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Experimental evaluation of an arrival time difference lightning positioning system

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ABSTRACT

Results from a five-station LPATS lightning positioning system covering the Netherlands are analysed and compared with observer reports and with registrations from lightning counters.
It is demonstrated that the median location accuracy of individual flashes is about 2 km. The reliability of detection is diminished by the occurrence of false alarms and the possibility of system saturation during widespread thunderstorms. Contrary to expectations the system may respond to intracloud discharges.
Despite these difficulties the system seems quite acceptable to replace the even more imperfect human observations for warning purposes and for thunderstorm statistics. In addition the system offers possibilities to collect statistics on lightning parameters like peak currents and lightning discharge density.
A preliminary statistical analysis shows that the establishment of preferred lightning subregions in the Netherlands would require at least ten years of measurements, while small-scale so-called lightning spots will remain masked by the limited location accuracy.

Experimental evaluation of an arrival time difference lightning positioning system.

1 INTRODUCTION

In recent years lightning positioning networks have been installed in many countries. These networks are usually operated by meteorological services, forest services or power companies. The data are used primarily for meteorological forecasting and lightning research. Among the applications is the warning for new discharges to be expected from the same storm and also the collection of statistical lightning data (like the local probability of lightning incidence) that may e.g. be used for the design of protective measures.
The main practical interest concerns discharges from a thundercloud to the earth, in contrast to intracloud discharges. Discharges to the earth may further be subdivided in negative and positive discharges, depending on the upward, respectively downward movement of electrons (see e.g. Golde, 1977). The main discharge is prepared by a branching, relatively slow and weak 'leader discharge'. These usually start downward from the cloud, but may also start upward from high (e.g. 100 m) objects.
An important property of most discharges is their multiplicity: a lightning 'flash' may last up to a second and may consist of one or more subsequent component 'strokes'. This distinction between flash and stroke will be maintained in this report. Relevant quantitative lightning parameters include also the temporal behaviour of the current as expressed by e.g. peak current (typical values 20- 200 kA) and rise time (in the μs range).
Lightning detection systems use the radio emission caused by the changing electric current through the lightning channel. Reception is usually by a VLF receiver with a vertical rod antenna. Especially the rapid rise of current that occurs just after the leader discharge has created a conducting channel between cloud and earth, will cause appreciable vertical electric field changes at ranges up to hundreds of km. Intracloud discharges usually cause slower and weaker field changes, so their detection by the receiver described is less probable. This is usually considered an advantage, because most lightning studies are focussed on earth discharges.
Two methods for determining the position of lightning are currently used; one is based on at least two direction finder stations. The other method measures the time differences between the radio signals arriving at the respective stations. In the Netherlands a network of the second type was installed in 1987 by the N.V.Kema (the central research and testing institute of the electricity companies). Reports on lightning strokes are sent via a modem and telephone line connection to the Royal Netherlands Meteorological Institute (KNMI). Before using these data operationally for warning and climatology their accuracy had to be established.
Most published evaluations of lightning networks are about direction finder systems (Brown, 1989; Chagnon, 1989). The present report discusses the detection and positioning accuracy of an arrival time difference lightning network by comparing data covering a full year and an area of more than 40000 km^2 with conventional observations (official and volunteer observers) and

simultaneous measurements by the KNMI lightning counter network. Especially this comparison with lightning counters is a rare and interesting opportunity.

2 DESCRIPTION OF THE LIGHTNING POSITIONING NETWORK

The Kema network, a Lightning Positioning and Tracking System type LPATS-III, was purchased from the Atlantic Scientific Corporation (now: Atmospheric Research Systems Inc.). The positioning is based on the measurement of differences in arrival time (further referred to as: ATD) between radio waves from lightning at three or more stations. A general discription of the Netherlands network is given by Janssen (1988). Contrary to Western hemisphere versions of this network, the synchronisation of the stations is not accomplished by LORAN navigation signals but by using the signal of a TV satellite broadcast. If the satellite remains on its specified location (± 20 km) this provides an accuracy of better than 1 μs for the measurement of time differences between stations. Simulations by the manufacturer indicate that such synchronisation errors alone would still allow a positioning accuracy of better than 1 km over most of the territory of the Netherlands.
The electric component of the lightning's radio transmission in the band 2-500 kHz is measured by a vertical rod. Signals above a predefined noise threshold are sampled at a 5 MHz rate and the occurrence of a signal peak is used to 'time' the stroke. If a stroke is detected on two stations, the time difference for these stations locates the lightning position on a hyperboloid dissecting the earth surface. If a third timing is available we have an analogous curve for a second station pair. The crossing of the curves determines the stroke position, but there may sometimes be two crossings. Therefore, to obtain unambiguous location of all lightning occurrences, we need al least 4 stations. Since early 1988 the Kema network used 5 stations.
Once the location is known, the measured electric field E allows us to estimate the peak lightning current. The lightning is usually modelled as an suddenly increasing current i(t) in an upward growing channel with height h(t). At a distance r beyond 10000 m the electric field change is mainly determined by the so-called radiation term (e.g. R.B. Anderson in: Golde, 1977, p.450)

$$E\ (V/m) = \frac{\mu_0 . d[2i(t).h(t)]/dt}{4\pi r} \quad , \qquad (1)$$

where μ_0 is the magnetic permeability of a vacuum ($4\pi\ 10^{-7}$ H/m). In the following the channel propagation speed v=dh/dt is assumed constant with a value of 10^8 m/s. Equation (1) reduces to

$$E\ (V/m) = \frac{\mu_0 . v . i(t)}{2\pi r} \quad . \qquad (2)$$

The measured fieldstrength E is corrected by a receiver calibration factor K, which accounts for local field distortion. This factor has to be determined for each station separately and individual station values of K may suffer from systematic errors.
Equation (2) is also valid at the moment of maximum current i_p

$$E_p(V/m) = \frac{K . \mu_0 . v . i_p(A)}{2\pi r} \quad . \qquad (3)$$

In the present situation the receiver threshold sensitivity is automatically raised during overhead storms to avoid capacity problems in the local processor. This action may temporarily restrict the use of that station to the nearby storm only, thereby increasing detection and ambiguity problems. The actual receiver gain settings are monitored at the central analyser and are applied in the evaluation of Equation (3). This facility has been used since June 10, 1988. From the same date automatic redundancy checks have been included in the processing: thereby an attempt is made to benefit from the redundancy inherent in the availability of 5 stations, providing 10 timing differences. During the year studied in the present report this situation remained the same. Just after the closing date for this report, at July 3, 1989 a further improvement was introduced in the form of a combination of redundancy checking and amplitude screening. In this more recent software version the signal strength is used as additional information to discard erroneous locations.

The capacity of the central analyser was sufficient to process even the most intense thunderstorms that occurred in this evaluation year. At one occasion more than 3000 strokes were received between two clock hours. Actual flash times in such storms are difficult to estimate, because incoming data are buffered and the time indicated in the flash reports is based on the processing time.

During such intense widespread storms loss of data is unavoidable, because the receiver will miss strokes arriving in intervals smaller than 0.015 sec. Especially subsequent component strokes in multiple flashes will be lost. In addition some of the computations do not result in valid solutions and will finally be discarded. This reduces the effective capacity of the system.

For all valid flashes in a 280x325 km area in and around The Netherlands a selection of the computer output is sent to KNMI, including time (i.e. processing time at the central analyser), coordinates, current, sign, and the (three-)station combination used for the actual solution. The present capacity of the telephone line, 1200 Bd, allows about 6000 strokes (each described with 70 characters) to be transmitted.

