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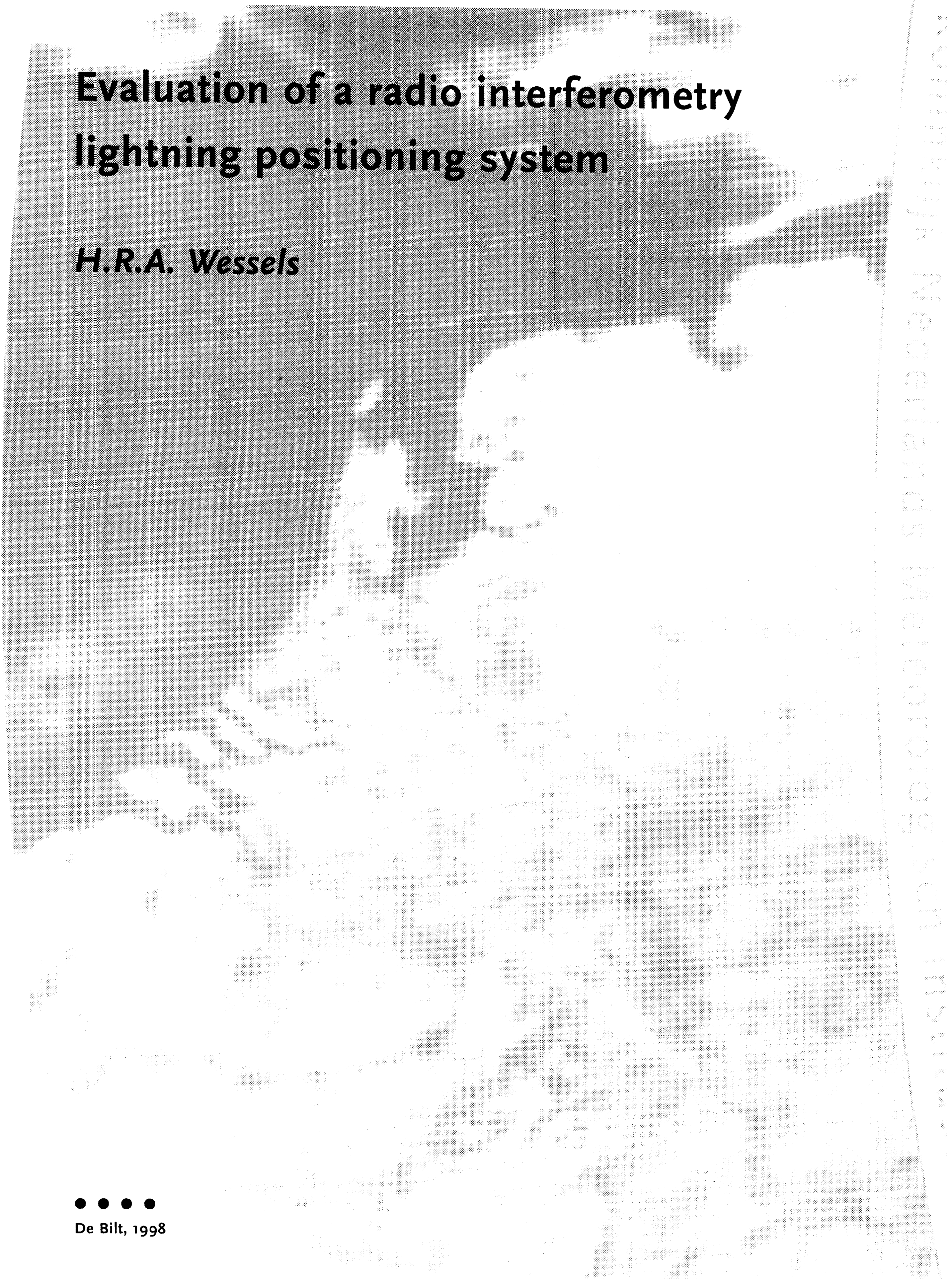
Evaluation of a radio interferometry lightning positioning system

H.R.A. Wessels



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CONTENTS

ABSTRACT

Results from a SAFIR lightning positioning system covering the Netherlands are analysed and compared with observer reports as well as with simultaneous registrations from a LPATS lightning detection network.
The median location accuracy of individual flashes is shown to be about 2 km. The capability of detection is acceptable at short range but diminishes strongly beyond about 150 km. The occurrence of false alarms is negligible.
Although the system is effective in detecting ground as well as intracloud discharges, the capability to distinguish between both types is limmited.
The report also discusses some statistical results on thunderstorm flashing behaviour and on estimated lightning parameters.
Instrumental data over the period 1974-1997 are summarized, showing the average lightning density in the Netherlands to be about 1.5 per square km per year.

1 INTRODUCTION

From 1976 to 1987 the Royal Netherlands Meteorological Institute (KNMI) used a network of lightning counters (Wessels, 1977). In 1987 the N.V.Kema, the research institute of the electricity companies, acquired a lightning location system based on the arrival time difference method (LPATS = Lightning Positioning and Tracking System). KNMI was one of the on-line users of the data. Starting from 1995, KNMI, the Royal Dutch Air Force and the Royal Dutch Navy joined in operating a lightning detection network that should serve the special requirements of operational meteorology. The new system is based on radio interferometry (SAFIR = Surveillance et Alerte Foudre par Interférométrie Radioélectrique / Lightning monitoring and warning by radio interferometry). During 1965 and 1996 a three-station network was used. Because the detection of thunderstorms in the southern parts of the Netherlands proved insufficient, the raw data of three stations of the Royal Meteorological Institute of Belgium (KMI/IRM) are included since early 1997.

The most important difference between the LPATS and SAFIR systems is the more complete inclusion of intracloud discharges by the latter. This is beneficial for forecasting applications. LPATS also detects a large fraction of the cloud discharges, although the original specifications stated differently. In later versions of the LPATS software a distinction was attempted between cloud and earth discharges.

Both detection systems can resolve component strokes of multiple earth flashes. The word 'flash' is used for the complete discharge that may last up to a second. The single components are called 'strokes'. If a stroke is immediately followed by another at (almost) the same location we may conclude that a secondary stroke occurred along the same channel.

A lightning detection system not only reports the time and location of discharges, but also electrical parameters. For earth strokes the direction (up or down) and the maximum value of the current are estimated. The SAFIR system also measures the rise and decay times of the radio signal transmitted by the lightning channel. These values are used to determine various properties of the discharge.

During 1995 data from both the SAFIR and LPATS systems were available, enabling a comparison. So this report contains not only an evaluation of the SAFIR system over the years 1995-1997, but also a comparison with simultaneous measurements by the LPATS system. An earlier evaluation of the LPATS system (Wessels, 1992) will be frequently referred to in the following as: 'WR92'.

The results presented here describe the properties of the Netherlands network over the period 1995-1997. As there is an on-going improvement in this type of instruments (Holle and López, 1993), future network versions may show better results. Also it is important not to confuse errors that are inherent to the measuring principle with errors caused by e.g. the imperfect alignment of an individual system.

2 DESCRIPTION OF THE SAFIR SYSTEM

The SAFIR system is derived from research equipment developed in France (Richard, Aubbray, 1985). The commercial version(s) are manufactured by Dimensions, St.Aubin, France.
A network consists of at least 3 stations and has baselines of about 100 km. Each station is equiped with 3 sensors exposed in a 17.5 m high mast:

- A GPS antenna for time measurement and synchronisation with 0.001 msec accuracy,
- Two localization antennas consisting of pairs of vertical rods at about a quarter wavelength horizontal distance. The pairs are crossed to enable omnidirectional detection. The localization uses lightning signals in a narrow VHF band (about 110 MHz), selected to avoid local noise sources. Location data are discarded if the signals are too weak (<1V) or if the interferometer results do not match, i.e. if the summed squares of the sine and cosine signals are not close to 1.
- A discrimination antenna receiving waveforms at frequencies below 4 MHz. These signals decide between cloud and ground strokes.

The 1995 Netherlands network is represented by the three most northerly dots in Fig. 1. Raw data from each detection station are transmitted to a central processor located in De Bilt. The raw data messages are a combination of: time signals, status information, localiztion data (time, direction and amplitude of a lightning VHF burst) and discrimination data (time, rise time interval, decay time interval and amplitude of the VLF signal).

Locations from two stations are combined by triangulation if they are nearly simultaneous (within 100 μsec), taking into account the propagation delay of the waves. Sources that have a too large azimuth variability are discarded. Furthermore source location restrictions are applied. The lightning source should not be closer than 20 km or farther than 250 km from each station. Also the source should not be too close to the line through the stations: the lines between the source and both stations should cross at an angle of at least 15 deg. If the source is between the stations a maximum angle of 150 deg is allowed.
Subsequent points are accepted as part of a lightning channel if they follow within e.g. 0.5 msec and are less than 7 km apart. Otherwise they are classified as isolated sources.

Finally, discrimination information is added to the interferometer results. The timings of the location data are compared with those of the discrimination data (after correcting for the radiowave propagation speed). Simultaneous points (within e.g. 0.3 msec) are classified as part of an earth discharge if the amplitude and the rise and decay times obey to certain criteria. The decision is predominantly based on the decay time: an earth stroke has a relatively slow signal decay.
Another use is the calculation of lightning parameters. Once the distance R(m) of a source is known, the measured field strength E (V/m) may be converted to an estimate of the maximum lightning current. The SAFIR system uses an empirical relation

$$I \text{ (kA)} = E * R^{1.137} / 58098 . \qquad (1)$$

By definition a negative discharge transports negative charge from the cloud to the earth. Other lightning parameters, like the rate of

