Final report on the NORDRAD QA project

Project period: 1.8.2000 - 31.12.2001

Project management group:
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1 Foreword

In the latter half of the 1990's, a NORDRAD project was set up to study and remove the cause of the significant difference found in the intensity between the Swedish and Finnish radars. This project, called as the NORDRAD continuation project, was carried out in 1996-1998, and successfully determined the main causes for the discrepancy, which were then removed. In April 1998, the NORDRAD Steering Group established this NORDRAD QA-project as a follow-up project on the quality assurance.

This final report is organized as follows. The foreword is followed by an executive summary with conclusions and recommendations. After that follows a section describing the most important results, a description of the software components and of the practical issues in the analysis including a description of the numerical analysis method created during the project. The original project plan dated April 15, 1999, and the Interim report dated May 10, 2001, are included as appendices.

2 Executive summary

2.1 Project aim and timetable

The aim of the project, as set in the project plan, was to improve the intensity level harmonization of the NORDRAD network to within ± 2 dBZ, and to establish workable and efficient quality assurance and maintenance practices. The project was divided into three sub-projects:

- SP1 Monitoring of all NORDRAD radars using the NRDTOOLS software. Sub-project SP1 produced regular reports of the relative intensity levels and of the pointing accuracy of the radars for use in the other subprojects. It was carried out by FMI on behalf of all parties with their cooperation.
- SP2 Investigation of angular pointing accuracy of all NORDRAD radars, and implementation of improvements to achieve the agreed level of performance.
- SP3 Investigation of calibration and radar parameter value accuracy at all NORDRAD radars, and implementation of improvements to achieve the agreed level of performance.

The project was originally started in March 1999 with a Workshop in Helsinki, where experts of the participating institutes and invited guests from Germany and Estonia met to discuss the project plan. The agreed active project period was from May 1999 until April 2000. However, the project was at standstill at FMI until August 2000, when the project was finally started. First results were presented to NOCORD at its meeting on October 18-19, 2000 in Helsinki. The project management group met in Helsinki on November 21, 2000. It was agreed that the work concentrates to SP1 in the beginning and that the work on SP2 and SP3 is started when the Institutes have found resources to carry out the projects. An Interim report was presented to NOCORD in May 2001. It became apparent during the project that resources to carry out subprojects SP2 and SP3 to full extent could not be found in the participating institutes. Thus the advances of the QA project concentrate mainly in the SP1 and separate reports on SP2 and SP3 will not be presented, contrary to the original project plan.

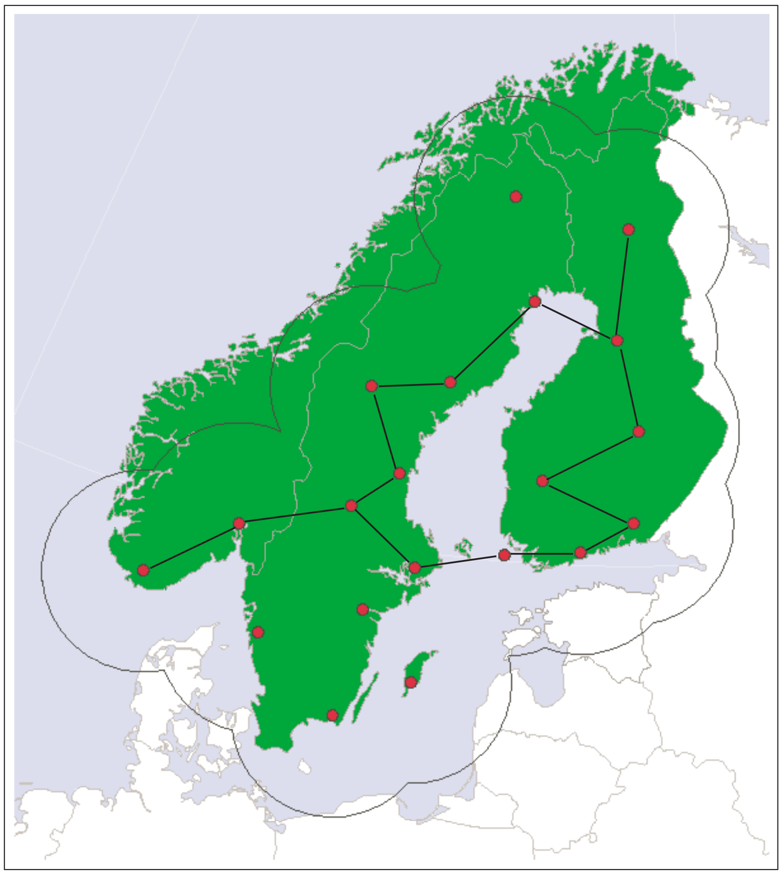


Figure 1: The NORDRAD network (August 2000) and the radar pairs used in this study. © FMI and National Land Survey of Finland, 30/MAR/99.