3 ADDITIONAL DATA PROCESSING

After reception at KNMI the data are reduced in two ways. Firstly, multiple discharges are combined into one message, containing the time, current and location of the first return stroke and an indication of the number of component strokes. The criterion for multiplicity is based on the subsequent stroke with the same sign to be reported within 0.2 s at a location not further than 5 km from its predecessor. Unfortunately these time-differences refer to processing times; a better criterion could be defined and better results could be obtaind if actual stroke times were available. The choice of 5 km depends on the present location accuracy (Section 4) and might be made more restrictive in the future. This multiplicity criterion is also used by N.V.Kema (Janssen, 1989).

Secondly, very weak discharges are considered to result from invalid solutions, which are presently not discarded by the software. So, e.g. intense thunderstorms in southern Europe may sometimes result in false lightning reports located near the North Sea coast off Rotterdam. As the signal amplitudes are erroneously assumed to origin from a too close location, the currents assigned to such flashes will be rather small. At present all strokes with reported current below 3500 A are discarded, because they are considered to result from false solutions. This criterion is derived from comparison of the amplitude distributions on days with and without thunderstorms.

We should mention that, considering lightning protection, the neglect of low current strokes is by no means trivial. Such strokes, if they really occur, are difficult to trap with lightning conductors. They can, e.g., hit overhead power lines after evading the shield wires. If protection against such strokes is necessary, as in the case of explosives storage, the cost may be very high. Statistics on low-amplitude lightning is therefore of practical importance, but difficult to obtain.

4 LOCATION ACCURACY

4a. Location errors.

In Section 2 a positioning accuracy of better than 1 km was attributed to the timing synchronisation. Additional positioning errors are due to uncertainties in the lightning signature used for detection. The radio signal of a lightning stroke originates from the lower part of the lightning channel. Due to the tortuosity of the channel and the finite propagation speed of the current along the channel the measured origin of the stroke may be displaced with respect to the ground strike point by as much as half the horizontal channel dimension (Lee, 1989a). This would imply a location error of 0.5 km or so. This strictly applies to VLF monitoring of thunderstorms and might be less favourable for the present system, which includes reception of higher frequencies as well.

The waveform received may also be distorted by terrain-dependent propagation characteristics. So the phase speed of the signal's maximum may be slightly different from the velocity of light (Le Vine et al., 1986). This effect may be different for the paths to the different receiving stations. Typical errors from these time differences are in the μs range and might thus lead to positioning inaccuracies of 1 km or more.

Finally we must consider errors caused by the digital sampling of the signal: the time is measured in steps of 0.2 μs (total 512 steps) and in addition the maximum can only be recognized from a step difference with preceding or following samples, all quantisized in 128 levels. The estimation of the maximum may attain a better accuracy than 0.2 μs by means of interpolation, but a very flat maximum may still lead to poor timing.

In principle it is possible to recompute lightning positions with different triplets of receiving stations and so reduce the influence of random errors. However, this is not implemented in the present software. Off-line computation of arrival times at redundant stations has been used by Janssen (1989) to estimate timing errors. For an arbitrary subset of the available observations he found a median error of 0.4 μs, and a maximum of 1.9 μs.

Among the errors mentioned so far, are systematic (satellite position, terrain conductivity) as well as random influences (channel morphology, digitization). As the combined effect of the errors is difficult to estimate, we will attempt in the next Subsections to obtain evidence from observations.

4b. Differences between subsequent strokes.

As stated in Section 3 subsequent strokes occurring within 0.2 s at computed locations not farther apart than 5 km were considered components of a multiple discharge. This criterion was based on an analysis of the original data regarding the time and range-intervals between subsequent strokes. Random errors in positioning accuracy may result in different positions for subsequent strokes in multiple flashes. It is therefore difficult to distinguish multiple strokes (at one location) from different strokes that nearly simultaneously occur at different locations. The identification of separate flashes with uncertain location can be made more easily by assuming that rapidly following flashes in the same neighbourhood are highly improbable. The distance between consecutive flashes in the same large thunderstorm complex is on average 29 +/- 13 km (Brown, 1988). This may be explained by the fact that flashes discharge the cloud locally, thereby temporarily preventing new flashes nearby. At larger ranges, however, nearly simultaneous discharges seem to become more probable, as was e.g. observed from Space Shuttle (Vonnegut et al., 1985) and with VHF radars (Mazur, 1982). This triggering action seems to be effective between ranges from several km up to hundreds of km.
A second problem is the analysis of the time-intervals. From lightning studies we know that typical stroke-intervals vary between 0.01 and 0.7 s with a median value of 0.04 s (Golde, 1977). The manufacturer states that each LPATS receiver is capable of processing strokes being only 0.015 s apart. However, the times in the stroke messages are the processing times and not the actual stroke times. Processing times of subsequent strokes may be up to 1 s apart (as observed for the 1989 configuration). The time-intervals between strokes are therefore known with an accuracy of about 0.5 s.
As a typical example of the distribution of time- and distance-intervals between subsequent stroke reports we consider the data from thunderstorms occurring on June 21, 1989 in the northeastern part of the Netherlands as presented in Table 1.

Table 1. Distance (km) between 6220 subsequent stroke reports on June 21, 1989 for two classes of (processing) time interval between those reports.

	km:	<.5	1	2	3	4	5	6	7	8	9	10	>10
time	<.8 s	321	551	365	264	185	125	83	50	41	28	26	623
diff.	>.7 s	19	56	64	58	69	55	51	43	45	40	31	3027

Because the distribution of the time differences has a minimum around 0.8 s (only 13% of the strokes follow between 0.4 and 1.5 s) the results of Table 1 are quite insensitive to the choice of the time cut-off at 0.8 s. This also justifies to draw conclusions on processing time intervals, where actually stroke times would have been relevant. The numbers in the first row may have been underestimated (by less than 10% as will be shown in Section 5 a.)

because strokes are sometimes missed during periods with high lightning frequency. It is also likely that some distant strokes are reported between two components of a multiple flash, thereby contributing twice to the >10 km group in the first row. Apart from the >10 km group, Table 1 shows a strong distinction between the distributions in both rows. The numbers in the upper row are concentrated at small range, even more so because the distance classes represent rings with increasing surfaces, which would have contained larger numbers if the area distribution of consecutive lightnings had been random. This is evidence, that the upper row contains mostly components of multiple flashes, while the second row refers to separate flashes. This distinction can be made despite the fact that processing times had to be used rather than stroke times.

If we accept thunderstorm cells to be unable of producing new flashes within 1 s. and consider rapidly following strokes within 10 km to originate from the same lightning channel we are left with a median distance between consecutive locations of 1.8 km. This is not the distribution of the actual error with respect to the true position but of the differences between wrong estimates. Assuming the actual error to be normally distributed the result of Table 1 can be explained with a standard deviation of 1.5 km.

Note that systematic errors will probably not contribute to different locations of component strokes. Some of the errors mentioned in Subsection 4a, like propagation speed differences or non-perpendicular channels could cause the positioning to be different for different three station combinations. We have repeated the analysis of Table 1 for discharges detected by one station combination only, but the resulting location error was reduced with only about 20%. Also we did not find a clear dependence of these errors from the location, at least not within the territory of the Netherlands.

Tables like this were produced for ten thunderstorm days, all leading to nearly the same conclusions. The criterium for multiplicity used in the present data reduction is based on this analysis. In addition the supposedly subsequent discharges have to be of the same polarity. In Table 1 about 5% of the discharges in the <10 km, <.0.8 s class changed sign. This becomes 1% for the class <5km, <0.2 s. These percentages could be 4 times higher on some other days.

The present criterium (5km, 0.2 s) probably underestimates the fraction of multiple flashes: in the example of Table 1 only 6% fitted in that category, while 30% would have been found if a cut off at 10 km, 0,8 s had been used. An improved criterium will have to be based on a possible future reduction of the random location error.

4c. Flash locations compared with ground observations.