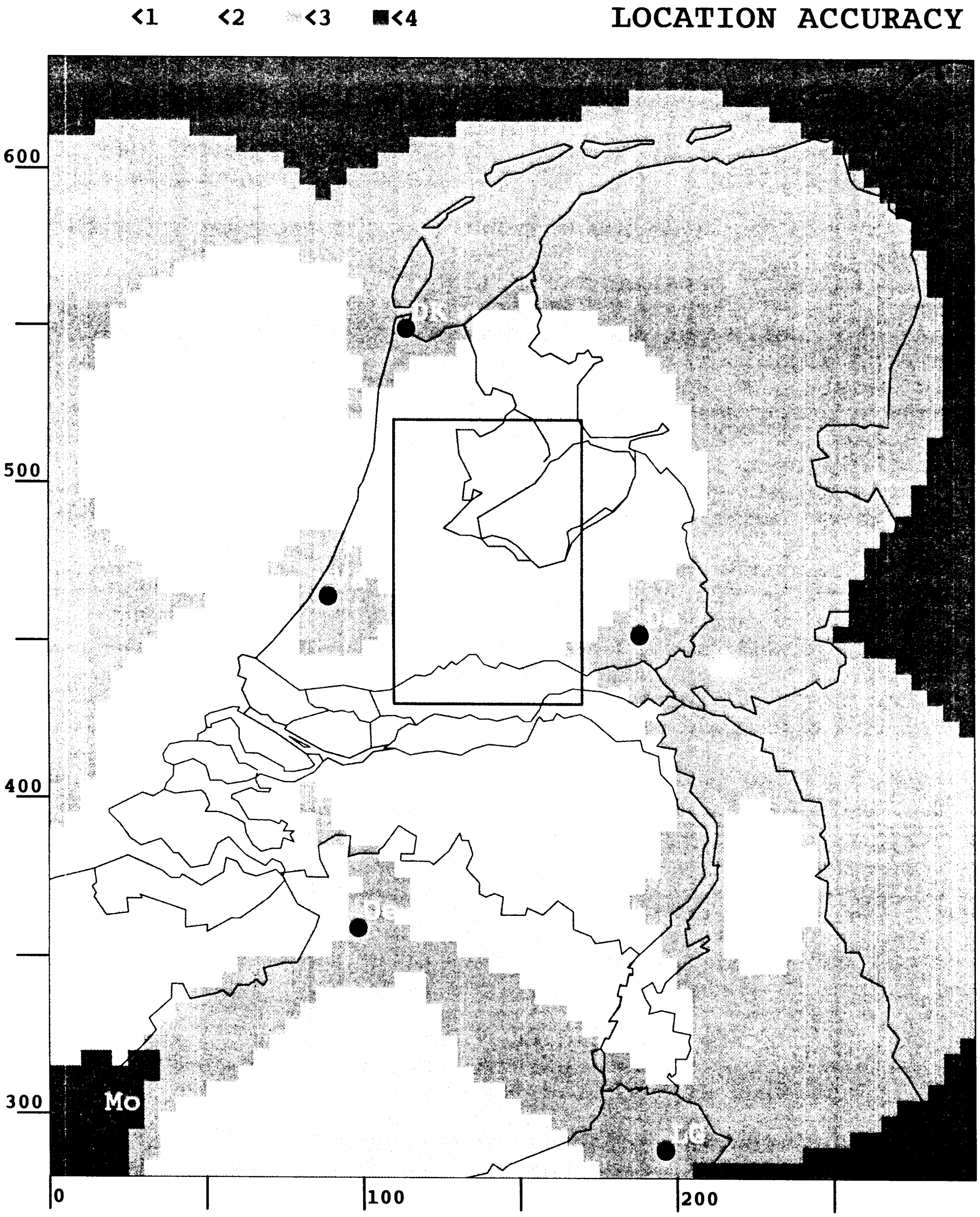

Fig.1. The SAFIR-network in 1997. The numbers along the axes represent positions (km) in the Netherlands national grid. The detection stations are indicted by two letters: De Kooy ((WMO code 06235), Valkenburg (06210), Deelen (06275), Oelegem, Mourcourt and La Gileppe. The shading shows the estimated location accuracy computed with Equation (2). During 1995 and 1996 only the 3 northern stations were used, so then the 4 km accuracy curve crossed the southern frontier of the Netherlands at some places. Some of the comparisons in this study were limited to a central rectangular region (110, 430 - 170, 520 in the km grid).

rise of the current and the charge transferred, are estimated from the peak current I in combination with the rise and decay times of the waveform received.

The results of the localization and discrimination system are combined into the output of the central processor:

- Localization file: co-ordinates and times of subsequent points of a lightning channel. The points are tagged with a discrimination code. This code indicates a single point, or the start, intermediate point or endpoint of a channel, or, alternatively, the association with a positive or negative earth discharge. The channels span a time of less than a second. The localization data are intended for display on a user terminal, but may be exported for other applications, e.g. combination with radar data.
- Contours of lightning density in squares of e.g. 3 x 3 km. If the storm is sufficiently intense, displacement vectors are calculated. Contours up to 40 min. ahead may then be forecast for warning purposes. Both density and warning results may be displayed on a user terminal.
- Automatic warnings may be transmitted to selected sensitive locations.
- Electrical parameter data of earth discharges: time, co-ordinates, maximum current, sign, charge transfer, etc. These files can be used for lightning damage and protection studies.

3 APPLICATION OF THE DATA

The central processor sends data to two user terminals, one at De Bilt, the other at the quarters of the Air Force Weather Service. These user terminals are also supplied with raw data, so the output may locally be recomputed with new criteria. The user terminals are provided with a large range of display facilities.
For use in the forecasting offices PC based remote SAFIR displays are available.

In addition, KNMI uses the localization files to merge the lightning information with radar pictures that are distributed at 15 min. intervals by telephone lines or videotex. The lightning information can be switched on/off in the radar displays. So a large number of users are kept informed on the location of thunderstorms.

Apart from this on-line application the lightning data are also important for climatological purposes and research. Therefore the location and discrimination data are combined daily into an archive file. In this archive file all vertical strokes with their physical parameters are kept. For each horizontal stroke only the average position and the east-west and north-south dimensions are recorded. This results in a tenfold data-reduction justified by the location accuracy discussed in the following Section.
The archive files are used to generate - e.g. on demand from insurance companies - detailed reports on past thunderstorm situations.

4 LOCATION ACCURACY

4a. Location errors.

For many applications, such as detailed warnings or insurance claims, a location accuracy better than e.g. 1 km is desirable. For other purposes the coincidence with radar echoes may be satisfactory (Kawasaki et al., 1994). In this Section it is attempted to verify the accuracy on the smallest scale possible.

The localization depends on angle measurements from two stations. Angular errors may have various causes:

Systematic errors, perhaps slowly changing:
- Both antennas may not be perfectly perpendicular.
- The orientation of the antenna system with reference to true north is not known exactly. The orientation of the mast may also gradually change due to instability of the soil around the mast foot and the guy mounts. There might also be a temperature influence.
- Curving of the propagation path from source to antenna, e.g. caused by buildings in the neighbourhood.

Random errors or variable errors:
- The phase characteristics of the two amplifiers may not match completely. It is indeed very difficult to obtain differential phase measurements over a wide dynamic range of input signals. This error may fluctuate slowly due to differential heating by the sun.
- The source may be poorly defined: the channel may not radiate isotropically, so two stations may select a burst from different parts of the channel. Another factor is that VHF propagation demands line-of-sight view between transmitter and receiver. A more distant receiver will therefore use signals from a higher section of the channel. Both effects result in a position error for points of non-vertical channels.
- Digitization uncertainty caused by the transmission of angular values to the central processor with a step size of 0.7 deg (180 deg in one byte). So the digitization contributes at least 0.4 deg to the total random error.

The manufacturer specifies a RMS azimuth localization accuracy of 0.7 deg. As part of the maintenance procedure an offline coherence analysis is advised that uses all available localizations of the three stations in situations with widespread thunderstorms. Each of three pairs of stations estimates the source at a different point. The triangle connecting these points can be made as small as possible by applying corrections to the azimuth settings of the three stations. If we assume that this procedure reduces the systematic error to zero, we are left with a random error with standard deviation 0.7 deg. According to the manual these azimuth corrections should be repeated twice a year. The size of such corrections is typically a few 0.1 deg. These corrections are only estimates and depend on the particular position of the thunderstorms used in the analysis. It is advisable to apply individual corrections with caution and to use subsequent coherence tests to arrive at optimum corrections. Such a series of tests can then be used to verify whether receiver changes have occurred.

In normal operation the localization is based on two stations and the resulting (one-sided) inaccuracy can be visualised as the area covered by the intersection of two cones with an opening angle of

$\delta=1.0$ deg. The resulting area is approximately a parallelogram with longest diagonal:

$$\text{distance error}= \sqrt{(R1^2+R2^2-2R1*R2*|(\cos\phi)|)}\ /\sin\phi\ *\tan\delta \qquad (2)$$

If we assume a 1.0 deg angular accuracy the resulting positioning errors are typically 1- 4 km over the territory of the Netherlands (Fig.1.).
In principle it is possible to improve the accuracy by using more than two stations, if available. However, the present software chooses just two stations and uses extra stations only for offline coherence analysis.
The errors listed above follow from an analysis of the measuring procedure. In the next Subsections we will try to estimate errors from actual observations.

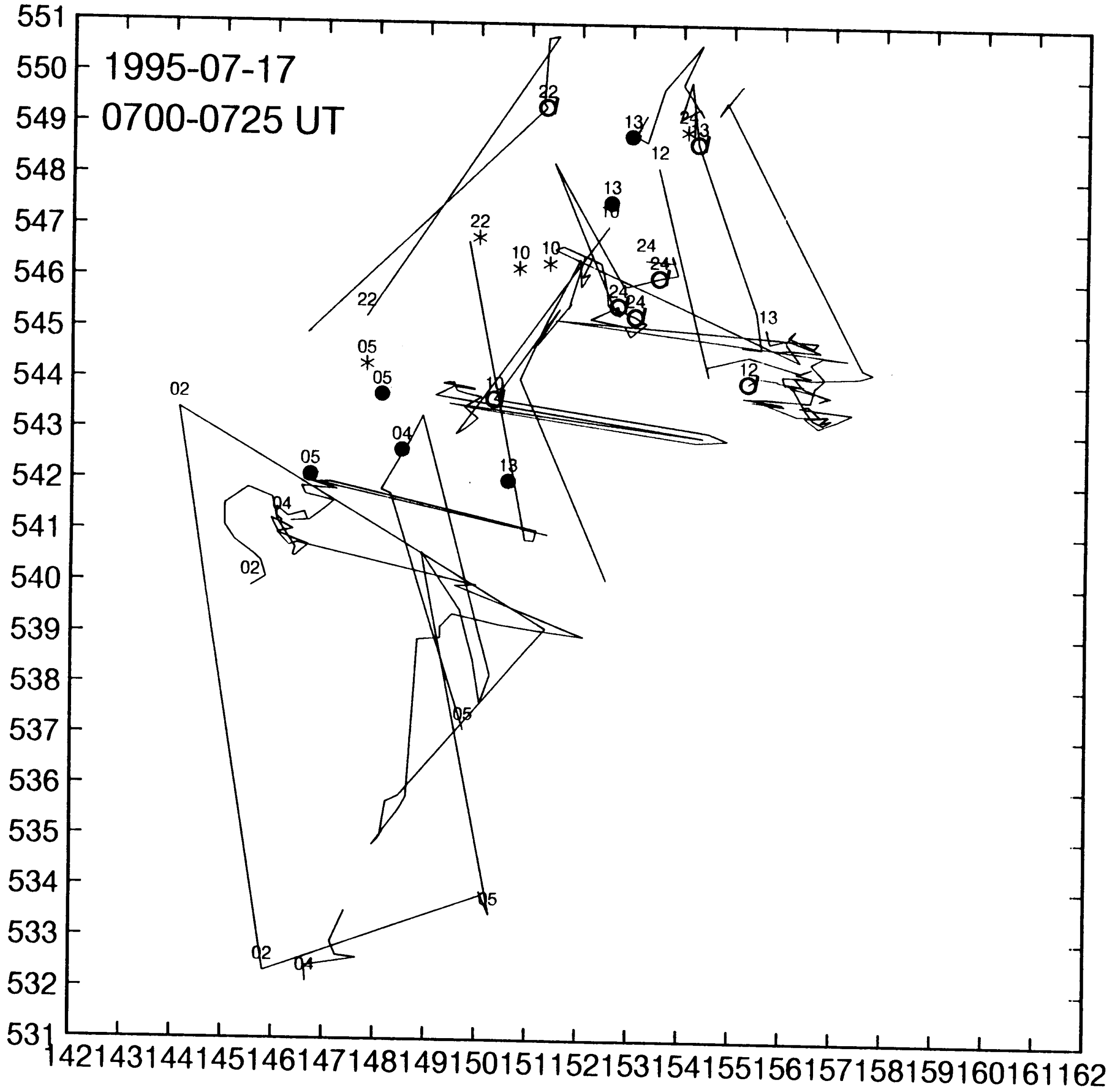

Fig.2. SAFIR and LPATS localization during 25 minutes in a 20 x 20 km area identified by national grid references. The time is indicated in minutes (after 7 UT). Horizontal SAFIR channels are shown by uninterrupted broken lines. On these lines open circles with a separate time stamp represent SAFIR vertical discharges. Dots and asterisks are LPATS ground and intracloud strokes respectively.

