seems to be possible that these positive currents arise from the positive-charge cloud generated from the high object itself. An argument for this opinion in Figs. 6 and

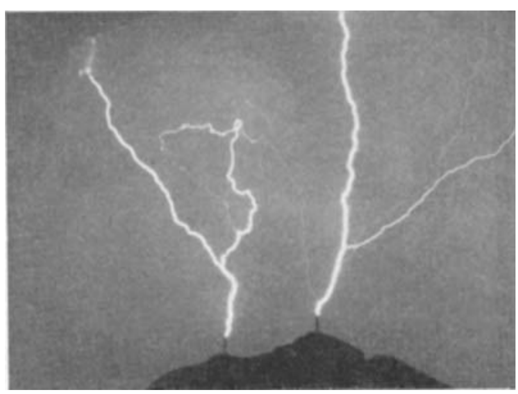


Fig. 6. Lightning flashes, starting from both towers, with upwards directed ramification. Tower distance 400 m, in direction of the figure 260 m. Visible channel-length 850 m.

Fig. 7. Oblique discharge 6 min. 20 sec. later. The dotted line is the contour of the mountain, the top of which is concealed behind a cloud. Dischargelength at least 1.000 m.

7, lightning flashes on the 70-m-high towers on Monte San Salvatore near Lugano, Switzerland. We get these pictures in connection with lightning researches in collaboration with Prof. Berger, Zürich. The exposure-time of a 16-mm-film was 8 sec. The discharges start from the top of the tower and the channel's ramification is directed upwards.

Experimentally this phenomenon is not confirmed owing to the difficulties in getting sufficiently large space-charges. But with negative space-charges produced by impulse discharges we can get a back-discharge from these space-charges to the electrode. As an example Fig. 8 shows a negative corona from a 6.2 cm sphere with a 1/50-μsec wave and a voltage of about 1 MV in a photograph kindly offered by Mr. O. Salka. From the space-charge flashes a spark goes back to the electrode.

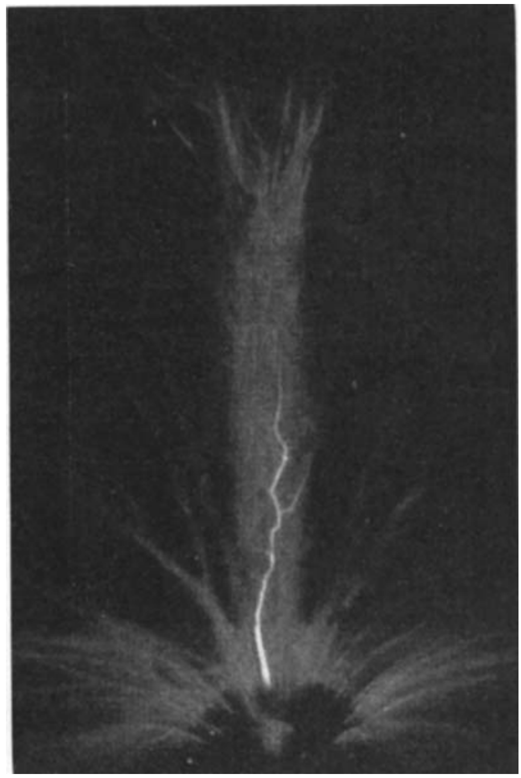


Fig. 8. Negative impulse corona with a back-spark (photograph by O. Salka).

This experiment is not a proof of the existence of this phenomenon and may only give an explanation and an idea of how we imagine the occurrence of small positive lightning currents of the order of some hundreds and thousands of amperes with chimneys.

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