A New Method for the Measurement of the Site Errors of a Lightning Direction-Finder: Description and First Results

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ABSTRACT

One of the major limitations in the use of magnetic direction-finders for locating lightning is the presence of systematic angle errors that are due to the local antenna site. An attempt was made to measure this systematic error, by using a reciprocal method, i.e., interchanging the rôles of transmitter and receiver. The correction functions obtained in this way were tested and partially improved. After applying a correction for site errors, we improved significantly the lightning localization accuracy, but there remained a residual error, partly because of the geometry of the lightning localization network.

1. Introduction

In recent years, networks of wideband magnetic direction-finders have been used to locate lightning in many countries (see Krider et al., 1980). It is a well-known fact that the direction-finders with crossed loop antennas can have large systematic errors as related to the site (see Horner, 1954). Until recently the methods used for measuring this angle error were

1) to measure them directly using TV cameras or some other form of "ground truth" (Mach, 1984);
2) to use the redundant data contained in more than two stations, assuming that some of them are correct.

A step forward in the investigation of the angle error is the fitting of correction functions; for example, trigonometric polynomials in minimizing the overall error (Huse, 1983; Hiscox et al., 1984) and theoretical work on the error triangles (Enayatollah and Michnowski, 1983; Pisler, 1980). Another way is the comparing of localizations with ground truth data such as reports on lightning damages or radar echoes of very compact thunderstorms (Christensen, 1983). All of these methods have deficiencies. There are insufficient radio stations distributed over all angles, which are strong enough to obtain the angle error for all directions.

The assumption that some direction-finders give the correct angle is fairly arbitrary. Relaxation methods require a dense network and extensive collection of data. The assumption, that the angle error function can be approximated by a double sinusoid (corresponding to a radiating dipole) is, as we observe later, rather optimistic. Since reports on lightning discharges or compact radar echoes are so rare, the method of Christensen (1983) is therefore restricted.

There is need for a method that makes it possible to determine the angle error of a separate direction-finder (DF) station for all directions with sufficient accuracy. The present reciprocal method, which is based on the fact that the antenna characteristics for receiving and transmitting are the same, is a step forward. Site errors are expected to be usually constant, so they can easily be corrected once they have been determined; the locating system has the capability of making these corrections during real-time operation.

2. Measuring method

The base for the measurement design is the reciprocity theorem. From this, it follows that the antenna characteristics (for a loop antenna the simple cosine characteristic) are the same for transmitting and receiving (Flügge, 1958). This means, it is equivalent to calculate the angle from the DF antennas to a transmitter (lightning) from the voltage ratio of the both loops (proportional to the magnetic flux change ratio through the loops) or to calculate it from the ratio of field strengths, originating from the loops on an electric antenna in a measuring point (see Figs. 1 and 2).

In our method, we send a high frequency current through each of the loops in succession, with the DF unit disconnected, and then simultaneously measure the electric field strength at a distant point by means of a rod antenna placed on a car roof.

The measuring frequency, 1.084 Mc s^{-1}, was chosen in consideration of the following: There exist conflicting requirements; on the one hand, the frequency has to be as low as possible because the lightning radiation spectrum has its maximum in the low frequencies; on the other hand, we have to work in the radiation field, which requires a minimum measurement distance of about one wavelength. Furthermore, the radiated power of a loop antenna (a very poor transmitter) increases quadratically with the frequency, and we have

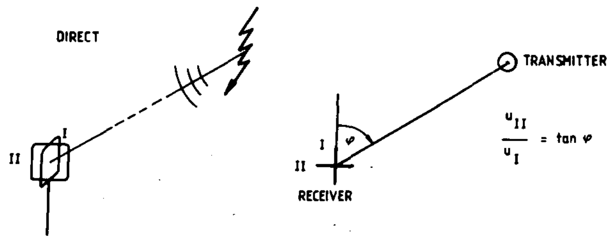

FIG. 1. Direct measurement outline.