4b. An example of SAFIR localizations.

Localization errors are best illustrated by an actual example. Fig.2. shows 9 flashes detected by SAFIR in a small time interval on July 17, 1995. The area is located 40 km east of the most northerly detection station De Kooy.
The filled dots and asterisks are LPATS locations. The broken lines are horizontal channels detected by SAFIR. In 5 of these channels earth strokes, shown by empty circles, were identified, namely at times 10.17 (07 hours, 10 minutes 17 seconds), 12.22, 13.56, 22.07 and 24.04. The last one had 3 components.
There evidently is a preference for channel sections to be directed towards one of the three detection stations! If e.g. the angle measured by De Kooy is stable and the angle from Valkenburg varies between two or three values at 0.7 deg interval, an east-west orientation of the channel is quite understandable. In both directions an average of some 10 samples is taken, but the angle discretization remains visible.
So, the broken lines only partly reflect the real lightning channels. Random-like excursions of 2 or 3 km may be attributed to angular measurement errors. The length of horizontal channels can only be estimated by the system if they are long compared to the location accuracy. During 1997 about 50% of the channels was longer than 4 km, 5% longer than 11 km and 2% exceeded 17 km.
Because earth discharges are located by searching simultaneous points on a horizontal channel, the localization of vertical strokes also has an uncertainty of about 2 km.

4c. Differences between subsequent strokes.

A channel may have zero, one or more source points identified as earth strokes. Quite a number of channels represent multiple flashes, i.e. the first return stroke is followed by one or more subsequent strokes. The identification of component strokes is made by assuming

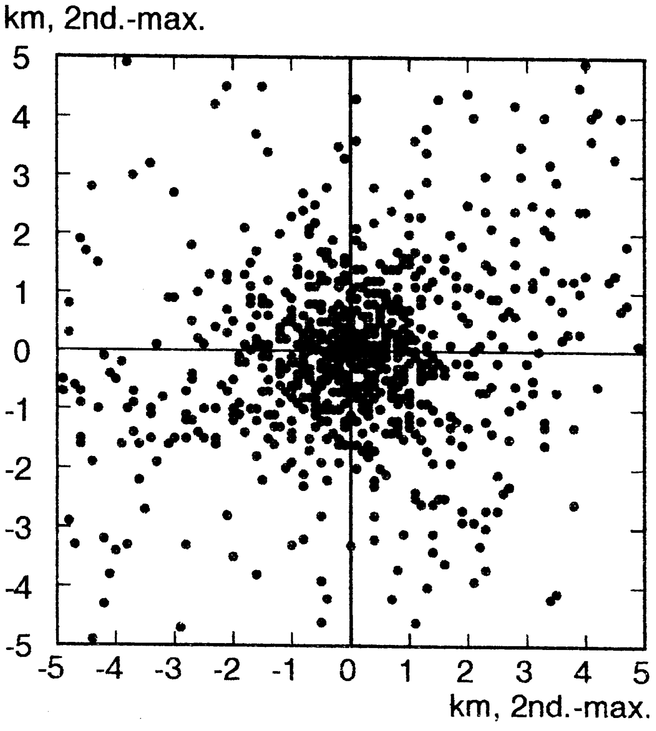

Fig.3. Position difference of the second strongest compared to the strongest component in multiple flashes during 1995 in the central rectangle of Fig.1.

that rapidly following flashes in the same neighbourhood (10 km or so, which is larger than the localization accuracy) are highly improbable, because thunderstorm charges need time to recover (WR92). In the SAFIR system two source locations are attributed to the same channel if they are closer than 7 km and follow within 0.5 msec. The time resolution of the SAFIR discrimination is capable of resolving component strokes at 10 msec intervals, depending on the actual wave form.
For the LPATS data the multiplicity criteria were 5 km and 200 msec (WR92). There the time window had to be quite large because the LPATS time stamp is based on output time rather than stroke time.

A lightning positioning system usually reports component strokes of one flash at slightly different locations. If we suppose the actual striking point to be the same, we can use subsequent component stroke positions to estimate the size of random positioning errors. However, recently some doubt arose about this assumption. Thottappillil et al. (1992) found quite a number of flashes in Florida to have multiple rather than single earth terminations. The mean distance between these terminations was 1.7 km. Another objection to this method is that it assumes the main radiating section of the channel to be the same for all subsequent strokes. If this is not true and the channel is non-vertical, the source positions of subsequent strokes will vary.
For all multiple strokes in the central region of Fig.1. a comparison has been made of the positions of the two component strokes carrying the largest current. The results in Fig.3 do not represent the actual positioning error, but the difference between two error vectors. The cluster of points is not symmetrical but more or less elongated in the west-east (left-right in the Figure) direction. This may be explained by the frequent selection of De Kooy for triangulations in this particular region.
The results of Fig.3. can be compared with an similar test on LPATS data in WR92. By assuming a normal distribution of the location error a 1.5 km standard deviation for the single stroke LPATS error was found. Here the resulting standard deviation is 1.9 and 1.2 km for the west-east and north-south direction respectively. The clustering of points in the centre suggests a distribution with a larger kurtosis than a normal distribution. This may have been caused by the discretization of the anglular sampling.
A more practical criterium than the standard deviation is the maximum error for 80 % of the strokes: 2.6 km compared to 2.3 km for LPATS.

4d. Comparison with LPATS locations.

During 1995 we had the opportunity to directly compare SAFIR data with simultaneous LPATS results.
A major difficulty for this comparison was the poor timing of the LPATS system. The system clock could drift tens of seconds from UTC time. Therefore a time correction had to be found for all individual thunderstorms. After applying these corrections discharges were accepted as identical if they were within 10 km and 500 msec. This time uncertainty is inherent to the LPATS system because the processing time is recorded rather than the discharge time.
The results are shown in Fig.4. The median distance between the localizations was 3.0 km. The SAFIR data have a systematic offset compared to LPATS data of 0.9 km to the west and 0.1 km to the south. Because the LPATS data have no large systematic offset, this suggests an azimuth error of 0.5 deg. at station De Kooy.

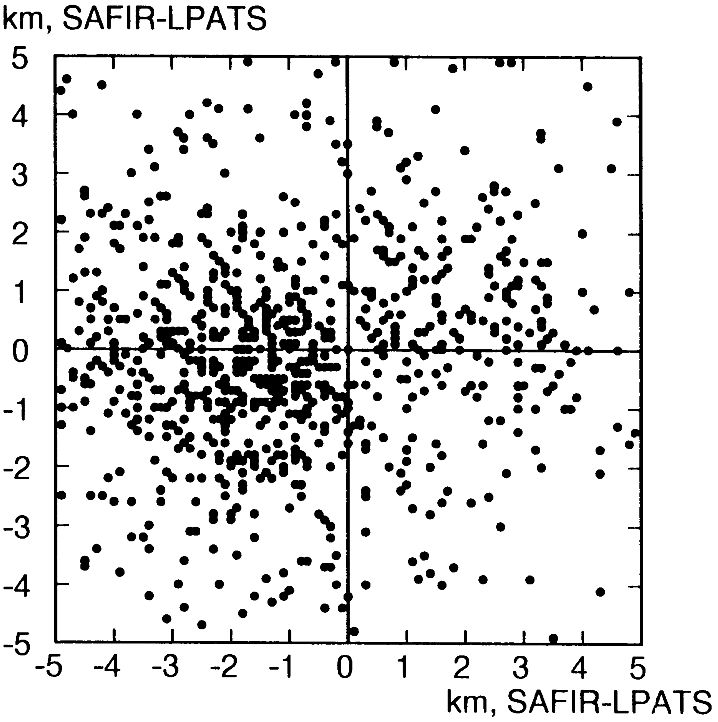

Fig.4. Position difference between simultaneous vertical strokes detected by SAFIR and LPATS respectively. The flashes occurred during 1995 in the central rectangle of Fig.1.

After subtracting this offset, we can separate the SAFIR random errors from those of LPATS by assuming both to follow normal distributions. If we use a standard deviation of 1.5 km for LPATS (WR-92), the standard deviation for SAFIR is 4.5 km (east-west) by 2.9 km (north-south). Apart from the systematic offset the median error for SAFIR is 1.8 km compared with 1.5 for LPATS.
These errors are twice as large as those in the preceding Subsection. This may partly be caused by changes in the systematic offset that could have occurred during the year. Another explanation of the large position differences is that the two systems observe different parts of a usually non-vertical lightning channel:

- The localization of return strokes by LPATS is based on signals from return stroke currents starting near the ground and gradually dissipating during ascent. The VLF radiation is easily transmitted over the horizon. The radiation source will therefore be close to the ground strike point unless the striking angle is very small.
- SAFIR detects VHF signatures generated in lightning channels at heights up to 10 km (Mazur et al. 1997). Moreover the line-of-sight propagation eliminates the lower sources for detection beyond, say, 100 km. The radiation source will in many cases be at a height of a few km.

4e. **Flashes near high towers.**

Towers with heights exceeding 100 m have the capacity to trigger lightning discharges with upward leader strokes. One of the conclusions of the LPATS evaluation was that such discharges were located with a median accuracy of about 0.5 km, i.e. much better than the 1.5 km found for normal earth discharges (WR92). Although this result is not fully understood, it indicates that the main radiating part of the channel (as observed by LPATS) stays very close to the tower.
The same test, counting in concentric equal-area rings, was aplied here and the results are shown in Figs.5 a and b. The earlier results (1988-1989) for the LPATS system were perfectly reproduced by the 1995 data (dashed line). The SAFIR data, however, showed no such concentration of discharges around high towers.