The total effect of random and systematic positioning errors will only emerge in comparisons of the network data with 'ground truth', i.e. observations of lightning discharges with known locations. Examples are damage reports. However, the timing in such reports is usually uncertain, so it is difficult to determine which of the nearby ATD positionings has to be associated with the ground strike occurrence. In the present study this approach was restricted to 20 ground strikes with known time and place. These cases were not in contradiction with the results of the previous section: differences

between 0.2 and 8 km with a median value of 2.5 km.
A second approach was the use of thunder reports by human observers. At the request of KNMI volunteer observers payed special attention to nearby (within 3 km) lightning discharges. From these reports 107 cases could be compared with data from the KEMA network and in 54 cases a flash was located within 5 km from the observer. Of course it is difficult to be completely sure of distance estimates based on the time difference between lightning and thunder. Some lightning flashes have been observed to run nearly horizontal before bending to the ground; this behaviour could easily lead to an underestimate of the range. These results provide at least some circumstantial evidence, that the median positioning error is a few km.

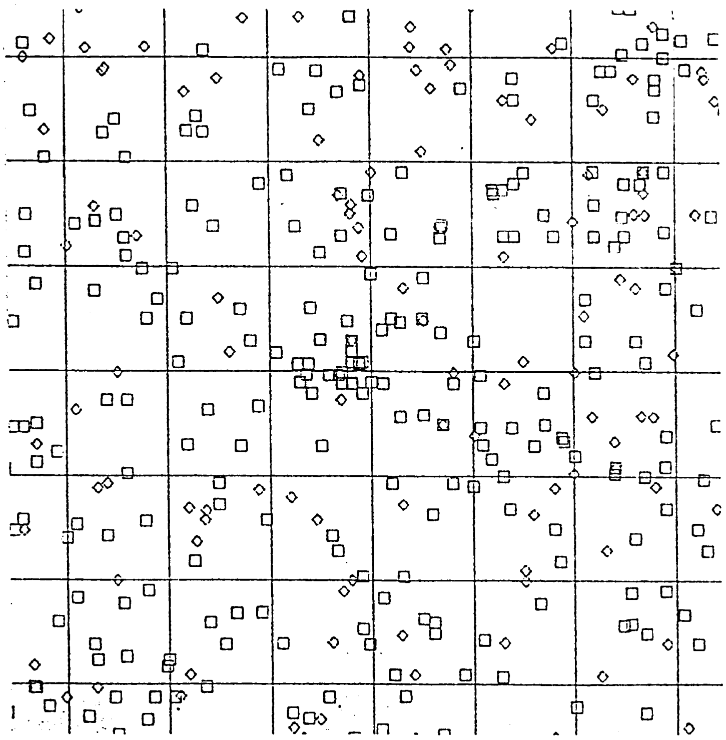


Fig.1.
Distribution of flashes during 1988-1989 around five high towers specified in Table 1. The pictures for the five towers have been superposed so that each tower is at the central crossing of the 1 km grid. Discharges carrying positive charge to earth are represented by diamonds.

4d. Flashes near high towers.

Towers with heights exceeding 100 m have the capacity to trigger lightning discharges with upward leader strokes. The resulting return strokes carry on average lower current than those to flat country, usually less than 10 kA. The circumstance that these strokes to the highest parts of the tower effectively discharge the overhead cloud regions, does not protect the surrounding terrain. On the contrary, the electric field distortion caused by the tower will attract discharges from outside the discharged cloud region, i.e. from ranges comparable to the height of the tower. These discharges have normal downward leaders and will strike in the lower parts of the tower, the guy lines, or the nearby terrain (Gorin et al.,1976). The latter authors report about 30 (upward leader) strikes per year to a 540 m tower and in addition a doubling of the normal lightning frequency in the 500m circle surrounding the tower.

An attempt has been made to verify this suspected higher lightning incidence in and nearby high towers with data from the ATD network. The results are presented in Figures 1 and 2 and Table 2. To obtain a sufficient amount of data the results of five towers have been considered, and, in this Section only, the period covered has been extended to 2 years.

As the distance ranges in Table 2. represent equal areas we may conclude that a significant concentration of discharges is found in the first 1000 m from the three highest towers. Conclusions with regard to the two last towers cannot be made, because they experienced too few nearby flashes.

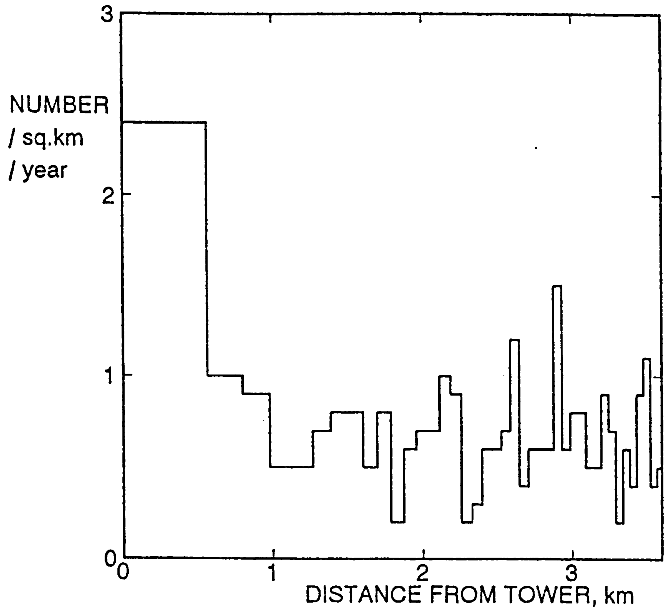


Fig.2.
Flash frequency (per km^2 per year) for the data of Fig.1 as a function of distance towards the tower.

Table 2. Number of flashes located in concentric rings of 1 km^2 around five high towers in the Netherlands during 1988-1989 (2 years). The towers are listed in order of decreasing height: Lopik-TV (380 m), Hoogersmilde-TV (312 m), Cabauw KNMI meteorological tower (214 m), den Oever-TV (200 m) and Roermond-TV (192 m).

range (km)	0.56	0.80	0.98	1.12	1.26	1.38	1.49	1.60	1.69	1.78	1.87	
Lopik	14	3	6	3	2	2	3	1	1	3	1	4
Smilde	3	3	1	0	0	2	2	2	2	2	1	1
Cabauw	5	3	0	1	2	1	3	2	1	1	0	0
den Oever	1	0	1	1	1	2	0	1	1	0	0	0
Roermond	1	1	1	0	0	0	0	2	0	2	0	1

An interesting question is, whether the strokes in the nearest group have struck the tower top or have merely been attracted towards the tower. The flashes in this group have a quite usual distribution of currents with a median value of 24 kA, i.e. much higher than the values reported by Gorin. Inspection of the original data does not reveal the frequent occurrence of low current strikes into the tower that have later been removed by the 3.5 kA criterium. The final decision on the striking point of these flashes can only be based on local measurements in or near these towers.

The coincidence of flashes with the tower position looks better than the 1.5 km median error found in the previous sections. This could point to a smaller random error for this special category of flashes. It seems probable that these data refer to strokes into the towers and that those strokes were located with a median accuracy of about 500 m. The discussion of Subsection 4a. dealt with comparisons between subsequent component strokes; it is possible that the main radiating part of a lightning channel is found at different heights for first, respectively following strokes. For non-perpendicular channels this could explain part of the difference. This explanation, however, does not help to fix the actual lightning position any better.

5 DETECTION CAPABILITY

5a. Evidence from system limitations and system redundancy.

The usefulness of the data for forecasting or climatology depends on the certainty of capturing all ground flashes and the avoidance of any false alarms. The software necessarily contains compromises which lead to removing valid data and accepting false data. New versions of the software will show a different behaviour in this respect.