2.2 Setup of the paired-radar analysis

The radar pairs chosen for the study are shown in Figure 1. These form a chain through Finland from Korpo to Luosto, a chain through Sweden from Stockholm to Luleå, and a chain from Vantaa to Hægebostad in Norway. Thus we have included all three types of radars in the comparison (Gematronic/Sigmet, Ericsson, Gematronic). Two products are created for each pair, the total number thus being 30, and the products have been created at 15 min intervals. The analysis has been run in the SGI computers at FMI. During the project, the NRDTOOLS software was installed in the computers, new software components were created, and a set of shell scripts were written to facilitate the analysis of the data and the production of the pictures.

The analysis has been running in full since the beginning of February 2001. The results of this report are based on data collected since then. Early results on data collected in 2000 are presented in the Interim report.

2.3 QA web pages

A dedicated web server (nordrad.fmi.fi) was set up in October 2000, with access by the project team. The web pages contain documentation on the project, pictures produced by the NRDTOOLS, and the numerical results by the analysis program. The web pages has been the key method to make the paired-radar results available to the project team.

2.4 Numerical analysis of paired-radar pictures

The main task in the project was the creation of a numerical analysis program by which one obtains estimates on the calibration difference of the radars and difference of the lowest elevation angles used by the radars. The analysis method is explained in Chapter 5. The first running version of the program was ready in February 2001. Since then numerical results have been available at the project web pages. The final version of the software was ready in November 2001, when handling of the blocked sectors was added to the software.

2.5 Resources used at FMI in subproject SP-1

To carry out the sub-project SP-1, both computer and man power resources have been used at FMI. During the project period up to one year of data has been kept on-line, requiring some 8 GB of disk space. Creation of the QA products has used some 50 % of the resources of a workstation. The computer resources needed for running the NRDTOOLS to create the paired-radar pictures and for running the analysis program are negligible. By far the largest cost has occurred from the use of manpower resources. Some 480 hours of work has been done to set-up the analysis, to create the numerical analysis program, and to run the analysis during the project period. This work has been done mostly by the program manager, supported by the computing branch of FMI. The project proposal, included at Appendix 1 to the report, estimates the amount of work to 42 working days, which is equal to 304 working hours. Thus the estimated amount has been exceeded by some 60 %. The main cause for this is the designing and programming of the numerical analysis program.

According to the project plan, the cost of SP-1 is divided between the institutes according to the number of operational radars included in the project, to which one radar is added as an overhead. As the number of radars included is 7, 6 and 2 for FMI, SMHI and met.no, respectively, the cost would be divided in ratios 8/18, 7/18 and 3/18 between the institutes.

2.6 Advances on elevation angle accuracy and intensity calibration

The work within SP1, i.e. the production and the analysis of the paired-radar images was intended to serve as input to the subprojects SP2 and SP3. Due to the unavailable resources at the Institutes these subprojects could not be carried through. Yet some advances were obtained. The report "Preliminary phase report from NORDRAD QA-project phase1: 1999-01-01 — 1999-03-31" prepared by Madelen Nilsson, the then project manager Sweden on SP2 and SP3, presents a thorough study on the angular pointing accuracy and calibration accuracy of the Luleå radar. This document is a good reference to the work which was planned within SP2 and SP3.

Also, the input from subproject SP1 was utilized in the normal maintenance work of the radar networks. We may note, by studying Fig. 2 that there is no apparent discrepancy in the intensity calibration within the part of the NORDRAD network included in this study.

In some single cases the analysis pointed out clear problems in the pointing or the intensity. A notable example is the Korpo radar, in which the antenna pointing was found to be wrong by 0.2^o in elevation, and adjusted.

2.7 Work not done

The analysis of the single radar pictures could not be started, because the creation of the paired-radar software needed most of the available resources. The work concentrated mainly in the SP1, and the tasks of the subprojects 2 and 3 have by large been left undone, as described above.

2.8 Conclusions and recommendations

The most important conclusions based on the project work are as follows:

1. NRDTOOLS has been used routinely for more than one year and has found to be mature enough to be run on an operational basis. It has also been found as a valuable tool for monitoring the state of the network. A suitable length for the analysis period is about two weeks, during which sufficient rainfall normally occurs. It is most useful in monitoring gradual long term changes in the radars, abrupt changes caused e.g. radar malfunction are better seen in radar composites or accumulated rainfall rates.

2. Results show that the network is in a good state in general. We may also conclude that there is no significant calibration difference between the Finnish, Swedish and the Norwegian networks, within the part of the network used in this project.

The project management group makes the following recommendations:

1. NRDTOOLS should be taken into operational use within whole NORDRAD network. This would require some additional 20 radar pairs to be defined. The appropriate bodies should consider whether this work is best implemented, in all Institutes for their own networks, or in one Institute for all.