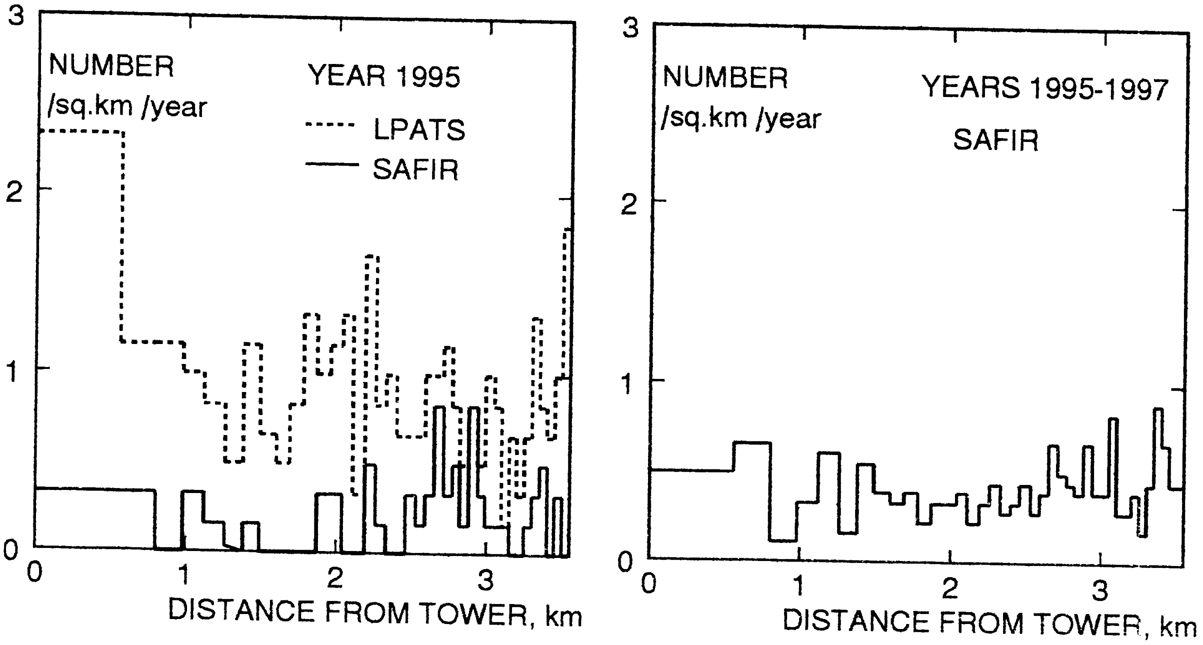

Fig.5 a,b. Flash frequency in concentric rings of 1 km^2 around six high towers in the Netherlands.
The towers are: Lopik-TV (380 m), Hoogersmilde-TV (312 m), Cabauw KNMI meteorological tower (214 m), den Oever-TV (200 m), Roermond-TV (192 m) and Markelo-TV (170 m).

This test is evidently too severe for the SAFIR location technique. The angular resolution would not allow a precision of 500 m. Moreover, the LPATS errors are only random, while the SAFIR data may have a systematic error of about 1 km, probably in different directions for each of the towers. Preferred striking locations are therefore easily smoothed out, as indeed is seen in Fig.5.
The different effective source locations for SAFIR and LPATS - as mentioned in the Subsection 4d - will certainly contribute to the smoothing observed.

5 DETECTION CAPABILITY

5a. System limitations and system redundancy.

One of the main problems with the LPATS system was the occurrence of false alarms caused by the fact that arrival time differences are equal along hyperbolae rather than straight lines. A distant storm located at the far crossing point of two hyperbolae may be imaged at the nearby crossing point, i.e. inside the network area.
In the past years there also have been a few 'unexplained' localizations by the SAFIR system, maybe caused by artificial radio noise. However, their occurrence was an order of magnitude less frequent than with the LPATS system, so with the new network false alarms can be considered as operationally insignificant .

The usefulness of the data for forecasting as well as climatology depends on a high detection rate. One of the problems with lightning detection is the coincidence of flashes. Because the network covers a large area, there may be occasions that many thunderstorms have to be monitored at the same time. The localization of a channel may last up to 0.5 sec. so it is possible that signals from another thunderstorm try to interfere. As in WR92 we may estimate the probability of overlap for a flash rate of 1 per sec, the approximate maximum in this country. The probability of flashes with average flash duration of 0.2 sec. to partly overlap is $1-\exp(-1.0*0.2)= 18\%$ (Poisson statistics). The probability that a flash is completely masked will be much less. The triangulation is based on sample times of 0.0001 sec, so the SAFIR system may still distinguish two separate flashes. Inspection of localization results indeed shows that sometimes a flash is interrupted by a single localization of distant source. So nothing is lost, but the nearby flash is reported as two shorter flashes.
Because the discrimination criteria involve an analysis of signal changes during periods up to 0.1 sec, the selection of ground strokes may become less acccurate if signals overlap.

There may be other problems that reduce the detection rate: distant signals may be too weak to be distinguished from noise. Also, the software contains various acceptance criteria which -unavoidably - sometimes discard valid data and sometimes accept false data. In the following Subsections we will try to base conclusions about the detection rate on actual data.

So far we considered a fully operational system. However, in the evaluation period some failures have occurred. Their cause may have been a SAFIR problem or an external factor. As an example thunderstorms were missed in the morning of July 9, 1995 and the evening of July 20, 1995.
More likely than a total system breakdown is the malfunction of one of the stations. These receivers must obey to very restrictive requirements regarding sensitivity and alignment and are suspectible to failures. If one station is missing we will get a situation where the remaining stations are unable to locate storms near their connection line and in too distant regions. Fig.6 shows 4 examples how the network deteriorates if one of the four most northerly stations is missing. Especially the receiver at Deelen is badly needed. Unfortunately this station was missing in late 1995 and early 1997. Clearly some redundancy in the form of an extra station near the north-east frontier would be advisable.

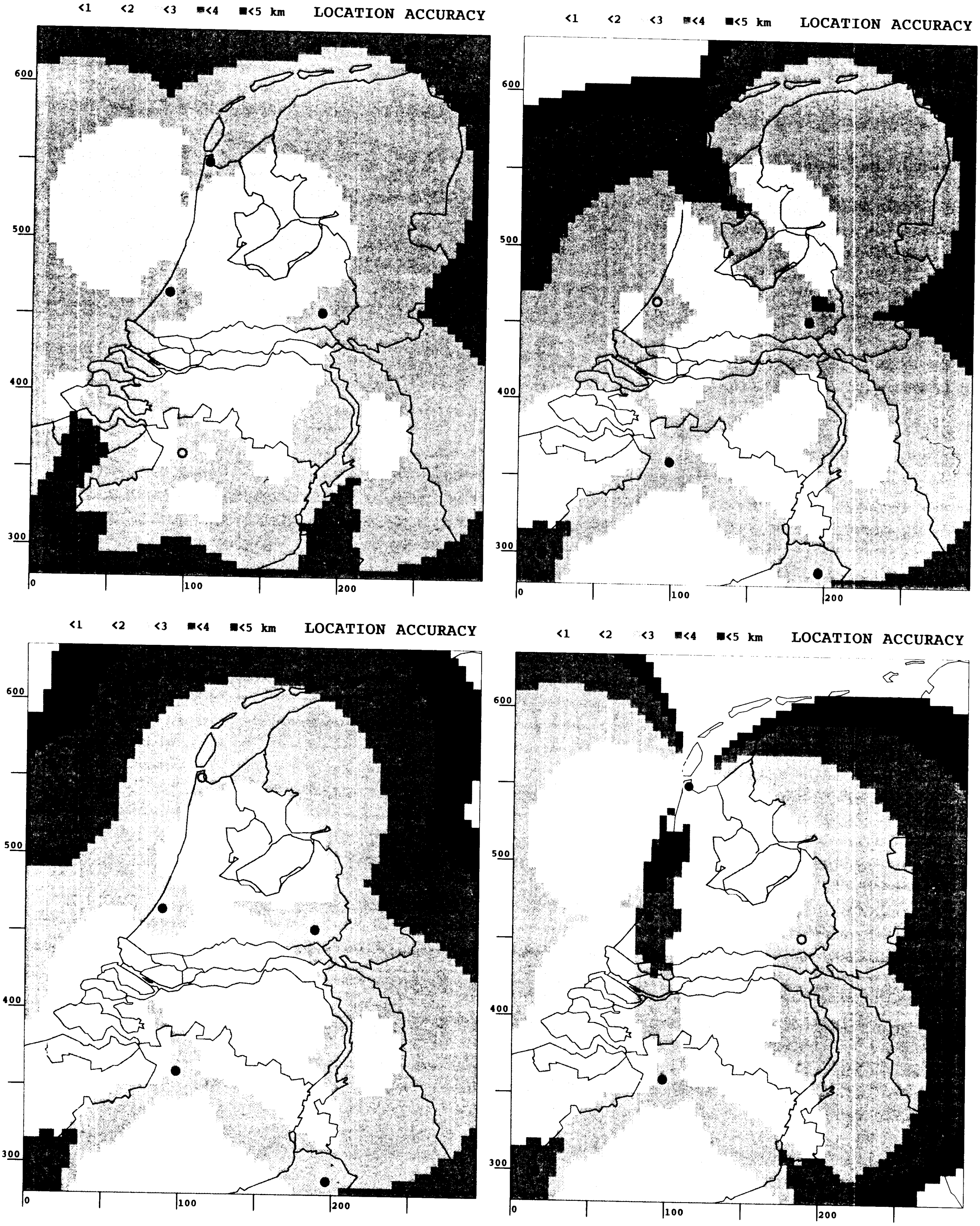

Fig.6. Four examples of the reduced coverage of the SAFIR network when a station is missing. The missing station is indicated by an open circle: Oelegem (upper left), Valkenburg (upper right), De Kooy (lower left) and Deelen (lower right). The shading shows the simulated accuracy - as in Fig.1. According to Fig.8 the 50% detection limit is close to the 4 km accuracy curve.