Timing inaccuracies lead to a certain margin of acceptance. Unfortunately, the timing is based on the flat peak of the signal rather than the steeply rising flank. The removal of false data by amplitude comparisons in the newest software version is hindered by the limited validity of Equation 1. The actual dependence of amplitude on lightning current depends e.g. on the morphology of the lightning channel, the range of the receiver and the variable electromagnetic properties of the terrain. In addition the accuracy of the gain setting and the effects of the digitisation have to be accounted for.

Before starting a comparison with other data, we summarize the possible causes of detection errors as follows:
- general or partly system failure,
- reduced sensitivity during overhead thunderstorms,
- missing of data due to system saturation,
- missing data due to coincidence of flashes,
- discarding of valid data by a too restrictive algorithm,
- erroneous acceptance of displaced solutions.

Some information on the second and third problem (system properties) can be extrapolated from the statistics of the availability of redundant positionings. It is estimated that only 8% of the flashes will be missed by these causes (Janssen, 1989). The possibility of the coincidence of flashes may be estimated with a statistical analysis as follows. A complete flash may sometimes last longer than 1 s. However, the median value of the total flash duraton is about 0.2 s. Assuming a fixed duration of 0.2 s for each flash and assuming the flashes to occur independently with an average frequency of 1 s^{-1} (about the maximum flash frequency observable with the present system) we may apply Poisson statistics. The probability that flashes will partially overlap is then approximately $1-\exp(-1.0*0.2) = 0.18$. This is an estimate of the number of cases that a new flash starts before an earlier flash has ended. Strokes in the non-overlapping part of the flashes may still be detected. The probability that a flash is completely missed is probably below 10%, even at such a high flash frequency.

5b. Comparison with thunder reports.

Thunder reports are obtained by professional (full-time) observers or amateurs. The range of these observations depends on the observer, the ambient noise level and the type of thunderstorm. In most cases the limiting range will be around 15 km. A major problem for the comparison with the lightning location network is the inevitable inclusion of cloud to cloud discharges in the thunder observations. Although rather different quantities are compared, the result is of interest for the possible extension of long-term climatological thunder frequency records. The main results for the comparison with 16 synoptic stations are summarized in Table 4, but a more detailed account is given in Table 3 and Figs. 3 and 4. The network data have been selected on two criteria, namely lightning located within circles of 15 respectively 20 km radius around the synoptic station. Table 3 shows that - regarding hourly data - the 15 km radius gives the best comparison with the human observers. A discussion on choice of the observer range and a detection criterium for the network and their influence on detection probability and false alarm rate is also given by Brown (1989).
According to Table 4 the observers miss 44% of the 'lightning' hours, (the network reports false alarms or more probably weak solitary flashes) and equally 44% of the thunder hours are missed by the network (system or software failure, intracloud lightning). The latter figure was 34% for the 20 km radius, which compares well with the results of Brown (1989) and is also in the range (20-37%) reported by Changnon (1989) for a comparison of thunder events (not necessarily 'hours') with results from a direction finder network. The right half of Table 3 is a comparison with thunder days. Due to the less stringent time coincidence the fraction of missed thunderstorm days in the right part of Table 4 is only about 20% compared to 44% for the hourly data. We note that the number of days with only one report is quite large. Days with 1 count overestimate the thunder frequency, while the occurrence of two counts is a too pessimistic estimate. The reason is that many isolated single counts are false alarms (dislocated solutions). These are rare, but so are thunderstorms. If we consider the whole territory of the Netherlands the network reports at least one discharge on 200 days of the year, while thunderstorms occur on only about 110 days.
From both parts of Table 3 it appears that there is a seasonal tendency in the comparison between observers and the network. This may be caused by a higher percentage of intracloud discharges in the summer months; these are heard but will not so easily be detected by the locating system. The comparison has also been carried out for separate stations and those results have been presented in Figures 3 and 4 for hours and days respectively. Apart from the contribution of false reports along hyperboloid sections near the stations VB, GR and BK no systematic difference between the stations can be pointed out.

Table 3. Comparison of hourly/daily thunder observations (average of 16 synoptic stations) with network lightning reports (rep.) within 15 km or 20 km (1988-1989). Hours with system failure have been corrected. Numbers between brackets refer to occurrence of both lightning positioning and thunder in the same hour or day.

	hours			days		
	thunder	network reports		thunder	network <15 km	
month	observed	<20 km	<15 km	observed	1 report	2 report
jul	10.8	11.1 (6.7)	8.4 (6.2)	4.5	4.9 (3.6)	3.8 (3.3)
aug	8.6	12.2 (6.3)	9.2 (4.9)	4.0	4.9 (3.3)	3.8 (3.2)
sep	5.5	9.2 (3.9)	6.5 (3.1)	2.5	3.7 (2.0)	2.7 (1.8)
oct	6.9	7.8 (5.2)	6.2 (4.6)	2.3	2.8 (2.0)	2.3 (1.7)
nov	0	0.8 (0)	0.5 (0)	0	0.4 (0)	0.1 (0)
dec	1.2	1.2 (0.7)	0.9 (0.5)	0.8	0.8 (0.6)	0.4 (0.3)
jan	0	0.3 (0)	0.1 (0)	0	0.1 (0)	0 (0)
feb	0.7	1.4 (0.1)	0.9 (0.1)	0.4	0.5 (0.3)	0.2 (0.2)
mar	0.8	0.7 (0.3)	0.6 (0.3)	0.4	0.4 (0.3)	0.2 (0.3)
apr	1.2	1.8 (0.3)	1.3 (0.3)	0.7	1.4 (0.6)	0.7 (0.4)
may	2.8	3.9 (1.9)	2.6 (1.7)	1.2	1.6 (1.1)	1.2 (1.1)
jun	7.5	11.6 (4.8)	9.4 (3.9)	2.9	4.1 (2.5)	2.9 (2.2)
year	45.8	61.8(30.2)	46.1(25.7)	19.6	25.4(16.2)	18.0(14.6)

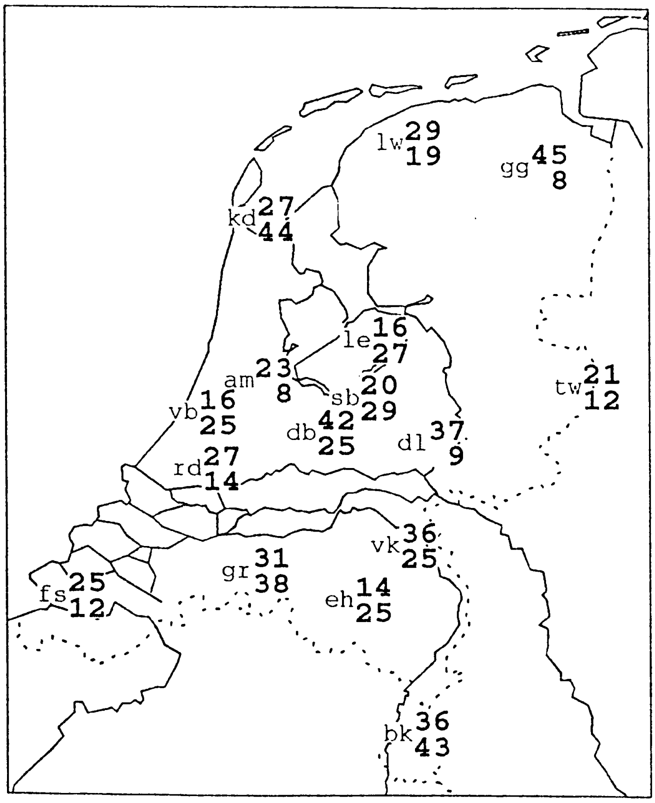


Fig.3.
For each station (coded with two letters) two numbers are presented, comparing thunder days and the network detection of at least 2 lightnings within the 15 km range:
- the percentage of thunderstorm days missed by the network criterium and
- the percentage of network lightning days without thunder.