2. Sufficient resources should be assigned at the Institutes so that the results by the NRDTOOLS can be utilized to full extent. The tasks of the subprojects 2 and 3, which were by large left undone during the project period, should be incorporated in the operational maintenance and development work.

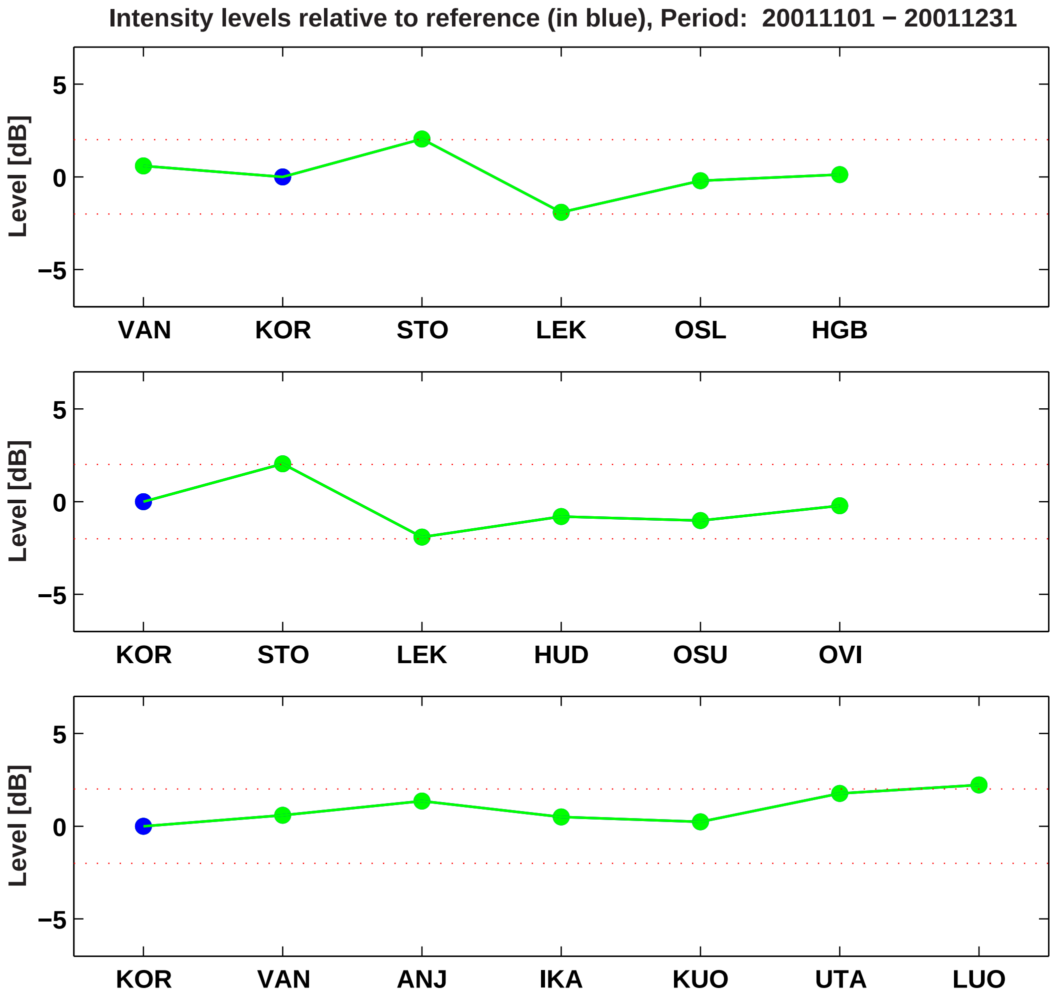


Figure 2: The intensity level of radars with respect to the Korpo radar in November-December 2001. The levels are obtained by integrating the pair wise differences along the comparison chain.

3 Results

3.1 Relative calibration levels

The results from February-December 2001 are summarized in Figs. 2–4. Firstly, Fig. 2 shows the relative reflectivity measured by each radar, with respect to the Korpo radar. These results are averages from November–December 2001, so that the most recent situation is shown.

We see that the calibration levels are within ±2dB throughout the network analyzed. Apparently the Stockholm radar gives slightly higher reflectivities than the other radars, and the Leksand radar slightly lower. The Korpo radar shows somewhat lower reflectivities than the rest of the Finnish network, and the Utajärvi and Luosto radars are a bit above the others. Comparing the average of the Finnish chain with that of the Swedish chain (excluding Stockholm) we note that the average difference is of the order of 1 dB. The two Norwegian radars are very well aligned with the others. We have excluded Luleå from this comparison, because the blocked sectors of the radar make the results highly unreliable.