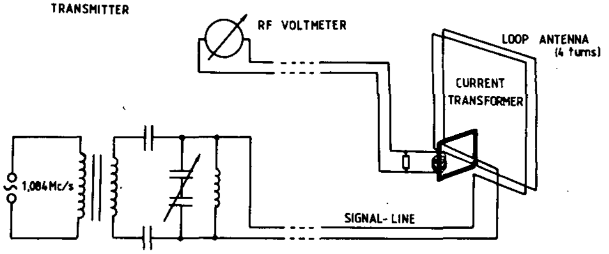

FIG. 3. Transmitter arrangement.

to choose a spectral region free of broadcast transmitters, which can disturb the results. The chosen frequency seems to be the best fit to these requirements with this choice of frequency; a minimum distance of about 280 m and a range up to 1.5–2 km is obtained without exceeding a transmitting antenna current of 1.5Å. Higher current would have excessively heated the thin wires in the loops.

3. Description of transmitting and receiving devices

The high frequency source was a frequency stabilized signal generator (HP 8640 B) followed by a 50 dB broadband amplifier (EIN 350 L). Through a symmetrizing transformer a tuning arrangement was fed and tuned to resonance in order to maximize the current in the loop (see Fig. 3). For the current measurement, we used current transformers, built at our institute, with a high relative accuracy. These could be divided into two parts and then combined around a loop. We measured the voltage drop on a 5Ω resistance and in this way, the transformer was only a slight resistive load which did not change the antenna characteristics. A calibration showed that the transformers were identical within 0.5%.

This possibility of measuring the current directly in the antennas was crucial for the method. For example, a current measurement on the output of the tuning unit can be completely incorrect because of losses in the feed line. We used the signal lines as feed lines. An equal current in both loops is essential for our method.

As receiver, a "Collins" radio receiver type 51 J 4 was used. Within the frequency range of interest, the interfrequency output voltage was an almost perfect linear function of the input voltage. An accurate calibration was done and the best least-squares fit for the calibration function was a power law $U_{\text{in}} \sim (U_{\text{out}})^{1.033}$ with a correlation coefficient $r^2 = 0.9998$. The interfrequency output was measured by a vacuum tube voltmeter. When choosing a narrow bandwidth (approximately 400 Hz), a narrow antenna filter and a 3 m rod antenna, we obtained proper signal-to-noise ratios. The receiving devices were installed in a car and on a car; as a power source we used lead batteries and a DC/AC converter. Thus, the equipment was mobile. By means of a map scaled to 1:10000 of the DF site and in some cases a theodolite, about 20 measuring points around the station were chosen and the field strength ratios measured. The arctangent of this ratio was compared with the real angle, measured on the map or by the theodolite. The overall accuracy was estimated as follows:

Measured quantity	Error (%)	Resulting error (deg)
Real angle	—	1
Difference between current transformers	0.5	0.2
Reading error transmitter (always on maximum scale value)	1	0.3
Reading error receiver	2	0.6

Thus, the average total error is not greater than approximately 2 deg. Only relative values were needed

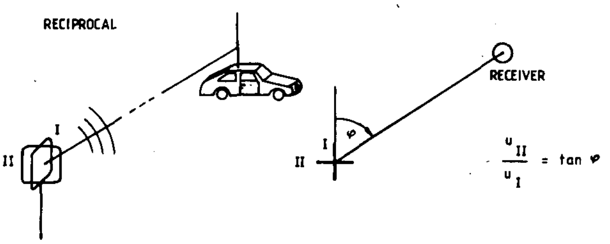

FIG. 2. Reciprocal measurement outline.

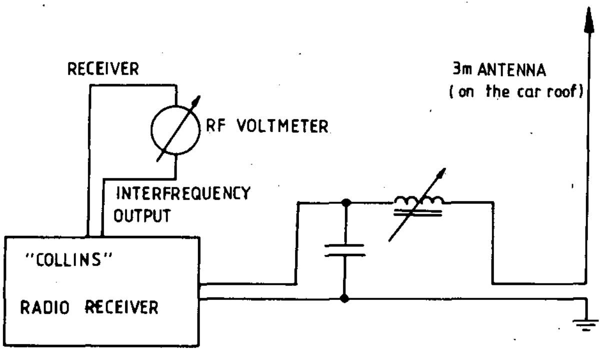

FIG. 4. Receiver arrangement.

and, therefore, we do not need to account for the absolute accuracy of the voltmeters. Repeated measurements at the same points never displayed more than a difference of 1°; in most cases there is no difference at all. The deviation of the antenna from the N–S direction agreed in all cases with the measuring results. All results were rounded off to whole degrees.