Table 4. Contingency tables summarizing the results of Table 3.

hours/year	thund.	no th.	+
rep.<15 km.	26	20	46
no rep.	20	8694	8714
+	46	8714	8760

days/year	thund.	no th.	+
2 rep.<15 km.	15	3	18
no rep.	5	342	347
+	20	345	365

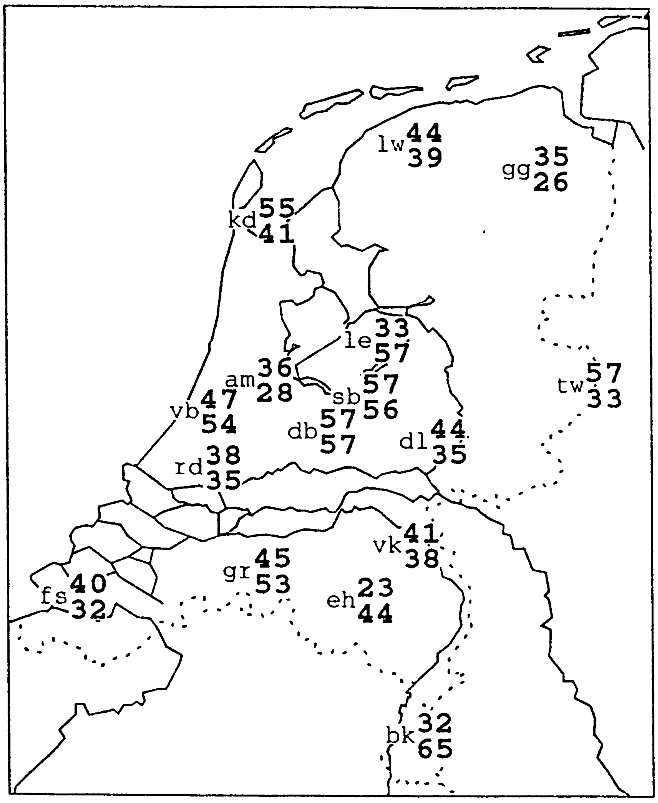


Fig.4
As Fig.3 for hourly thunder observations and hourly network counts of at least one.

We may conclude that a reasonable correlation between the traditional thunder observations and the modern lightning network results exists. For continuation of observation series located lightning within 15 km simulates thunder hours, while two such reports relate to thunder days. These figures depend on both observer and network quality. Of course every located lightning should be used if the system is applied for warning purposes.

5c. Comparison with flash counters.

The 6 lightning counters used for this comparison were spread over the centre part of the Netherlands. These instruments have been in operation since the early seventies (Wessels, 1977). The aerial is a vertical rod of about 4 m and the received frequency band is from 5 to 70 kHz (centered at 17 kHz). Only positive field changes are accepted: this reduces disturbance by point discharge through the aerial, without affecting the effectivity of the counter. The median triggering distance was shown to be about 10 km in the summer months. Within the frequency band of these counters, Equation (3) will approximately be valid. A flash will be counted if a certain triggering field strength is exceeded. The counters will not accept pulses following faster than 0.22 sec, so many subsequent strokes will be rejected. Due to the restricted range the probability of missing succeeding flashes is low.

To compare both detection systems we have recomputed for each of these counters the expected field strength caused by any of the flashes detected by the ATD system during one year. To avoid problems caused by the sometimes inaccurate timing the lightning counter recorders, we compared daily totals.

From inspection of counts by both systems it appeared that the range dependence of Equation 3 did not fully apply for distant strokes: the lightning signal seems to decrease with range with a power <1. This might be caused by ionosperic reflection sometimes favouring the triggering of counters by normal amplitude strokes as far away as 100 km. On the other hand, theory predicts for the lightning counters an increased sensitivity compared to Equation 3 at ranges smaller than 20 km. Indeed an overall range dependence with power -1.2 had been found during the evaluation of these counters (Wessels, 1977). Israelsson et al. (1984) reported a -1.29 dependence for propagation over land in connection with a direction finder system. In spite of these incertainties, Equation 3 has been maintained for the following comparisons. This decision is supported by a statistical comparison between various one-term power relations for the decrease of signal with range. A relation with power -1 provided the best correlation between the simulated and measured lightning counts.

An illustration of the differences between simulated and real counts is given in Table 5. The results should be looked at with reservation, because the simulation-equation is only tentative and systematic differences in 'K' of Equation 3 may influence the results. Furthermore the individual counters may have different sensitivity due to instrumental defects or antenna exposure. During short periods the network was temporarily out of order, notably on Aug.8, May 12 and a few of the 'other dates'. The totals will therefore not be very accurate. The voltage threshold (20 V/m) used for the simulation has been chosen to 'tune' the average totals from the two series.

The following conclusions can be drawn:

- Comparison with the counters -on an hour to hour basis- shows that about 4.5% of the flashes during this year were missed in this part of the country due to temporary network failure.
- On single days most of the counters demonstrate the same pattern: the network counts are systematically lower or higher.
- Taken into account probable systematic differences between counters and the suspect or incomplete data (* in the table) the counters are reasonably well simulated on most days.
- On some days, notably July 23 and August 28 the present simulation overestimates the actual counts. This cannot be explained by the $^{-1}$ power relation used for the range correction, because most of the flashes involved were located within 10 km of the counters and should have caused easier triggering than predicted by Equation 1. A clue to the cause of the tabulated differences comes from many volunteer observers, who noted a remarkable high percentage of horizontal discharges on precisely these days. The claim of the manufacturer that the system detects

only cloud-to-ground lightning is not based on any observational evidence, but on the supposition that intracloud lightning follows perfectly horizontal paths. Lightning counters with a similar low frequency response as the ATD system have been reported to respond to nearby and/or strong cloud flashes (Cooray, 1986). It is reasonable, that a major part of the triggerings results from cloud flashes on days that these occur abundantly. An independent confirmation of the counting of cloud flashes on some days is found by noting on precisely those days the large number (up to 20%) of sign changes in nearby strokes, for that reason not accepted as subsequent strokes.

An interesting relationship can be found between the data of Table 5. and the height of the freezing level. This is illustrated in Fig.5., which shows for rising freezing level a transition from under- to over-estimation of the simulations compared to the flash counters. The same trend is found for the other 5 counters. Indeed, intracloud discharges become more probable if the main charge centers rise to greater height; a phenomenon well illustrated by the predominance of intracloud lightning in equatorial regions.

Table 5. Comparison of daily lightning counts (right columns) with simulated counts from ATD detected lightning (E > 20 V/m). Selected are days with at least 12 counts on one of the stations. Data with '*' are incomplete (network) or suspect (counters).

station:	SP		LE		RD		DB		GR		VK	
1988												
Jul. 4	37	24	1	10	16	11	1	2	2	0	2	0
13	83	66	12	23	67	53	20	15	3	3	0	1
14	4	3	6	22	23*	23	3	5	19	46	4	5
23	33	10	37	8	12	14	24	4	39	11	246	151
29	1	1	2	12	0	1	1	0	0	0	0	0
Aug. 8	0	0	17*	46	0	0	0	0	0	0	4	0
10	22	18	7	12	36	30	26	2	119	1*	10	2
20	33	51	35	57	26	19	18	11	2	2	1	0
21	6	5	27	38	1	2	3	1	0	0	3	0
25	2	12	11	20	4	4	2	2	0	1	0	1
28	93	13	68	31	45	9	56	14	69	42	19	0
Sep. 2	3	15	4	11	2	10	1	4	4	6	9	16
12	34	71	9	31	22	24	16	21	5	11	3	9
23	6	20*	23	23	3	15	10	11	7	10	4	10
Oct. 5	7	7	1	2	35	56	2	2	1	2	0	0
6	29	32	26	24	5	7	12	8	0	0	0	0
7	26	21	30	34	38	73	41	43	47	64	35	55*
10	8	11	11	15	3	5	0	5	0	0	0	0
Dec. 6	5	5	5	16	4	12	4	10	2	9	2*	9
1989												
May 12	10*	33	17*	31	8	25	11*	29*	18*	17	24*	29
13	2	1	7	20	1	1	1	1*	1	0	1	0
Jun. 8	6	13	9	25*	6	44	4	17	5	30	8	31
26	9	0*	17	10*	10	8	25	6	25	30	54	15
other dates	39*	57	22*	64*	39*	66	33*	49	39*	51	32*	27
1 year	498	486	404	580	406	511	314	261	407	336	461	355

Fig.5.
Daily lightning counts simulated with ATD data, divided by real counts for station Rotterdam(RD), as a function of 700 mbar temperature.
The line represents the log-linear regression curve.