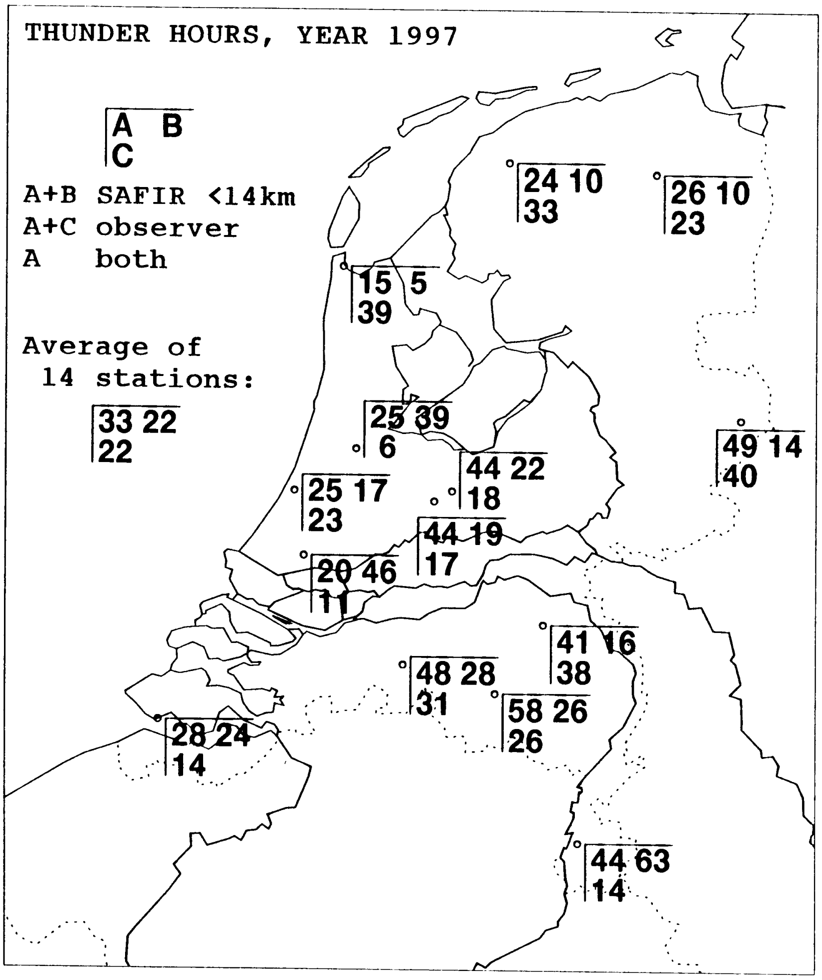

Fig.7. Comparison between the yearly number of thunder hours and the number of hours that SAFIR detected a flash inside a 14 km circle around the same station. As an example: at the most southwesterly station (Flushing) the observer heard thunder in 42 (=28+14) hours, SAFIR recorded flashes in 52 (=28+24) hours.

5b. Comparison with thunder reports.

Synoptic stations provide hourly reports on the occurrence of thunder during the preceding hour. The range of these observations depends on the observer, the ambient noise level and the type of thunderstorm. In most cases the limiting audibility range will be around 15 km.

Lightning detection networks are a serious candidate to replace human observers in the present shift from manned to automatic stations. It is of interest to compare both types of data for nowcasting purposes as well as for the possible extension of long-term climatological thunder frequency records. A further discussion on the comparison of observers to lightning networks is given in WR92 and Reap(1993).

Here comparison results are shown for 1997 only, when the network was complete (Fig.7.). If a circle of 14 km is chosen, the network detects on average the same number of thunder hours as the observer: 55. Various SAFIR detection ranges were tried, and it could be demonstrated that the number of lightning hours detected by the network is roughly proportional to the radius of the circle.

The average SAFIR detection rate of human-observed thunder is 60%. The remaining 40% are not necessarily false alarms, because thunder near the 14 km range is difficult to hear, especially against the wind. In WR92 we found for LPATS 56% respectively 44%. Compared to LPATS, data from SAFIR are expected to match better with station observations, because of their better inclusion of intracloud discharges.

Fig.7 shows interesting differences between stations. In the north and north-east the network might detect too few flashes, either systematically or due to temporary network faults as mentioned in the last Section. On the other hand the observer counts lower at the main airports of Amsterdam, Rotterdam and Maastricht/Aachen. This is most likely due to noise problems.

A 14 km radius can also be used to estimate thunder days. In 1997 the average station had 22 days with thunder and 23 days with SAFIR reports within 14 km. On 16 days (70%) both methods agreed; the 'better' stations reached 83%.

5c. Comparison with the LPATS network.

During 1995 the detection capability of SAFIR could be compared with LPATS data. The differences can best be commented by returning to a small but typical example: the 9 SAFIR channels of Fig.2. The following table compares both systems.

Table 1. Specification of flashes on July 17, 1995 (Fig.2.)
(v=vertical, h=horizontal, I=current)

min.+sec. after 07 UT	02.15	04.10	04.11	05.34	10.17	12.22	13.56	22.07	24.04
SAFIR	h	h	h	h	h+v	h+v	h+v	h+v	h+3v
max.I (kA)					-127	-37	-44	+21	-23
LPATS	-	-	v	h+2v	2h	-	3v	h	h
max.I (kA)			-284	-434			+794		

The LPATS system missed 2 intracloud strokes, as expected. The flash at 12.22 was also missed. Perhaps more interesting is the almost complete disagreement of the systems on the distinction between vertical (v or h+v) and horizontal dischasrges.
This example consisted of flashes in a region favourable for SAFIR detection (40 km east of De Kooy).

The complete datasets for 1995 have been used to establish the dependence of SAFIR's detection rate on distance. Because SAFIR needs two stations for triangulation, the 'distance' is not simply referring to the centre point of the network (3 stations in 1995), but to the farthest of the two nearest stations. As an example: 160 km 'distance' is near the 4 km accuracy limit. (see e.g. Fig.6, upper left section).
The peaks near the 60 and 200 km ranges may be attributed to the particular horizontal distribution of lightning in 1995 (Figs.10-11). The total lightning count is 70 to 80% higher for SAFIR, at least up to a range of 130 km. This confirms SAFIR's larger acceptance of intracloud flashes.

A second conclusion is, that, while the LPATS detection rate is maintained up to at least 260 km, the SAFIR data drop dramatically between about 150 and 250 km. From closer inspection it appears that that the drop starts already at a range near 100 km. Subsection 5.a. suggests that SAFIR has an almost 100% detection rate at close range. If that is true, it follows from Fig.8 that the detection rate falls below 50% at a range of 170 km. It is of interest to note that 170 km is near the 4 km location accuracy limit in Fig.1.
If all stations are available, the detection rate is still acceptable inside the territory of the Netherlands. The reasons for the reduced detection have been given in earlier sections: the signal

sources sink below the horizon and many remaining signals don't pass the angular triangulation criteria.

A third item of interest is the percentage of vertical strokes: for LPATS rising from 50% over the Netherlands to 72% at far range. For SAFIR the percentage lowers gradually from 27% nearby to 15% at 200 km. This suggests that discarding horizontal strokes (LPATS) as well as accepting vertical strokes (SAFIR) become more difficult if the VLF signal amplitude is smaller.
The results of Fig.8 suggest a method to correct the yearly lightning counts according to SAFIR (Figs.11-13) for range errors. Table 2 gives a correction based on the relation between the total lightning counts of SAFIR and LPATS given in Fig.8. These correction factors are the inverse values of the detection rates.

Table 2. Correction factor for SAFIR data as a function of distance to the second nearest station (this distance depends on the station configuration in the year concerned).

distance (km)	<80	90	100	110	120	130	140	150	160	170	180	190	200
correction(%)	100	105	110	115	119	124	128	136	147	168	203	247	322

An addition to this correction method is to accept the 27% percentage of vertical discharges at ranges below 80 km to be realistic for all ranges. Then the vertical count can be found as 27% from the total counts obtained with the corrections of Table 2.

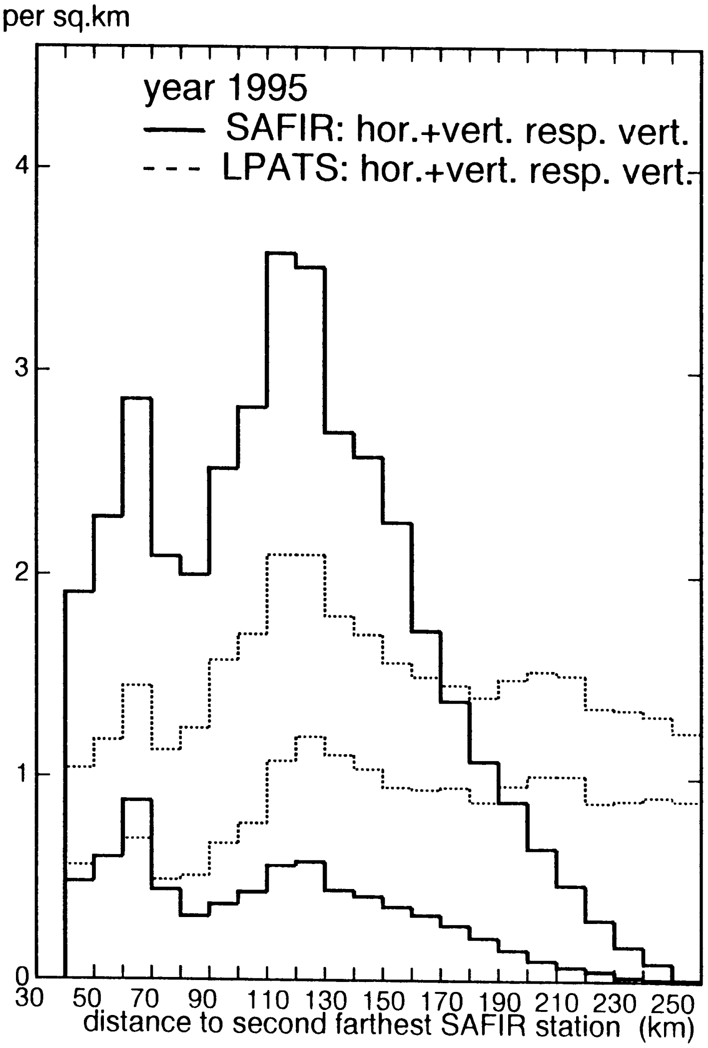

Fig.8
Average lightning density for both systems as a function of 'distance' from the SAFIR receivers.
Lower curves: only vertical, upper curves: both horizontal and vertical.

The SAFIR detection rate drops rapidly beyond about 150 km.

6 LIGHTNING PARAMETER ESTIMATION

6a Comparison with LPATS results.

Lightning parameters are estimated from the VLF radiation received. The most important parameter is the maximum current I estimated from the signal waveform with Equation (1).
The LPATS system records the maximum current of the vertical strokes in a similar way. In WR92 the frequency distribution of the LPATS current estimates was shown to be comparable to published values. The small sample of strokes listed in Table 1. already showed large differences between current estimates by the two networks. This is no exception.
As in Subsection 4d (Fig.4) simultaneous strokes during 1995 can be compared in the central rectangle of Fig.1. The results (Fig.9) show that, although both systems mostly detect negative discharges, the individual strokes match very poorly. The fraction of positive strokes is about equal, but in only six cases both systems agree on a positive stroke. Also, SAFIR frequently estimates larger negative amplitudes (left lower quadrant).
An explanation of these differences is not easy. Both systems observe VLF waveforms. The area chosen is far enough from the receivers to avoid confusing near-field effects.
Another fact that casts doubts on lightning network current measurements is the frequent combination of positive and negative stroke into the same flash. This happens in the LPATS as well as the SAFIR records. On this subject the SAFIR statistics are as follows: a first return stroke is accompagnied by one or more strokes with opposite sign in 22% of the cases: 14% for negative first return strokes and 60% (!) for positive ones. The generally accepted model of the earth discharge makes such a phenomenon very improbable.
There may be at least two reasons that could make the waveforms behave differently from model strokes:

- Field changes due to other storms could mask the signal of the stroke that we want to detect. Because the receivers of LPATS are at different locations, such noise effects would be different.