In spite of this accuracy, we have to bear in mind the big difference between a monochromatic wave and a lightning pulse. Furthermore, the reciprocality is limited by the induction field of the loop, perhaps interacting with the nearest obstacle in a way other than a pure radiation field. Considering these features, we do not claim to have measured the exact angle error. However, we believe that we have obtained a better knowledge of it by using the described method than by the methods formerly in use.

4. Evaluation of the measurements

For the DF stations, the following procedures were followed: Diagrams of angle error/real-angle and angle correction/calculated angle were drawn. The angle correction is the negative angle error. The expected change of the field strength of the radiation field with distance, r by $1/r$, was checked at all stations to detect eventual severe errors in our measurements. In all cases the field strength followed the $1/r$ law as expected for such short distances where propagation losses are not expected to be significant. By means of a computer program, Fourier analysis with nonequidistant measuring points was executed for the angle-error function and the angle-correction function.

5. Description of stations

a. Såtenäs

The first station investigated was the Såtenäs station, where the largest errors were expected (Christensen, 1983; see Fig. 5). The antenna is located on a large asymmetrical wooden house (see Fig. 6). The house is situated on a tongue of land in lake Vänern in southwestern Sweden. There are some buildings and trees in the area but most of it consists of fields or meadows.

b. Uppsala

The antenna was placed on a wooden carriage (see Fig. 7). This carriage is built on a massive steel construction; because it was used earlier for other purposes, the interior was shielded by iron plates. The carriage is located between fields, about 200 m from the institute; the area is largely of rural countryside, but there are power lines, a switching yard and the institute buildings which are not too far away.

c. Rörberg

The antenna is on the top of a small wooden house built for the DF station and is situated on an airport field. The airport buildings stand alone at a distance of some 100 m. Meadows surround the station and there is forest at a greater distance. The site is nearly ideal.

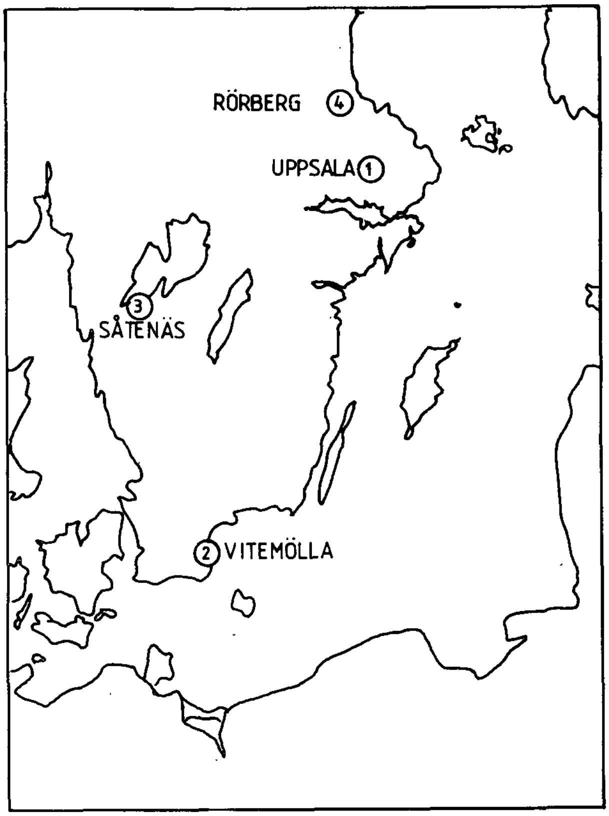

FIG. 5. The LLP network in Sweden.

d. Vitemölla

The last station investigated was Vitemölla on the east coast of Scania in southern Sweden. It is situated on a hillock only 300 m from the shore. The surroundings have rather pronounced height gradients. Close to the antenna are dunes covered with grass, and at a greater distance, there is farmland, the sea, a village (Vitemölla) and a forest. The antenna is in the middle of the roof of a small shielded wooden house. Like the carriage at Uppsala, it was earlier used for other types of thunderstorm research. After a heavy storm in the autumn of 1983, which damaged the signal lines, the station was repaired. This happened after the Uppsala measurements, which showed a decrease in the angle error as a result of the raising of the antenna. Therefore, it was decided to raise the Vitemölla antenna. At the same time, a large, old Faraday cage close to the house was taken away. This proved to be a shortcoming since the measurements performed after the raising are not truly representative of earlier angle errors.