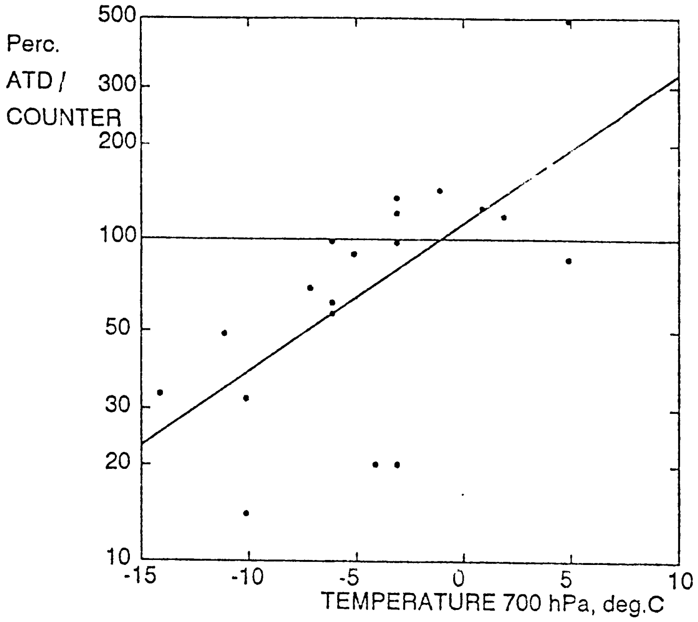
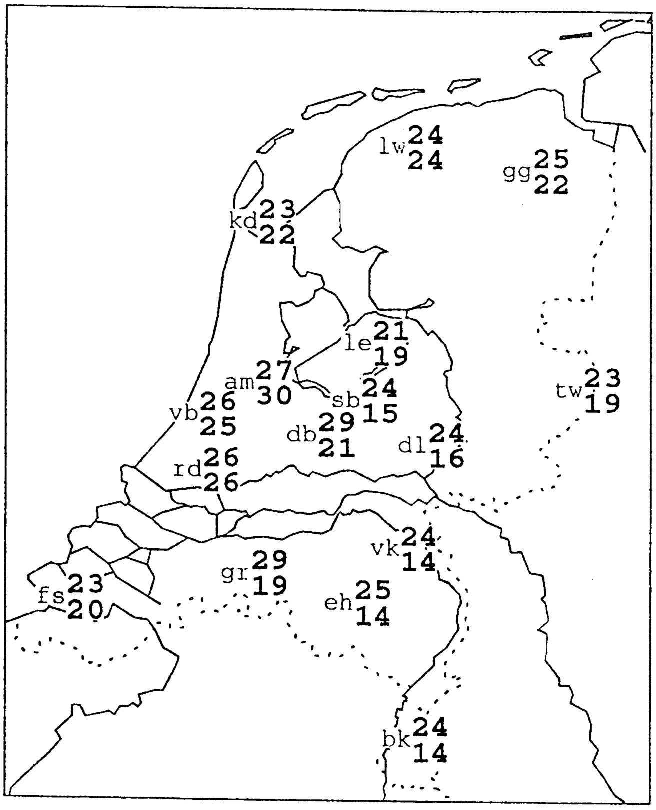


Fig.6.
Thunderstorm days in the comparison period of 1 year 1988-1989, compared with the yearly average number of thunderstorm days 1951-1980 (in brackets).
Values for the newer stations DK and LE are partly estimated.



6 CLIMATOLOGICAL RESULTS

6a. Average lightning flash density.

A further use of the data from Table 5 can be made if we want to establish whether the present measuring year was representative of the local lightning climatology. Long series of lightning counts (14 years: 1974-1988, 1980 excluded) are available for 4 of the stations tabulated in Section 5c. The average yearly count was 973(RD), 630(DB), 782(GR) and 694(VK) (standard deviations respectively 381, 394, 323, 410).

Lightning was relatively rare during the present comparison year: only 46±6 % of the long term average was reached according to the counters. This is confirmed qualitatively by the lower number of thunderstorm days, especially in the south-eastern half of the country (Fig.6).

The average lightning density (ground flashes per km^2 per year) measured by the ATD network was 0.62. A small fraction of these will have been cloud discharges and an even smaller fraction are dislocated strokes that actually occurred outside the country.

The loss of data due to general network failure may have been 4.5 % if the comparison with counters in Section 3 is representative for the whole country. In addition some data may have been lost due to coincidence of flashes, or a too restrictive location algorithm. Moreover, if e.g. two receivers had a reduced sensitivity due to nearby storms, they may have missed flashes in a third storm farther away. This latter category may be estimated from redundancy statistics at 8% (Subsection 5a).

The average flash density so corrected will have been 0.70. It is tempting to extend the lightning counter statistics by assuming that this is 48% of the long term average, which then would be 1.5 (discharges per km^2 per annum). This preliminary result is at the low end of the value between 1.3-2.7 estimated with the lightning counter network during the years 1974-1976 (Wessels, 1977). In retrospect the average count obtained in those years seems to have been representative of the 14 year average available now.

A better estimate (with smaller spread) of the average flash density can be obtained if more years of data become available, hopefully with improved processing software. Major unknown quantities are the numbers of discharges missed and the number of intracloud flashes inadvertently included. Most probably the lightning density will not only vary from year to year, but will also experience climatological fluctuations. Therefore permanent monitoring is advisable.

6b. Horizontal variability.

A second point of interest is the average horizontal distribution of lightning incidence. In particular, the occurrence of 'hot spots' is of interest with regard to lightning protection and damage insurance. In this section we are concerned with general meteorological and topographical influences and not with preferred lightning strikes into single towers or trees.

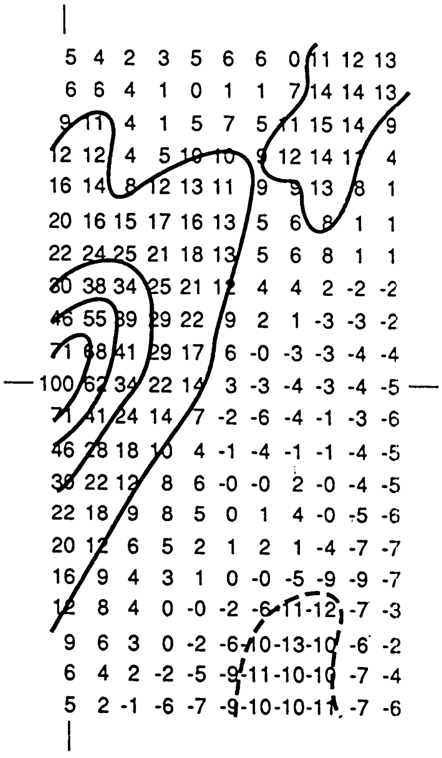
The measured ground flash density during the period investigated is shown in Figure 7. The concentrations of flashes, e.g. near the west coast, can be attributed to the few heavy thunderstorms that passed the country during this year. Such storms have a typical diameter of 20 km and move during their lifetime over a distance of

50 to 100 km. In other years (usually more) comparable storms may follow different tracks.