3.2 Elevation angle differences

Fig. 3 shows the fit residual as a function of the elevation angle difference. The formula for the fit residual is given in Eq. 6. The result is an average from March to October, which dates are determined by the two occasions when the Korpo antenna elevation was adjusted. The elevation pointing difference at the minimum of the residual curve is the best estimate for the difference. The form of the curve gives some indication of the reliability of the results. The deeper the curve extends, i.e. the smaller is the value of the minimum, the more reliable the result is. The width of the minimum gives some indication of the probable error of the result. A rough estimate tells that the most accurate results have errors less than 0.1^o.

We will pick the Korpo radar for a closer scrutiny. We see that the KORVAN elevation difference is 0.16^o and the STOKOR difference is -0.16^o. Both results are rather reliable judging from the shape of the residual curve. This is especially true for the KORVAN pair. We are tempted to explain the situation as follows: As the Korpo antenna measures at a higher elevation than the Vantaa radar and the Stockholm antenna at a lower elevation than the Korpo radar, the Korpo antenna is misaligned. However, it has to be noted that the two Finnish radar have the same nominal elevation angles, whereas the Swedish radars measure at a 0.1^o higher angle nominally. Solar measurements by pointing the antenna to the Sun confirmed the finding and in October the Korpo antenna was adjusted by lowering by 0.20^o. The effect is seen in Fig.4. We can also note from that figure that the elevation of the Korpo antenna had been lifted in March by some 0.35^o to get it to the right position, which change turned out to be too large.

Please note that the elevation angle of the radar is determined by two factors. The elevation angle may be incorrect, and the antenna base may be tilted. Good maintenance practices should guarantee that the tilt is less than 0.1^o.

3.3 Paired-radar results

Fig. 4, which extends to several pages, contains one figure for each radar pair. Each figure consist of two panels giving the elevation angle difference and the calibration difference. The results are given for two week intervals, spanning either the first or the second half of a month, since the beginning of February. No results are available for the latter half of April.

The elevation angle panel shows the results by solid dots. Dashed lines are drawn at $\pm 0.2^o$ values to guide the eye. Zero difference is drawn on a thin solid line. The