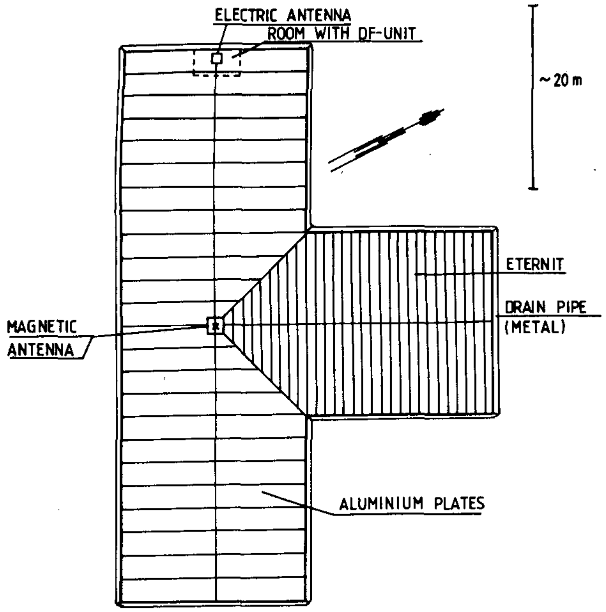

FIG. 6. Antenna site, Såtenäs.

6. Results

The correction functions obtained directly from the measurements gave the following results: 1) Large differences in shape are observed from one station to another with an amplitude at Såtenäs about 20° and at the other stations between 5° and 10°; 2) correction is made of a large misalignment of the antenna at Uppsala (9°); and 3) the error amplitude at Uppsala is reduced after the antenna was raised and a new adjustment was made using theodolite. First tests of this correction function on lightning flashes showed a clear improvement, but they also showed that the correction function for Såtenäs was not working well in all directions. The reason for this was thought to be the resonance effect of the plate roof, which roughly has the same dimensions as a quarter wavelength. Due to the shortcomings of the equipment, other frequencies could not be used.

In order to rectify the erroneous standard of the localizations without any corrections, the system was run since June 1984 with preliminary corrections made directly from the measurements of three stations, partially from the measurements and partially from the evaluation of nearly point-shaped thunderstorms (Christensen, 1983) for Såtenäs.

The experiences with these preliminary corrections were satisfactory and encouraged a more extensive evaluation. The only practically reliable sources of information for the efficiency of a localization system of this kind are the error triangles, made by three bearings or the error figures for more than three stations, composed of error triangles. The damping conditions over the low conductive Swedish ground made the use of signal strength information nearly impossible.

Simulations of error triangles yielded the following, partially surprising properties: small triangles alone are not proof of good correction; often the small triangles are far from the real position. The assumption that the real position is inside the error triangle is found to be incorrect in most cases, as shown theoretically by Stansfield (1947). He proved that only one-fourth of the true positions are inside the error triangle. A good criterion for effective correction is a nearly overall decrease of the error triangles and a significant decrease of divergent localizations, namely, noncrossing bearings.

About 130 lightning strokes, localized by three or four stations and spread over the whole area of interest, were chosen. The error triangles were calculated and plotted on a map. As a measure of the size of the error triangle, the radius of the circle inside the triangle, (Stansfield, 1947) respectively half the distance between the two remaining crossings when the third was divergent, were chosen. As expected, use of the first correction gives a clear improvement. A further improvement was made in the following manner: The much larger error amplitude at Såtenäs and the uncertainties in the correction of this station led us to make a further correction, assuming that the corrected bearings from Uppsala and Vitemölla were accurate. This yielded a significant improvement. The correction function of the third station, Rörberg, has now been optimized at one quadrant. In all the calculations, the correction functions are represented by trigonometric polynomials including the sixth order (the fifth harmonic). The contribution of higher harmonics was negligible. We also noted that the modifications of the correction functions showed a decrease of the amplitude of higher harmonics and an increase in the amplitude of the first and third harmonic (periods 180° and 90°).