Of practical interest is the question, how many years of data are needed, to establish statistically valid evidence on the (non)existence of favoured lightning spots. Longer series of data are needed if the differences are small and/or are studied on a small horizontal scale. So a few years of data would probably allow to demonstrate the frequency of flashes into the North Sea to be significantly lower than over land, but it is more difficult to indicate preferred regions over the land.

Fig.7.
All flashes located by the system from July 1988 until June 1989.

Due to possible location errors, the 5x5 km squares are about the smallest suitable scale for studying horizontal variability. For the last part of this Section the study was restricted to a 200x 200 km square. The standard deviation σ of the differences between neigbouring 5x5 km pixels is 13.5, compared with a mean number of 17.5 flashes per pixel per year. If these data were representative for the horizontal variability of the flash density, we would need 10 years of data to demonstrate whether long-term differences of 50% between pixels existed or not (i.e. $0.50*17.5 > 2\sigma/\sqrt{n}$, where n is the number of years). If the actual differences are only 20% the data set would have to cover even 60 years.
The horizontal correlation of the 5x5 km totals (Fig.8.) suggests a decorrelation distance of about 20 km, which conforms well with the typical dimension of a heavy thunderstorm. If the pixels are combined into 20x 20 km boxes, the data become more independent and horizontal differences on a larger scale can be explored. The average number of flashes for this year was 285 per box, while the differences between neighbouring boxes had a standard deviation of 200. Data for 8 years would then be needed to confirm 50% differences.



5	4	2	3	5	6	6	0	11	12	13
6	6	4	1	0	1	1	7	14	14	13
9	11	4	1	5	7	5	11	15	14	9
12	12	4	5	10	10	9	12	14	11	4
16	14	8	12	13	11	9	9	13	8	1
20	16	15	17	16	13	5	6	8	1	1
22	24	25	21	18	13	5	6	8	1	1
30	38	34	25	21	12	4	4	2	-2	-2
46	55	39	29	22	9	2	1	-3	-3	-2
71	68	41	29	17	6	-0	-3	-3	-4	-4
100	62	34	22	14	3	-3	-4	-3	-4	-5
71	41	24	14	7	-2	-6	-4	-1	-3	-6
46	28	18	10	4	-1	-4	-1	-1	-4	-5
30	22	12	8	6	-0	-0	2	-0	-4	-5
22	18	9	8	5	0	1	4	-0	-5	-6
20	12	6	5	2	1	2	1	-4	-7	-7
16	9	4	3	1	0	-0	-5	-9	-9	-7
12	8	4	0	-0	-2	-6	-11	-12	-7	-3
9	6	3	0	-2	-6	-10	-13	-10	-6	-2
6	4	2	-2	-5	-9	-11	-10	-10	-7	-4
5	2	-1	-6	-7	-9	-10	-10	-11	-7	-6

Fig.8.
Correlation surface of lightning density in 5x5 km boxes. Data of one year in a 200x200 km area.
The left half-plain is not shown, because it is the mirror image of the right half plane with respect to the box marked 100.

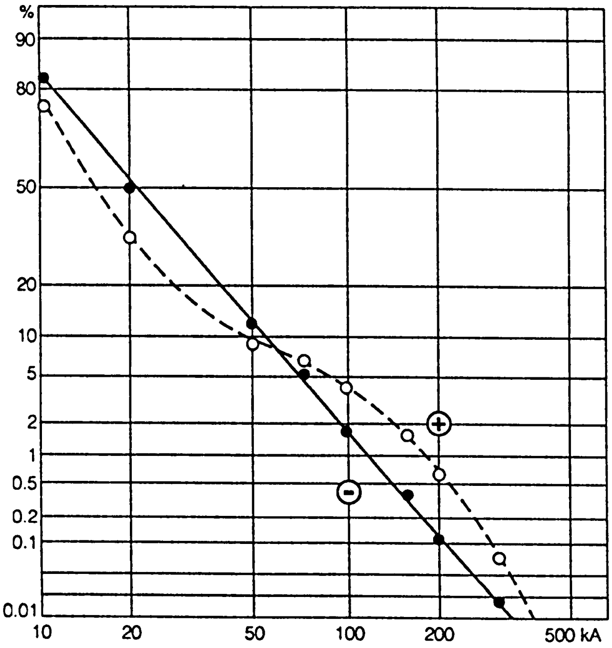


Fig.9.
Cumulative frequency distribution for lightning currents in the Netherlands during one year.
Separate curves are shown for positive and negative lightning currents.

Of course, we have collected only one year of lightning positions and the long term differences on a 20 km scale are yet unknown. However, a 20x 20 km box is comparable with the 10 km median detection range around a lightning counter. We have lightning counter data over 14 years and these suggest that possible systematic differences between adjacent counters are of the order of 20%. Such small differences could only be established with confidence by a series of about 50 years with ATD data.
The main conclusion of the results of Section 6 is, that many decades of data will be needed to investigate the average value of the horizontal variability of lightning incidence in the Netherlands.

7 ANALYSIS OF PHYSICAL PARAMETERS

7a. Flash frequency, current amplitude and polarity.

The frequency distribution of peak currents is of interest for the design of lightning protective systems. The results for the present year are shown in Fig.9 for positive and negative discharges separately. The frequency of currents larger than 100 kA is smaller than reported by Berger (Golde, 1977, p.316), but the slope and the relative position of the curves are the same. The results for negative currents follow quite well the log-normal distribution. Although only 31% of the flashes are positive, they dominate in the group with current exceeding 100 kA. Fig 9 gives a fair idea of the relative frequency distributions. The absolute values along the coordinates depend on the accuracy of Equation (3) and on the fraction of weak lightnings not detected or not accepted by the system.
The data available (a general view is presented in Appendix A) show no clear seasonal change of the current distribution. A possible dependence with e.g. the freezing level height could not be confirmed. Although there is a tendency for the percentage of strong (>50 kA) negative flashes to vary from 10% in cold atmospheres to 5% in warm atmospheres, the data of July 23, one of the warmest days with 21%, are in complete disagreement. As noted, in section 5c, it might be that the relationship is disturbed by the inadvertent inclusion of a large percentage of cloud flashes. The data processing of the present ATD system, offers no systematic analysis of other important lightning parameters, like current rise time and total charge.
The local intensity of lightning has been evaluated over fixed 5x5 km squares for 5 min. intervals. For each day the maximum of these 5 minute lightning densities, encountered anywhere over the Netherlands is plotted in Fig.10 against the 700 mbar temperature. As was found from earlier studies with lightning counters the maximum lightning intensity attainable is increasing with temperature (Wessels, 1977). The actual maximum lightning production on a given day depends also on the intensity of the convection. Part of the increase at higher temperatures might still be attributed to the increasing number of intracloud flashes.
In recent years, many attempts have been made to connect the percentage of positive flashes with meteorological parameters like freezing level height, windshear, and low level vorticity (Reap et al., 1989). Positive lightning is usually connected with the cold season. The data available now, show no relation with either the 700 mbar temperature or the 700 mbar wind velocity, the latter

being a course measure for windshear. The strong dependence on moisture convergence, found by Reap et al., was not confirmed by the available model output fields from ECMWF. Unfortunately, long series of low level vorticity fields from a smaller grid model were not available. Here again, the relations may have been disturbed by the frequent measurement of cloud fashes during warm weather: signals from such flashes will have no preference for either polarity.