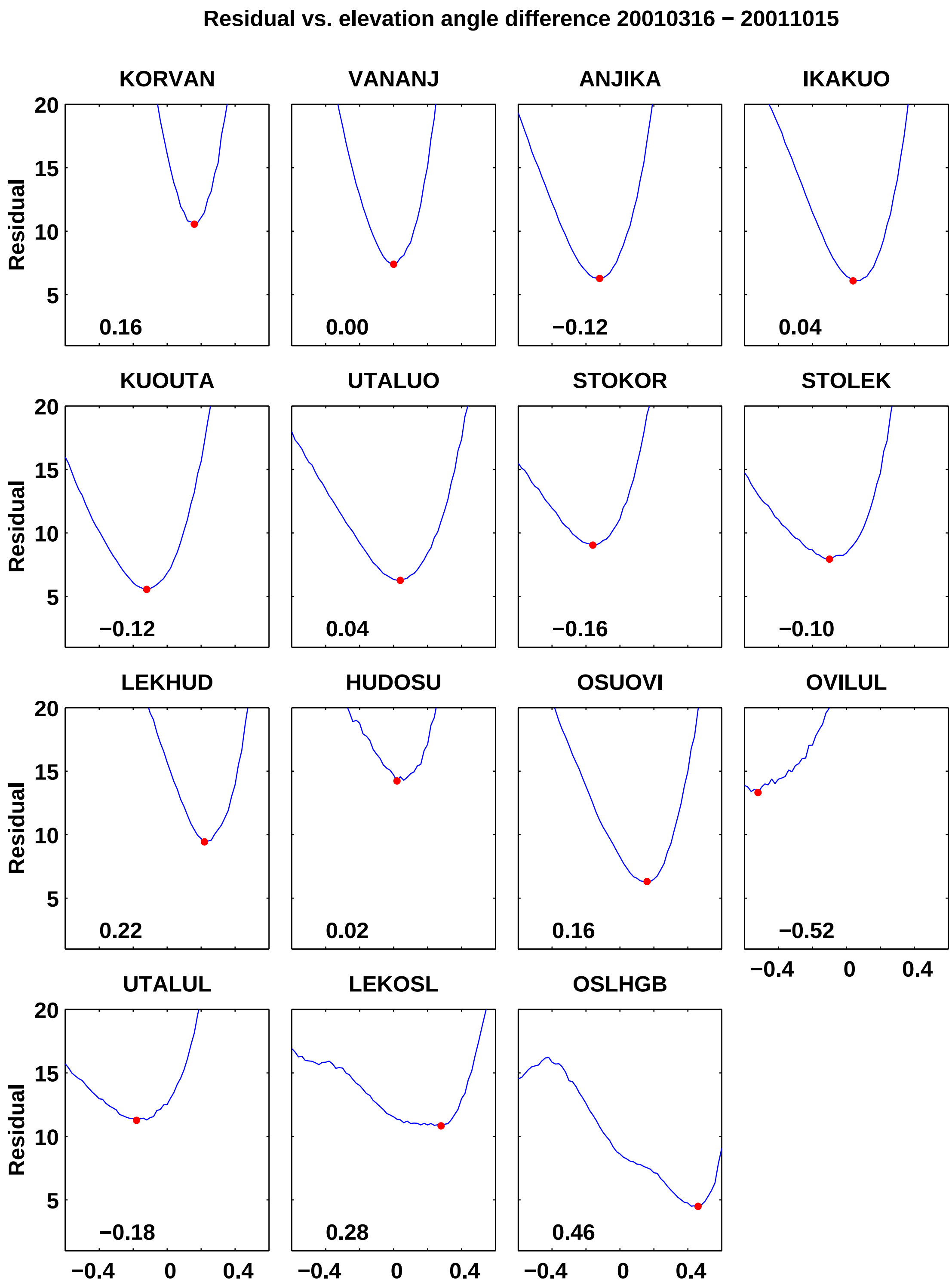


Figure 3: Residual as a function of the elevation angle difference. The maximum likelihood points are marked with dots, and the elevation angle values at these points are printed in the panels.

long time best fit value, given in Figure 3, is plotted by a thick red line.

The calibration difference panel shows the results in solid blue dots, which appear black in B/W copies. A positive value means that the first radar in the pair gives higher reflectivity values. The calibration difference for the best fit elevation angle is shown by solid green dots, connected by a green line, which appear grey in B/W copies. Dashed lines are again drawn at $\pm$2dB values. These limits were specified in the project plan as the goal of the project. Any calibration difference outside of these limits are marked by a red dot.

The small numbers in the calibration difference panels denote the times when either the first or the second radar in the pair was calibrated. This information is only available for the radars in the Finnish network. Some of the results in the panels are marked with small open circles instead of big full circles. This marks that the result is not as reliable as the other results. and that at least one of the following conditions is true:

1. The residual variance of the fit exceeds 12
2. The elevation difference is larger than 0.5^{o}.
3. The elevation differences determined from the median and average values differ by more than 0.1^{o}.

We can estimate the error of the calibration difference by looking at the fluctuation of the calibration differences from one analysis period to the next. That fluctuation is caused both by the random variation and the true changes in the radars. Thus the fluctuation gives a lower limit to the statistical error of the calibration difference. In some cases the fluctuation is clearly less than 1 dB, which means that the statistical error of the calibration difference may very well be of the order of 0.5 dB. See e.g. the LEKHUD pair on page 18, which is among the most stable pairs in the comparison. In some other examples, e.g. the VANANJ pair on page 14, the fluctuation is even smaller in June-July, but it is also easy to find examples of larger variation from period to period. It is not certain whether these changes reflect true changes in the radars or are statistical in nature.

Below we present comments on the pair-wise results. Conclusions on individual radars may be drawn by studying the pair-wise results of a single radar with all of its adjacent radars. In the present case only a limited number of pairs is available, and such conclusions are difficult to make. In a way it is difficult to tell which one of the two radars is in error, if the calibration difference is great. If the comparison net is made denser, and each radar is connected to all of its neighboring radars, it will be simpler to find out the radar not aligned with the rest of the network. In the present case we only can integrate along the comparison chain, and we have presented such results in Fig. 2.

KORVAN The Korpo antenna was adjusted twice. First in March by raising the elevation angle by 0.35^{o} and then in October by lowering it by 0.2^{o}. After the latter adjustment the antenna elevation appears to be correctly set. Large calibration difference are seen in the Summer months. Since the maintenance and calibration work in October the difference has been within the ±2 dB, as required.

VANANJ All normal. The calibration difference was large in May, probably due to a wrong calibration in the Vantaa radar.

ANJIKA The Anjalankoski radar give slightly higher reflectivities than the Ikaalinen radar. There appears to be a small elevation angle difference.

IKAKUO The differences get close to zero by the end of the year.

KUOUTA A small calibration difference and elevation angle difference is seen.

UTALUO The lowest elevation angle of the Luosto radar was changed during the project period. It was 0.4° until October and 0.1° since then. Thus the estimated elevation angle difference should be close to zero until October and 0.3° later. This is indeed the case in the first part, but after October the estimated elevation angle difference is somewhat higher, for which there is not explanation yet. The calibration difference was rather large all year, but did get close to zero by the end of the year. The Luosto radar was taken into operational use in the beginning of November.

STOKOR The estimated angular difference follows the adjustments in the Korpo antenna, although the scatter within the estimates is large. A permanent calibration difference, with the Stockholm radar showing larger reflectivities, is evident.

STOLEK The Stockholm radar gives clearly larger reflectivities when compared to Leksand.

LEKHUD Calibration difference is close to zero, but there is a permanent difference in the angles.

HUDOSU All OK, very stable calibration difference close to 0 dB seen.

OSUOVI Very stable calibration difference of about -1 dB and a small elevation angle difference.