Figures 8–11 show the final correction functions. The mean radius of the inside circle and the number of divergences have been calculated as a measure of the correction. First, we present some maps, which show (clearly) the pronounced changes: Fig. 12 shows

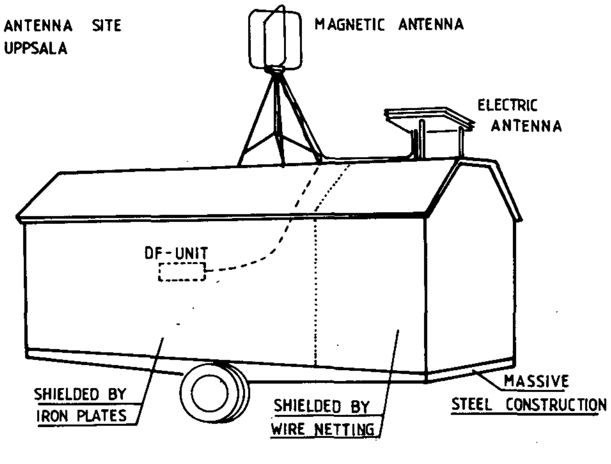

FIG. 7. Antenna site, Uppsala.

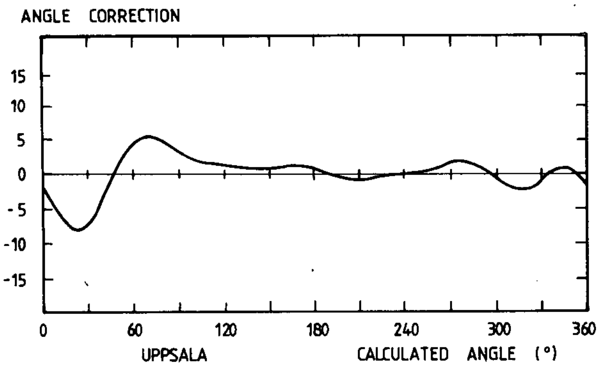

FIG. 8. Correction function, Uppsala.

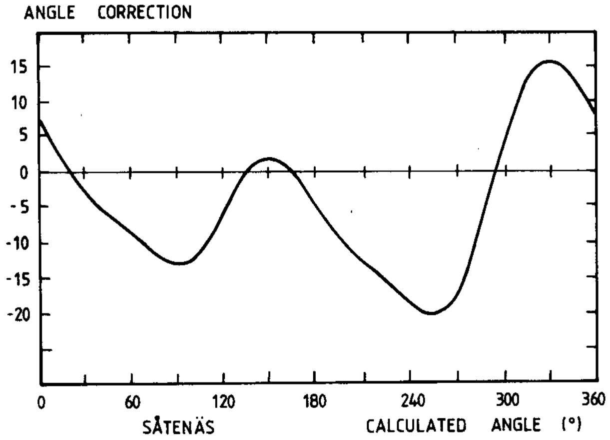

FIG. 10. Correction function, Såtenäs.

the error triangles of the three stations without any correction; Fig. 13 represents the same error triangles after a final correction. A significant decrease of the triangle size is obvious. Most of the larger triangles are situated near the baseline between the two stations and its prolongation, where the localization is always problematic due to geometrical reasons, namely, too small angles.

Strong evidence for successful correction is given by the error figures for four stations, not applicable to the whole region. Figures 14 and 15 show some of them in the Baltic Sea region before and after correction, respectively. Together with a clear improvement the figures also show the baseline effect for Rörberg and Uppsala.

Numerically, the following results were obtained for 120 lightning flashes detected by the stations at Uppsala, Vitemölla and Såtenäs:

Class	Mean radius of inner circle (km)	Divergence
Uncorrected (Fig. 12)	25.15	20 (16.7%)
Corrected (1)	12.78	12 (10.0%)
Corrected (2) (Fig. 3)	6.33	9 (7.5%)

Thus the results show a decrease of the radius of the inner circle by a factor of 4 and a reduction of the number of divergences of the half. The other three combinations, including Rörberg, show similar values. They are considered as less representative due to the fact that they do not cover all directions. The second correction of Rörberg gives a similar improvement effect.

Discussion

The results show that the described method cannot wholly correct the site error, but it gives a significant improvement, particularly after the data processing.