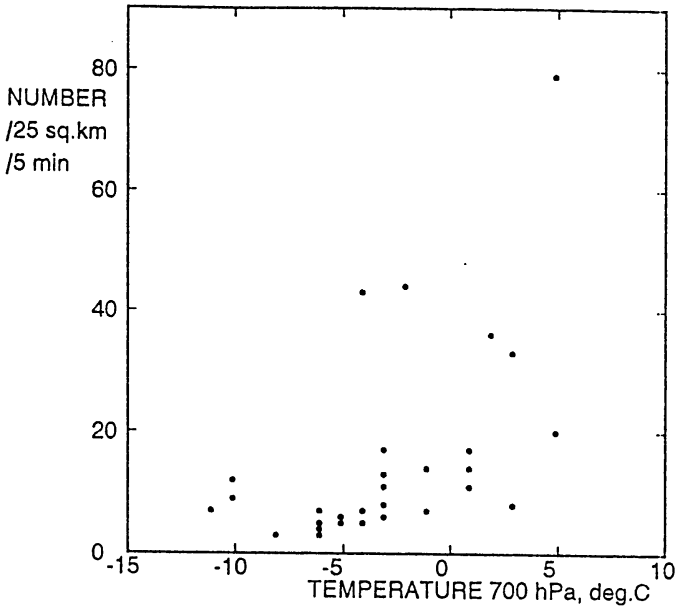


Fig.10.
Daily values of maximum lightning production over fixed 5x5 km squares in fixed 5 min. intervals. The lightning densities are classified according to 700 mbar temperature.

7b. **Multiplicity of lightning flashes.**

Table 1 illustrates that the present multiplicity criterium (Section 3) probably overestimates the percentage of single flashes. The average percentage is 65% of the strokes (82% of the flashes). This is much higher than the percentage found with photographic measurements in New Mexico and South Africa (Golde, 1977, p.130-132). Flashes observed by Berger were usually single, but these strokes were probably not representative for typical lightning in the Netherlands, because Berger measured in mountainous country and the flashes were usually preceded by upward leader strokes.

Evidently the present time resolution of the ATD system causes some multiple flashes to be classified as single. Also the present criterium (based on processing times and a relatively poor location accuracy, is too restrictive. Experiments with acceptance of strokes up to 0.8 s later and correction for intervening distant strokes, reduced the number of single flashes to 34% and showed flashes with up to 7 components. However, operational introduction of a better criterium will only be possible if the actual stroke times are included in the messages.

Although the percentage number of multiple flashes is underestimated, we can still note that multiplicity occurs less frequently for lightning with positive polarity. Positive discharges with currents exceeding 150 kA are almost exclusively single.

8 CONCLUSIONS

- Location errors up to several km are found from most comparisons. Only flashes striking high towers seem to be located more accurately. From the locations of successive components of multiple flashes a median location error of 1.5 km was estimated. The use of a 1 km resolution for data archiving is sufficiently accurate.
- On many days the system displays false alarms; these occur normally at intervals of an hour or more. For operational warning purposes combined presentation with weather radar would prevent any misunderstanding. A first impression of the results from the software installed in July 1989, suggests no spectacular improvement in this respect.
- During intense thunderstorms a small number of discharges is not detected due to system operation and capacity. This fraction is probably less than 10%.
- During summer thunderstorms the system accepts intracloud discharges. The percentage is yet unknnown, but probably quite significant.
- The detection efficiency of the system is sufficient for warning purpose. Caution should be exercised while using the system to confirm individual flashes (e.g. for insurance claims).
- Comparisons with observer networks and lightning counters show appreciable differences, most of which can be explained. The statistics presented in this report provide some means to combine these different measuring series. A rather rough criterum as 'day with thunder heard on a station' is reproduced with 80% compatibility by the ATD system (taking 2 reports inside a 15 km circle), while thunder hours match in only 56% with hours with 1 detected lightning within 15 km.
- The data collected until now do not contradict an earlier estimate (with lightning counters) of the lightning density in the Netherlands, which was about 2 per square km per annum.
- More than 10 years of data will be needed to specify horizontal differences of lightning incidence over the inland part of The Netherlands. Differences on a smaller scale than 5 km are probably untraceable with the present location accuracy.
- The system is capable to collect information on a limited number of lightning parameters. The first year's statistics of current amplitudes seem reliable.

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APPENDIX

Statistics of lightning data collected in the Netherlands during 1 year

The following table lists days with at least 45 discharges. The columns show: month, day, 700 mbar winddirection and velocity (kts), 700 mbar temperature, total number, median lightning current, percentage positive, percentage multiple (respectively for positive, negative and all discharges) and the percentage distribution in 4 current classes, both for negative and positive lightning.

day	ddff	T°C	nr.	kA	%+	%m+	%m-	%m	-50	-20	-10		10	20	50	kA
0701	2222	1	741	16	16	10	24	21	6	32	31	12	3	8	2	1
0702	2233	-5	159	13	27	9	13	12	3	22	33	11	9	10	3	3
0704	2040	-1	913	11	23	9	18	16	2	18	30	24	11	7	2	1
0709	2720	-6	49	31	28	0	11	8	8	44	16	2	2	2	10	12
0713	2132	-3	744	14	30	12	37	29	11	22	21	13	7	15	4	2
0714	2821	-3	643	19	18	9	32	28	12	32	24	11	7	4	3	1
0713	2440	5	3425	31	29	10	30	24	21	41	7	0	0	12	13	1
0727	2317	-4	96	16	25	4	9	8	3	22	38	10	5	7	8	4
0729	2530	-6	106	23	24	3	17	14	16	37	19	0	4	15	2	1
0808	1613	3	333	12	36	9	24	18	9	18	24	10	18	12	3	2
0810	2315	2	1840	16	52	15	24	20	8	16	17	4	7	25	14	4
0811	2534	1	895	11	47	14	19	17	2	17	18	14	22	16	6	1
0819	2241	3	113	13	29	6	20	15	0	23	33	11	15	8	3	0
0820	2330	-3	828	17	20	12	27	24	8	32	25	11	8	6	3	1
0821	2720	-4	430	27	18	8	35	30	16	40	15	9	6	3	3	4
0825	2828	-6	360	26	23	3	25	20	16	37	18	3	4	8	6	4
0828	2036	5	9315	15	32	12	18	16	4	22	29	11	5	16	8	1
0831	1928	-1	226	21	23	15	15	15	9	40	19	7	5	7	7	3
0902	2333	-4	149	15	37	16	17	16	4	18	28	9	12	8	8	6
0912	2640	-5	424	15	32	13	22	19	12	17	24	13	6	14	4	6
0923	2443	-3	601	14	30	13	19	17	4	22	27	14	9	10	5	4
1005	2127	-5	181	13	29	3	22	17	6	18	23	22	5	16	2	4
1006	2648	-7	329	25	22	12	19	17	26	27	15	8	6	7	7	0
1007	2638	-11	916	19	29	8	23	18	12	26	23	7	7	11	7	3
1010	2629	-6	136	19	24	9	18	16	15	23	25	10	5	7	6	5
1012	1723	-4	58	26	10	16	17	17	5	60	22	1	1	8	0	0
1206	3531	-14	45	16	35	12	20	17	17	17	22	4	6	20	6	2
0316	2336	-6	95	23	20	10	22	20	3	49	26	1	4	6	4	5
0410	2039	-7	56	16	35	5	19	14	5	19	33	5	5	8	10	8
0512	2443	-10	708	10	31	8	5	6	5	13	22	23	11	6	4	4
0513	2531	-9	50	9	36	0	15	10	10	10	12	24	10	10	2	8
0603	3307	-8	75	9	33	0	18	12	4	17	12	28	10	13	5	1
0604	3409	-8	178	19	29	5	30	23	7	25	25	10	1	7	5	12
0608	2517	-10	619	9	33	4	8	7	3	12	19	25	12	7	4	4
0621	2710	-3	1144	17	14	7	6	6	6	35	30	13	4	5	2	1
0622	0513	-2	699	11	30	7	11	10	4	16	25	19	9	8	5	3
0626	2131	1	1520	14	36	15	21	19	7	27	15	11	18	6	5	2
0627	2034	-4	248	12	37	6	9	8	0	18	18	21	9	14	6	4