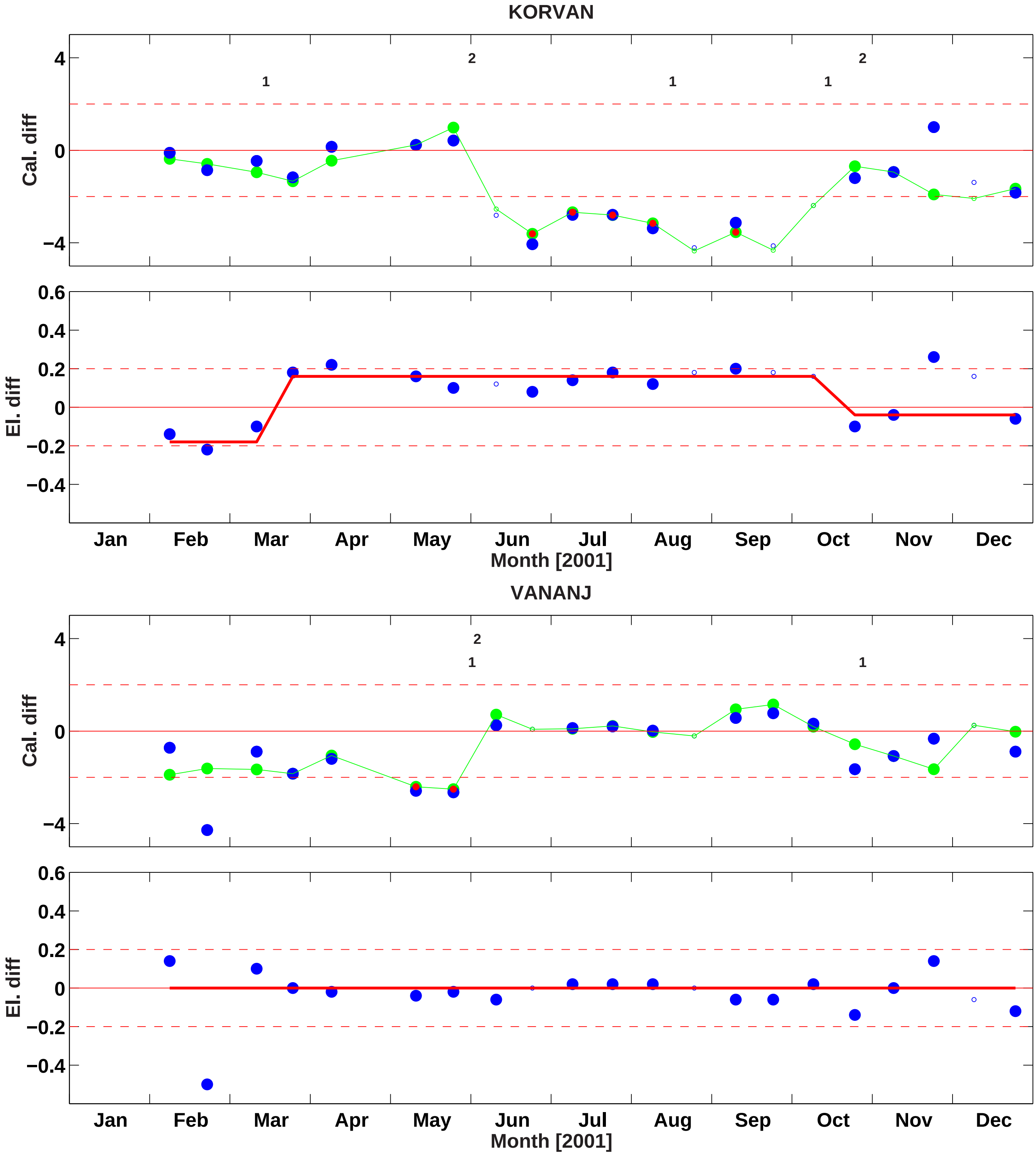
OVILUL Very few reliable points are available, because the blocked sectors of the Luleå radar are quite large in this direction.