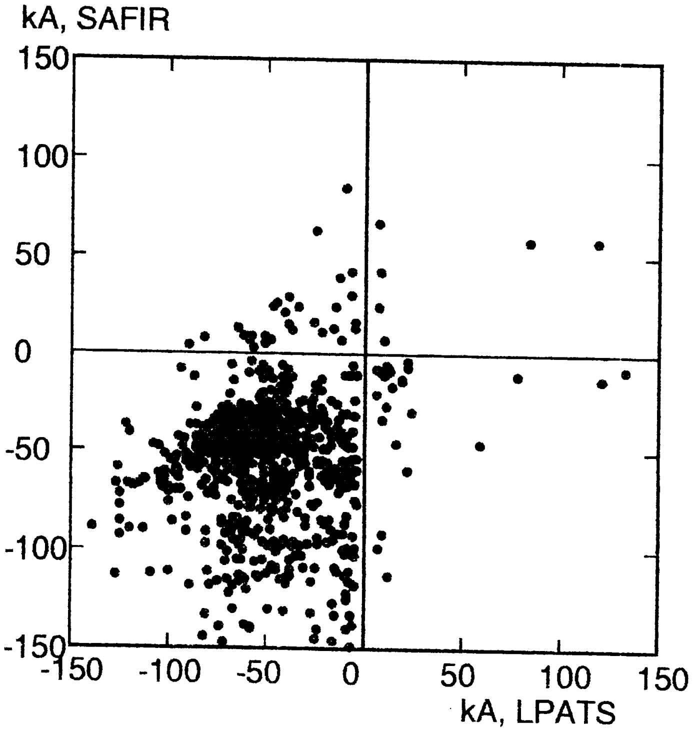

*Fig.9. Comparison of current and polarity for the same flashes measured by both networks. For multiple flashes the strongest strokes have been selected.
Strokes with currents larger than 150 kA are not shown.*

- Intracloud discharges do indeed show field excursions in opposite directions. If these flashes are erroneously classified as vertical, the observed problem would arise.

6b **Measurement of current rise and decay.**

The LPATS system has an option to monitor wave-forms for a selection of strokes, but in normal operation only the maximum current is recorded. SAFIR provides routine estimates for all strokes accepted by the discrimination receiver.
The SAFIR system records the 'rise time' needed to reach the maximum field strength and the 'decay time' needed to return to the pre-stroke field strength. These time differences provide information to discriminate vertical flashes from horizontal ones and for the computation of lightning parameters.
To estimate lightning parameters SAFIR applies the following procedure: The waveform is approximated by a triangle with the top at maximum field strength. The current I(kA) is combined with the rise time tr (μsec) and the decay time td (μsec) to other relevant parameters as follows

$$S\ (\text{slope}) = dI/dt = I/tr \qquad (\text{kA}/\mu\text{sec}) \qquad (3)$$

$$E\ (\text{energy}) = I^2 * (tr+td)\ /3 \qquad (\text{A}^2\text{sec}) \qquad (4)$$

$$C\ (\text{charge}) = I * (tr+td)\ /2000 \qquad (\text{C=Coulomb}) \qquad (5)$$

These parameters are important for the design of lightning protection equipment. They quantify various damaging effects of lightning:
- maximum current: potential over the earthing resistance,
- slope: induction effects around a conductor,
- energy (or 'action integral'): heating of a conductor,
- charge: the total charge displaced by the stroke.

Table 3. shows some statistics on rise and decay times. The current for positive strokes seems to rise slower and to decay faster than for negative strokes. Although the discrimination between vertical and horizontal strokes is also based on rise time and amplitude, in practice the decay time plays the decisive role. Table 3 shows that many strokes have decay times close to the decision value of 15.5 μsec. In a typical summer thunderstorm 20% of the decay times are between 15.5 and 17.5 μsec. Table 3 is restricted to vertical discharges, but it is evident that also many 'horizontal' ones had decay times close to this decision value. Therefore a small rise of the limiting value would drastically reduce the percentage of vertical strokes. Consequently, erroneous discrimination decisions seem quite probable.

Table 3. Rise and decay times exceeded for indicated frequencies in the central region of Fig.1. during 1997.

strokes	number	rise time (μsec)			decay time (μsec)		
		95%	50%	5%	95%	50%	5%
negative ≥30kA	1005	1.1	4.1	9.6	17	27	56
negative <30kA	848	1.4	4.9	10.9	17	22	47
positive <30kA	833	1.5	6.1	11.1	17	24	51
positive ≥30kA	181	3.7	8.4	11.9	17	23	49

The series of strokes described in Table 3. has also been used to test whether the estimated lightning parameters looked realistic (Table 4). Comparison values can e.g. be found in NNI (1992). The values for the slope and the peak current are close (within a factor 2) to the reference values apart from the too small value for the median current of positive strokes. The values for E and C are about ten times smaller than expected. According to Eqs.(4) and (5) this can only imply that the decay time derived from the VLF signal is much smaller than typical decay times reported for strucken objects.

Table 4. Lightning parameters exceedance values measured by SAFIR in the central region of Fig.1. during 1997. The lightning parameters are: slope S, peak current I, action integral E and charge C.

	negative strokes				positive strokes			
	95%	50%	5%	max	95%	50%	5%	max
S (kA/μsec)	1.1	9.1	43	150	0.6	2.3	16	62
I (kA)	7	36	109	295	5	9	121	444
E (kA^2sec)	0.0004	0.011	0.1	1.6	0.0003	0.001	0.16	3.9
C (C)	0.1	0.5	2.5	10	0.1	0.2	2.0	13

The main conclusion about the SAFIR discrimination system is that peak current estimates seem realistic, but that many errors occur in the distinctions negative/positive and vertical/horizontal as well as in the estimates of the lightning's action integral and charge transfer.

7 LIGHTNING CLIMATOLOGY

7a. Lightning flash density.

For the SAFIR measurements now available, the yearly horizontal distribution of lightning density (ground strokes per km^2) is shown in the Figs.11-13. For comparison Fig.10 has been included with LPATS results during 1995.

Horizontal differences on a small scale usually reflect the tracks of a few heavy thunderstorms. Usually less than 5 days are responsible for half of the yearly lightning count. Averageing over many years will be needed to smoothen out such 'random' peaks. There is some public of interest in the possible existence of small scale lightning 'hot spots'. The location accuracy of present lightning location systems will hide differences on scales smaller than about 5 km. In WR-92 it was argued from network and lightning counter data that tens of years of data would be needed to confirm 20% differences on a 5 km scale.

Experience with the new network did not alter these conclusions. The year to year lightning variability is large on all scales between 5 and about 100 km.

Horizontal differences on a larger scale reflect existing climatological effects or ,in the case of SAFIR, partly coverage problems. Over the North Sea thunder is less frequent than over the continent. During summer, air mass thunderstorms are favoured in eastern and southern districts. It is weel known that thunderstorms are more frequent over high ground in Belgium and Germany, but is uncertain that the relief in our country is strong enough to make a significant contribution. Also during summer, warm spells are often

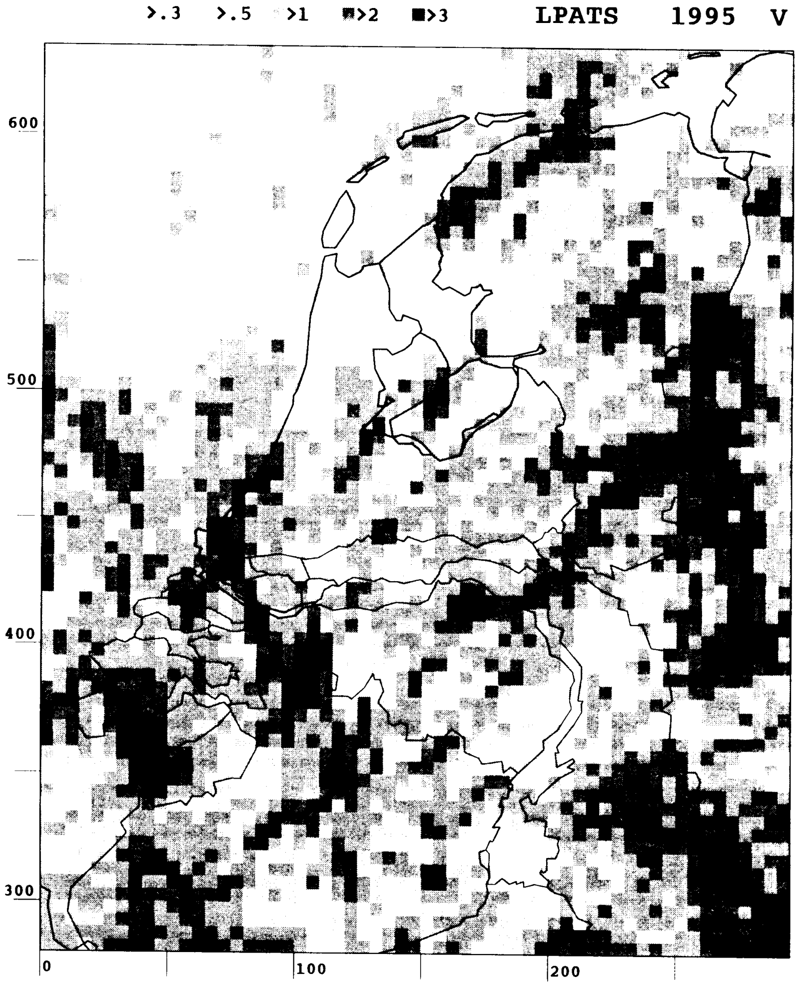

Fig.10. Vertical strokes detected by LPATS during 1995.