The purely technical accuracy of the measurements seems to be reliable and other explanations of the residual errors have to be considered. The fact that the differences between first and second correction were fairly high at Såtenäs probably indicates the role of resonance phenomena. Measurements at different wavelengths, comparison of curves obtained and removal of peaks observed at only one wavelength—all could be solutions. Although our work was planned

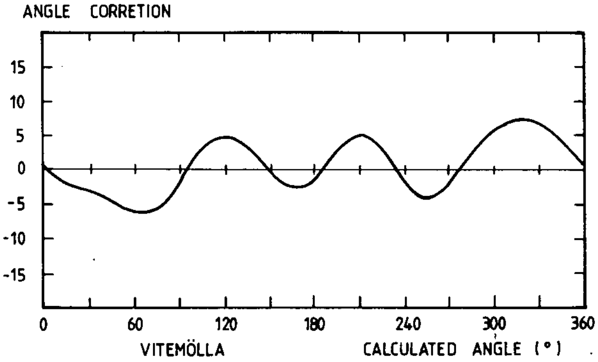

FIG. 9. Correction function, Vitemölla.

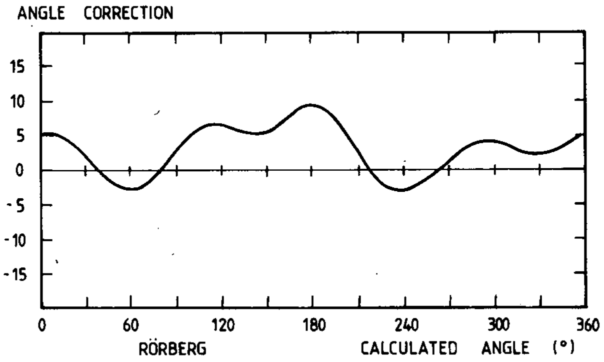

FIG. 11. Correction function, Rörberg.

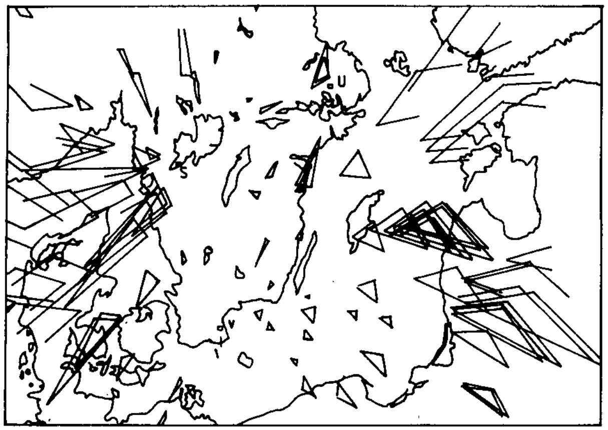

FIG. 12. Error triangles of three DF stations without correction.

this way it could not be done to shortcomings of the equipment.

The advantages of this method become most clear in the design of a new network. Before starting, one can get a rough estimate of the site errors and move extremely poor stations to other sites. The system can be operated for a short time using these first corrections. By the use of quite a few localizations an improvement of the corrections can be found. After a longer time, e.g., one thunderstorm season, the number of data is large enough for methods described in Hiscox et al. (1984). Because corrected data can be used as input, the chances for success are better, the danger of algorithm deroulement is less and the use of simplified (linearized) methods is more feasible than with totally uncorrected raw data.

It is easily understood that a network with bad geometry, i.e., with many crossings occurring under very small angles and high distances, is particularly hard to correct. Small angle errors can result in large localiza-

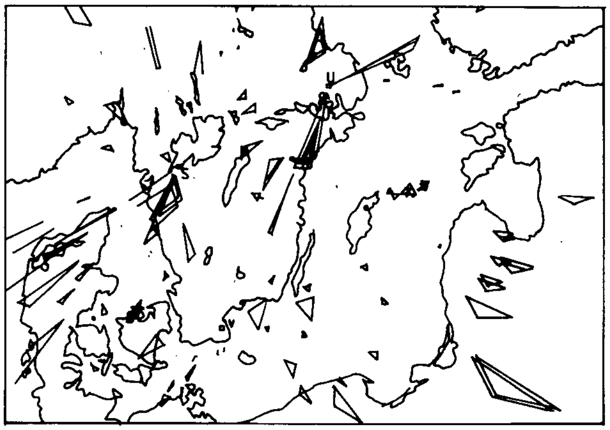

FIG. 13. As in Fig. 12 except with correction.