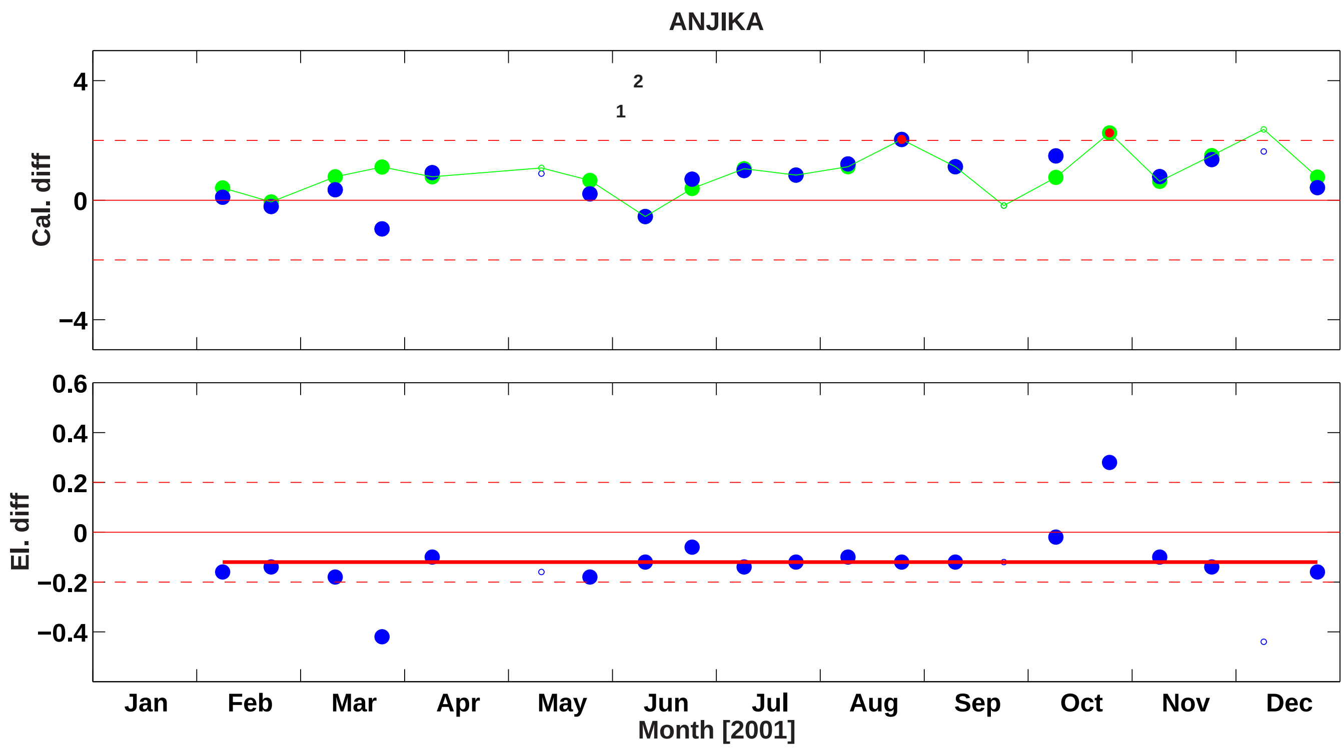
LEKOSL No calibration difference, but it is somewhat difficult to give an estimate on the elevation pointing difference. The curve in Fig. 3 is very flat on the bottom, and all angles between 0 and 0.4^o are nearly as probable.

OSLHGB The calibration difference is rather small, but the elevation angle difference is close to 0.4^o. It may be that this is caused by propagation effects, because the air close to the Hægebostad radar is more humid than close to the Oslo radar. This is evident in some individual cases, but there is no clear evidence that this effect would explain the average result. But is important to note the propagation effect. If the propagation form the two radars in the pair is not identical, the results will be biased.

UTALUL The blocked sectors of the Luleå radar may effect the results. It appears that there is no calibration difference, but that it is difficult to estimate the elevation angle difference.

Figure 4: Results of the paired radar analysis.