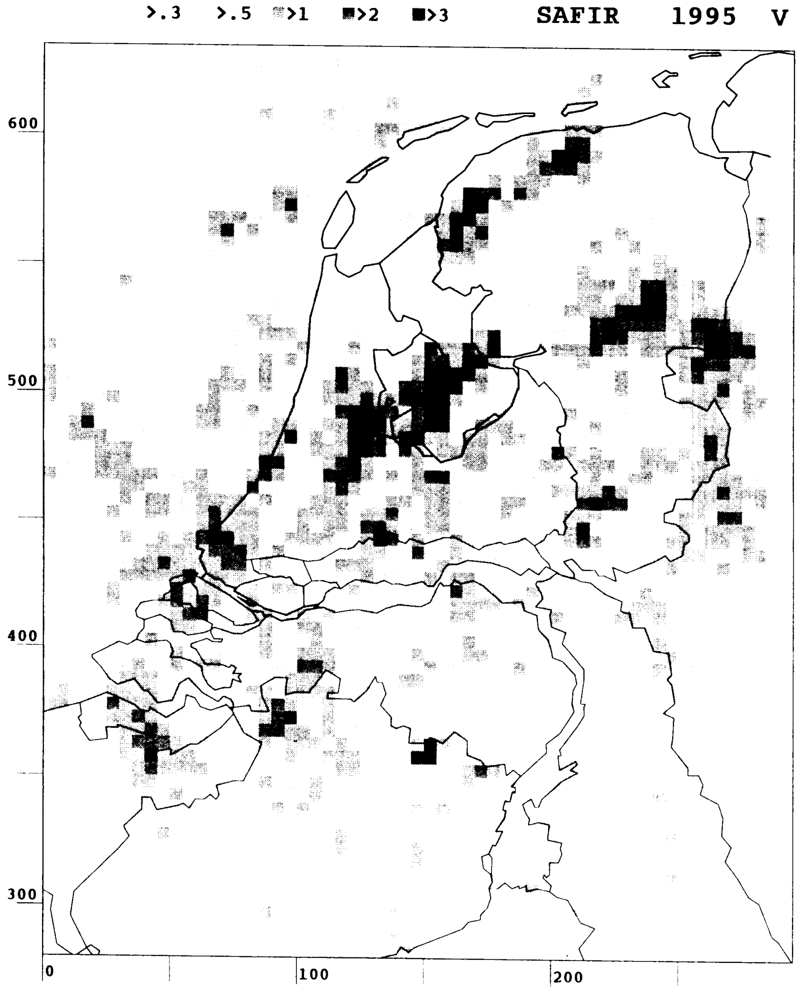

Fig.11. Vertical strokes detected by SAFIR during 1995. As only three stations were used the results in southern districts are small compared to Fig.10.

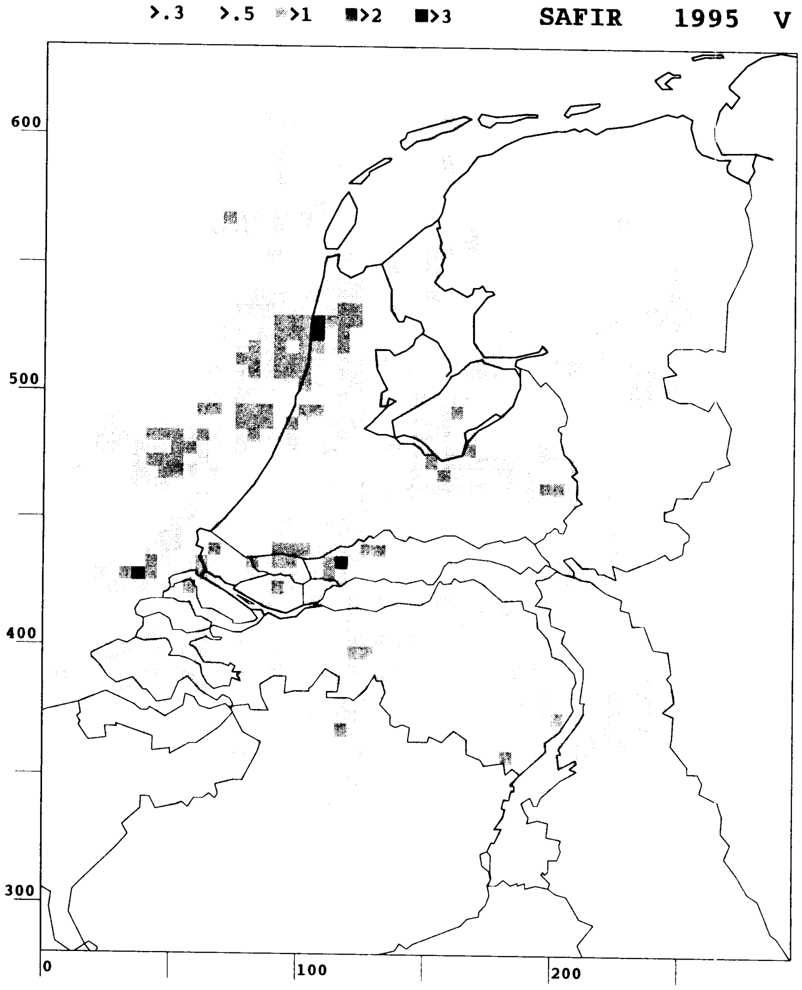

Fig.12. Vertical strokes detected by SAFIR during 1996, still with insufficient coverage of southern districts. In this year the lightning occurrence was below normal. Nearly half of the strokes over the Netherlands came from storms on July 23.

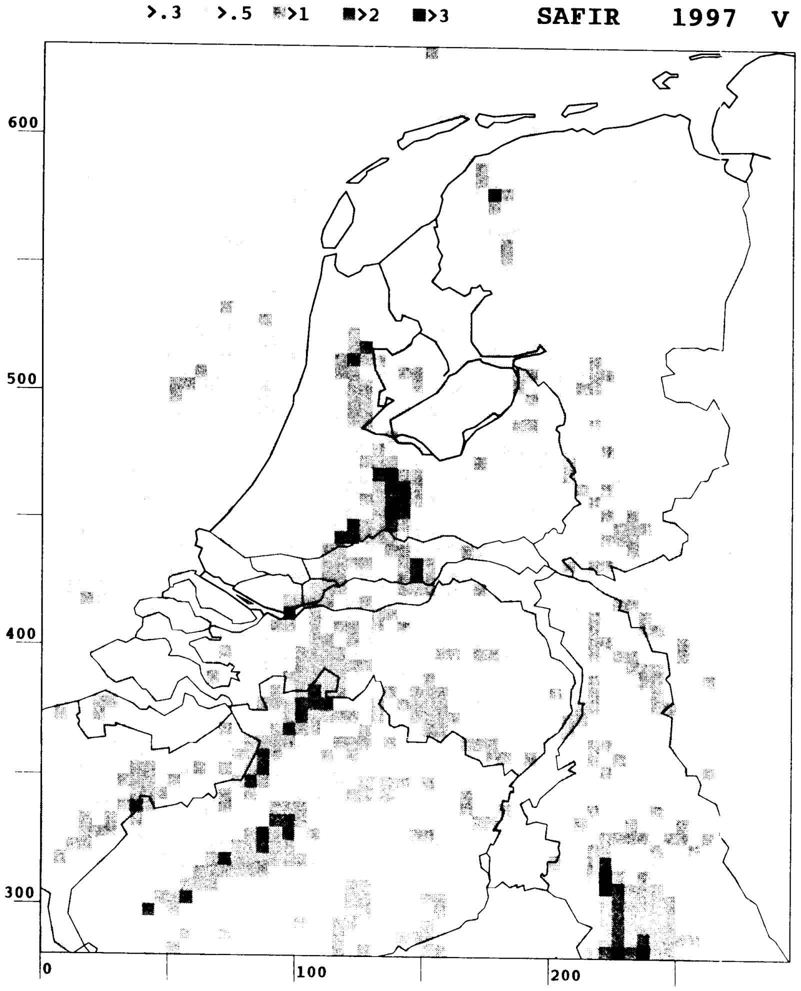

Fig.13. Vertical strokes detected by SAFIR during 1997. The first year with support from the Belgian stations. More than 50% of the strokes over the Netherlands occurred on 4 days: June 7,8 and Aug. 24,25.

disturbed by westerly's causing a thunderstorm maximum at about 80 km downwind from the shore. During winter the thunderstorms occur mainly near warm coastal waters.

The figures confirm that the SAFIR system had an insufficient coverage in the years 1995 and 1996. Even in 1997 lightning incidence in the north-east was probably underestimated.

7b. **Secular variability.**

The average lightning density (ground flashes per km^2 per annum) over the country is an important parameter to quantify lightning risk. Before 1974 only records of 'thunder heard' were available; these contain no information on the intensity of storms.

The first serious estimate of lightning density for the Netherlands was 1.3-2.7 ground strokes per km^2 per year. This result was obtained with a lightning counter network during the years 1974-1976 (Wessels, 1977). In WR92 it was argued that a representative estimate for the lightning climate of the Netherlands would be 1.5 (discharges per km^2 per annum).

Because the year to year variability of both thunder days and the average lightning density is quite large, it is important to obtain a homogeneous series of these data over a number of years. The thunder day count may be used as a rough measure for the representativity of the small number of years with instrumental records.

In this Subsection we will consider the average lightning frequency estimated from various sources around 5 stations spread over the Netherlands territory: thunder days, lightning counter and lightning network results (Fig.14).

The mean number of thunder days for these 5 stations varied between 16 and 32 during the climatological reference period 1961-1990 (average 23.6 days, standard deviation 4.1 days).

Lightning counter results for the years 1974-1987 have been included for the same 5 stations. It was assumed that the average effective range of the counters was 12 km (Wessels, 1977).

The LPATS and SAFIR data are averages for the territory of the Netherlands. The number of strokes has been presented. More appropriate would be the number of flashes (about 30% lower).

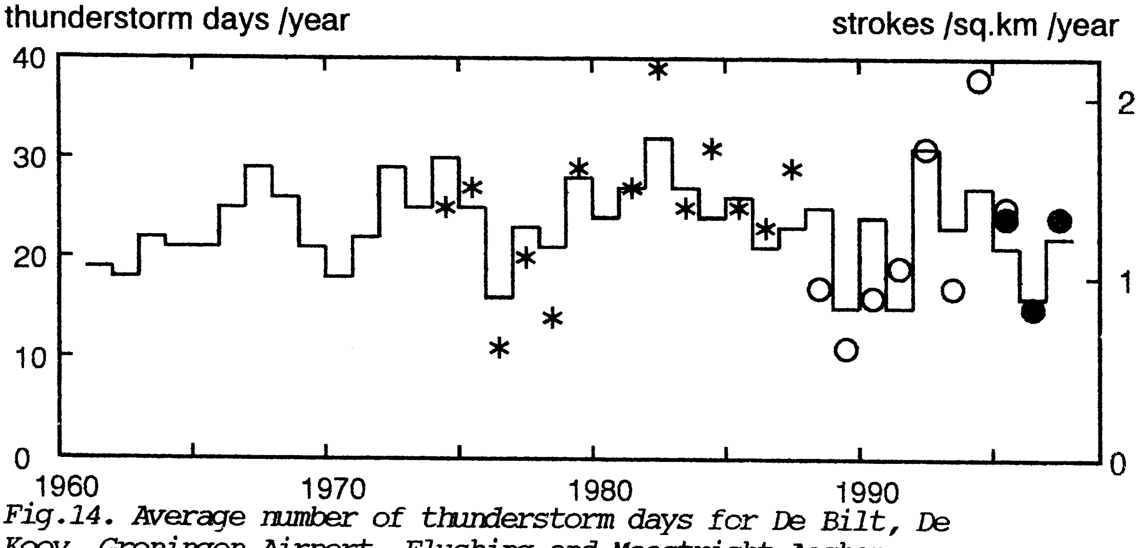

Fig.14. Average number of thunderstorm days for De Bilt, De Kooy, Groningen Airport, Flushing and Maastricht-Aachen Airport. Lightning density (scale right) from: asterisks = lightning counters near these stations (1980 missing), open circles = LPATS network, full circles = SAFIR network.