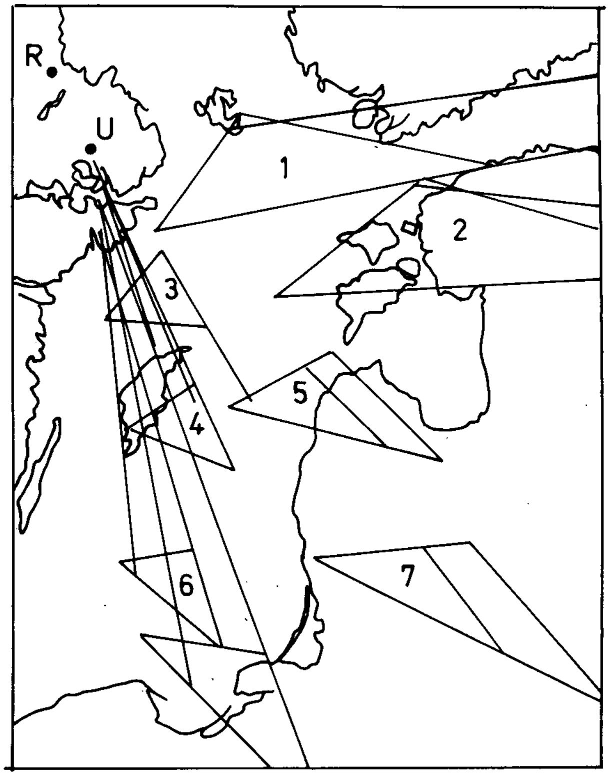

FIG. 14. Error figures of four DF stations without correction.

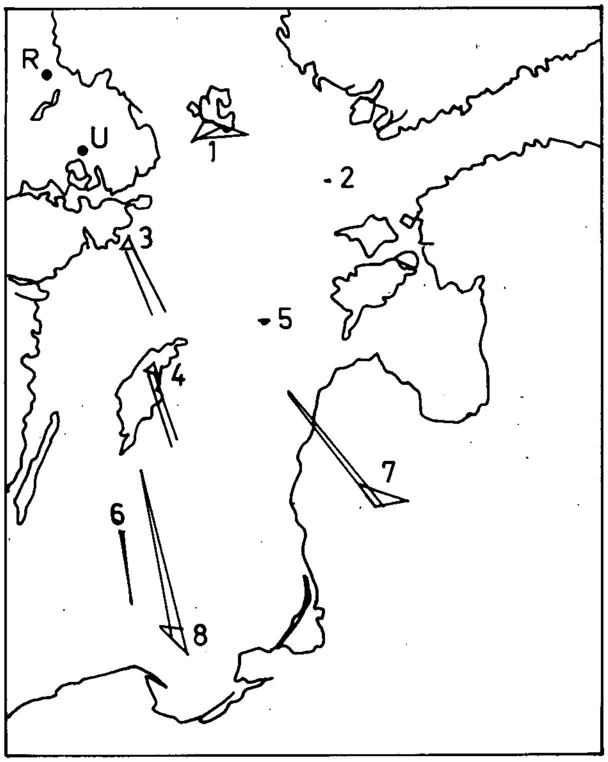

FIG. 15. As in Fig. 14 except with correction.

tion errors. But that is why this network is a good object for testing the skill of correction methods.

A short comment on eventual causes for the site errors at different stations follows: In Såtenäs, there is no doubt that the big plate roof plays an important rôle in the site error. At Uppsala, the iron content of the carriage seems to be of importance. This suspicion has been strengthened by the decrease of the error amplitude after the raising of the antenna (Schütte, 1984). The shape of the error function at Vitemölla is perhaps a kind of mapping of the surrounding dunes (Horner, 1954). In one direction, measurements were made at two distances, where the more distant measurement included a bit of the sea. There was no difference in the angle error in spite of the different propagation conditions. In order to check an eventual coastline effect, many measurements of this type are needed, however. The little house is quadratic and the antenna is placed in the middle of the roof, which does not have a larger influence in spite of the metallic shielding. In Rörberg, the site seems to be nearly ideal, which makes the site error rather difficult to explain.

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