Because the distinction between strokes is not unambiguous, we accept the difference as compensation for data lost due to temporary network defects, which occurred regularly.
The scales in Fig.14 have been chosen to enable a comparison between the traditional observations and the new instrumental measurements. The peaks in both series match more or less, but there is clearly no simple linear relationship beween the sets. Up to now the yearly lightning density varied between 0.6 and 2.2. The average value of about 1.5 still looks valid.

7c. Flash frequency and lightning characteristics.

A lightning detection system offers opportunities to collect complete and detailed information on all thunderstorms in a certain area. In previous sections it was shown that some characteristics of lightning are measured correctly, e.g. the frequency of flashes. The discrimination between vertical and horizontal discharges may not be correct in individual cases, but will probably be correct over a large sample of strokes. More doubtful proved estimates of the lightning current sign and amplitude.
Still, interesting details can be found for individual storms. In travelling storms vertical strokes mostly occur near the front edge. Positive strokes seem most likely in periphery regions such as anvils. SAFIR data deserve more studies beyond this evaluation.

An important aspect of lightning climatology is the seasonal distribution. Lightning production is favoured in the warm season, not only due to strong solar heating, but also to a larger atmospheric water content.
As a measure of lightning production strokes have been counted over

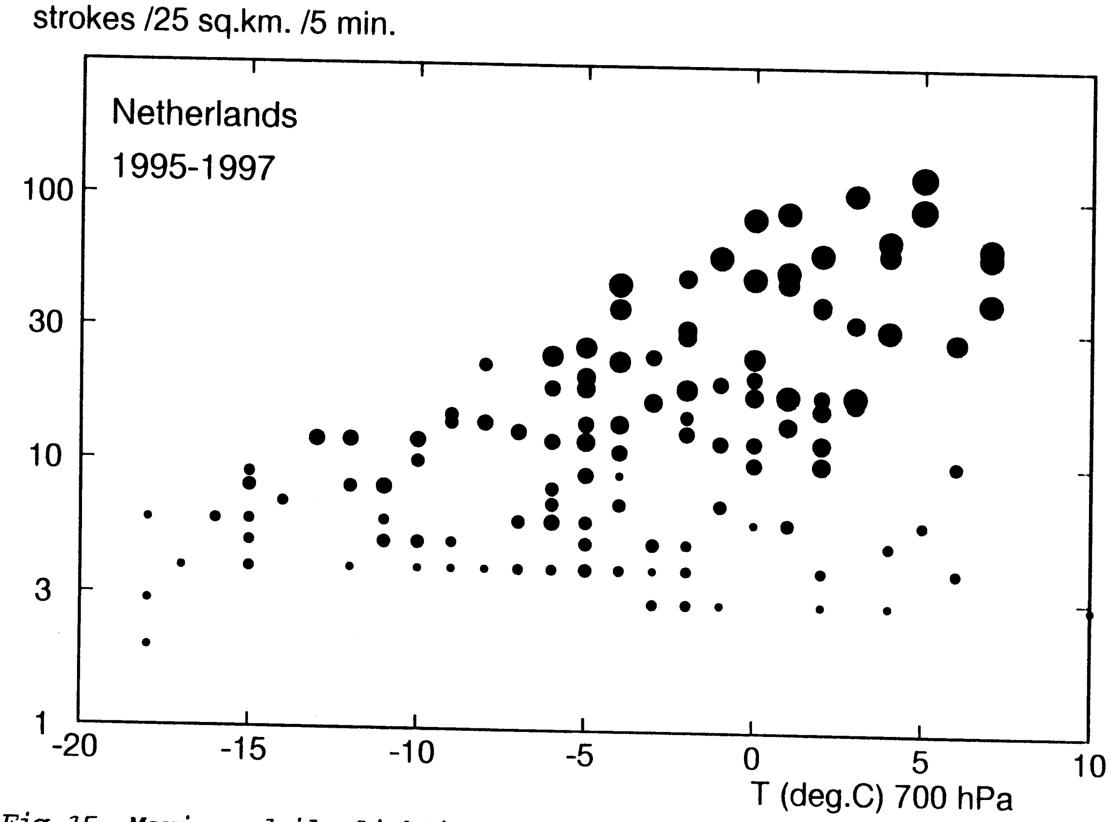

Fig.15. Maximum daily lighting frequency over the territory of the Netherlands as a function of the 700 hPa temperature. Days with a larger total of strokes are represented by larger dots.

fixed 5 x 5 km squares for fixed 5 min. intervals. For each day the maximum of these 5 minute lightning densities, encountered anywhere over the Netherlands is plotted in Fig.15 against the 700 hPa temperature. This confirmed studies with lightning counters (Wessels, 1977) and with LPATS data (WR92) that the maximum attainable lightning intensity increases with 700 hPa temperature.

A further item of interest is the percentage of vertical strokes. Although lightning is more rare in the cold atmospheres the relative probability of damage by ground strokes is large. The percentage of ground strokes increases with geographical latitude. In the Netherlands winter thunderstorms often cause problems. A possible explanation is the lowering of the main charge centres, connected to freezing temperatures, in cold atmospheres.
This effect is confirmed with SAFIR data (Fig.16). It should be remembered that the recognition of vertical strokes may be wrong in individual cases. At least the average behaviour seems reasonable.

Other lightning characteristics have been compared with meteorological parameters like the 700 hPa temperature and windspeed. The fraction of positive strokes falls above 0 °C at 700 hPa from about 40% to 20%, but the spread between individual days is even larger than in Fig.16.
The median peak current rises from 20 kA at -15 °C to 40 kA at 5 °C, but again the spread is very large.
The average multiplicity was about 1.27 strokes per flash. There were no clear variations with the season. It should be noted that the recognition of component flashes is not straightforward: a time and distance window has to be chosen and a decision has to be made whether to accept subsequent strokes with different sign.

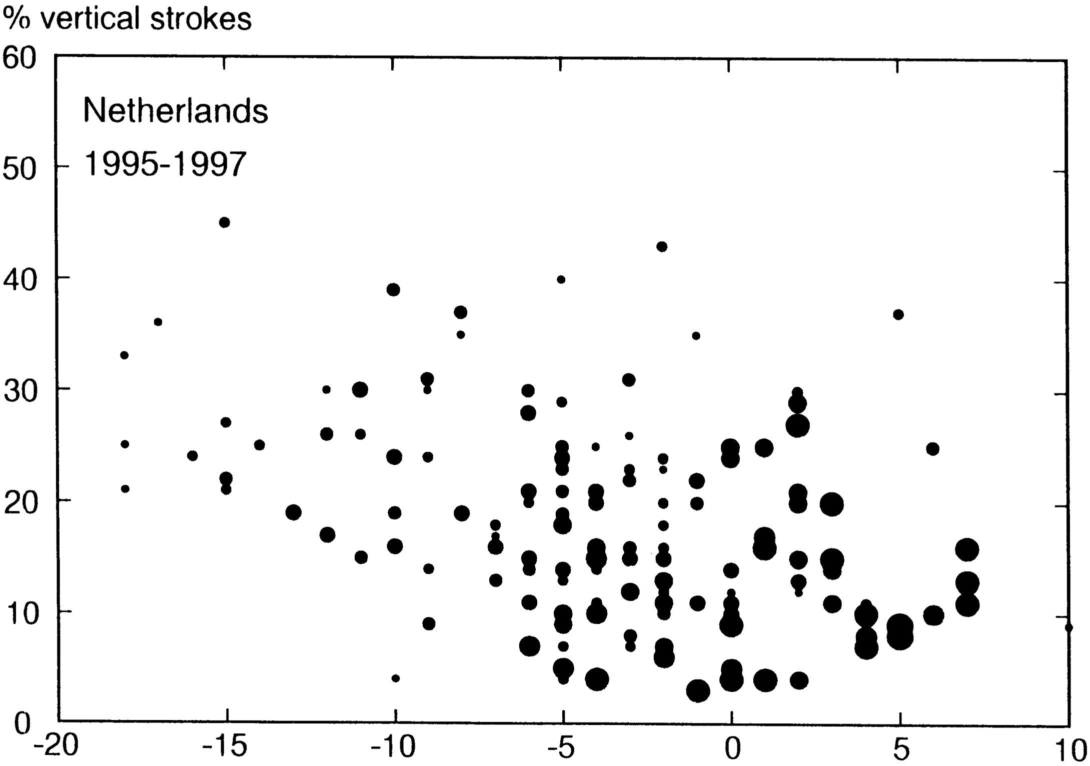

Fig.16. Daily relative frequency of vertical discharges as a function of the 700 hPa temperature. As in Fig.15 days with a larger total of strokes are represented by larger dots.

8 CONCLUSIONS

- The location errors of the SAFIR system can be split in systematic and random errors. Systematic triangulation errors can amount to several km, especially at large range. Their direction and size depend on the location of the flash with respect to the triangulation stations used. (Section 4, a,d)
- The remaining random location errors could be quantified by various tests: about 80% of the strokes will be located with an accuracy better than 2.6 km. Errors are partly caused by instrument limitations and partly by measuring elevated sources along non-vertical channels. (Section 4, c,d)
- The number of false alarms is neglectable. (Section 5, a)
- The detection rate seems adequate over the territory of the Netherlands. It could be shown that the 50% detection limit follows approximately the 4km location accuracy limit in Fig.1. (Section 5, c)
- The coverage of the network has improved significantly by the inclusion of the Belgian data. This is important for nowcasting as well as climatological applications. (Section 5, a)
- Both the high detection rate and the absence of false alarms make the system very useful for nowcasting purposes.
- Failure of single receivers was not uncommon during the evaluation period. If this occurs the coverage over some regions is severely disturbed. (Section 5, a)
- A radius of 14 km around a station may be used to simulate 'thunder heard' for synoptic observations. (Section 5, b)
- The discrimination between intracloud and earth discharges is not very successful in individual cases. (Section 6, a,b)
- The estimates of peak current and sign seem suspect in individual cases. The statistics of peak current and peak rise time compare well with published estimates. The action integral and the charge are probably underestimated. (Section 6, b)
- About 5% of the intracloud discharges measured during 1997 were longer than 11 km. (Section 4, b)
- The data collected until now confirm earlier estimates of lightning density in the Netherlands: 1.5 per square km per annum. (Section 7, b)

9. RECOMMENDATIONS

- The off-line coherence test recommended by the manufacturer to reduce systematic errors, should be performed regularly and at least twice per year, using all available data. Corrections resulting from an individual test should be applied with caution in order to avoid erratic system changes. Subsequent corrections values should result in final corrections, that can be used to re-process and improve the archived data.
- It is recommended to extend the network with a receiver in the north-east of the country, both to improve the overall redundancy and to increase the normal detection rate near the northeastern frontier.
- Caution should be exercised in using the data for verifying insurance claims. Reservations have to be made concerning the location error and the recognition of earth discharges.
- It is recommended to extend the comparison between 'thunder heard' and 'flashes located within 14 km' over a longer period.

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