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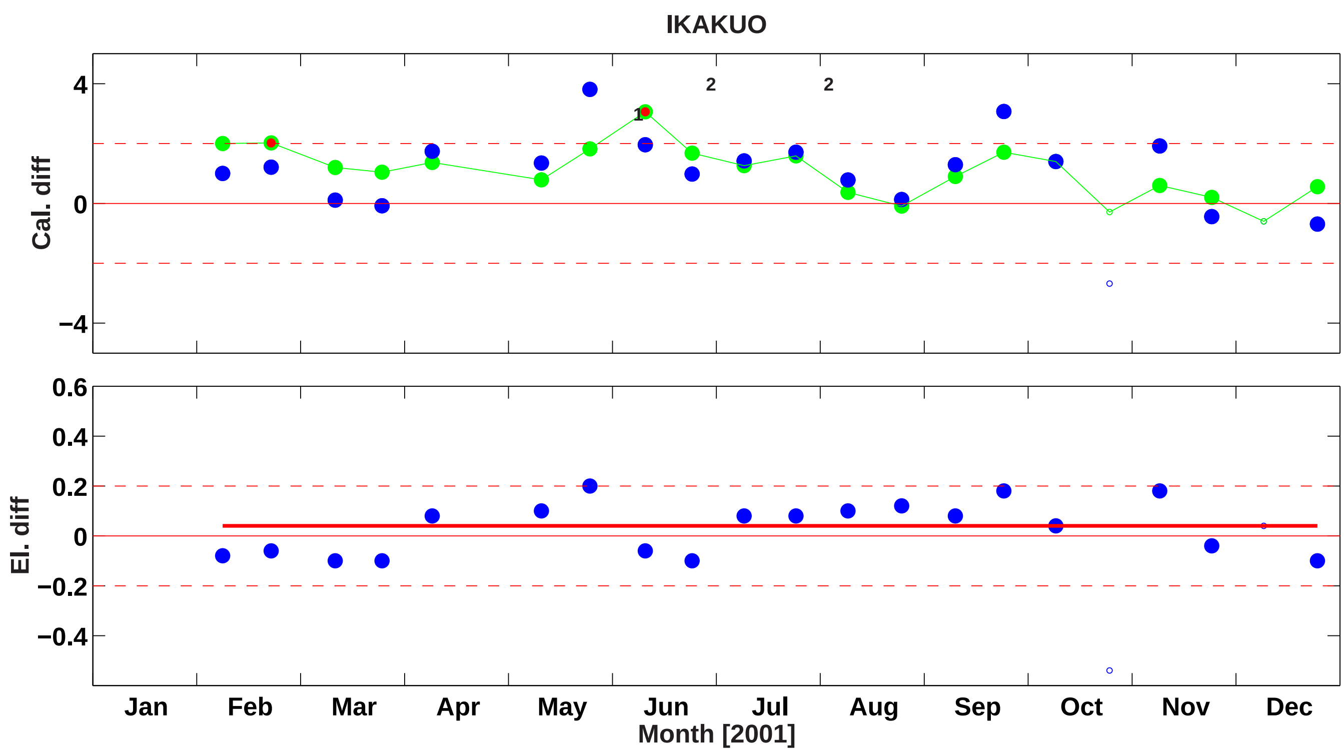
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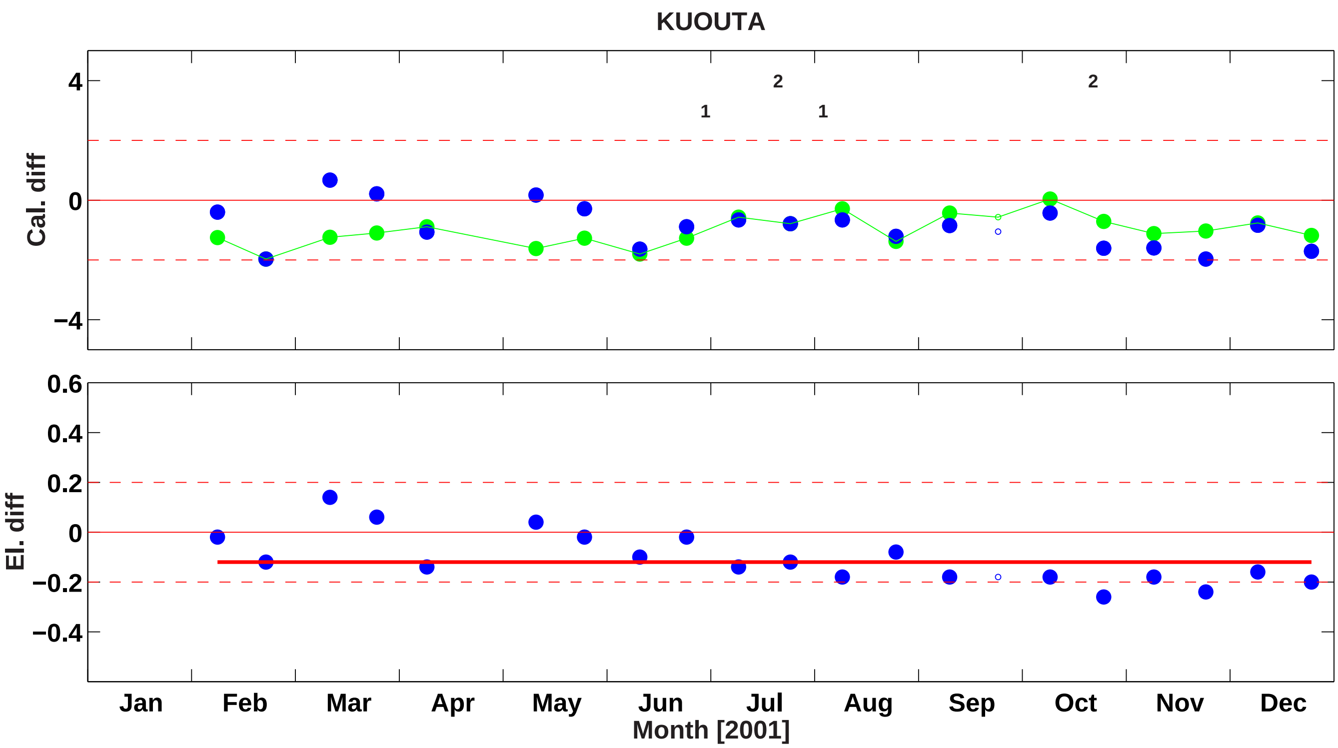
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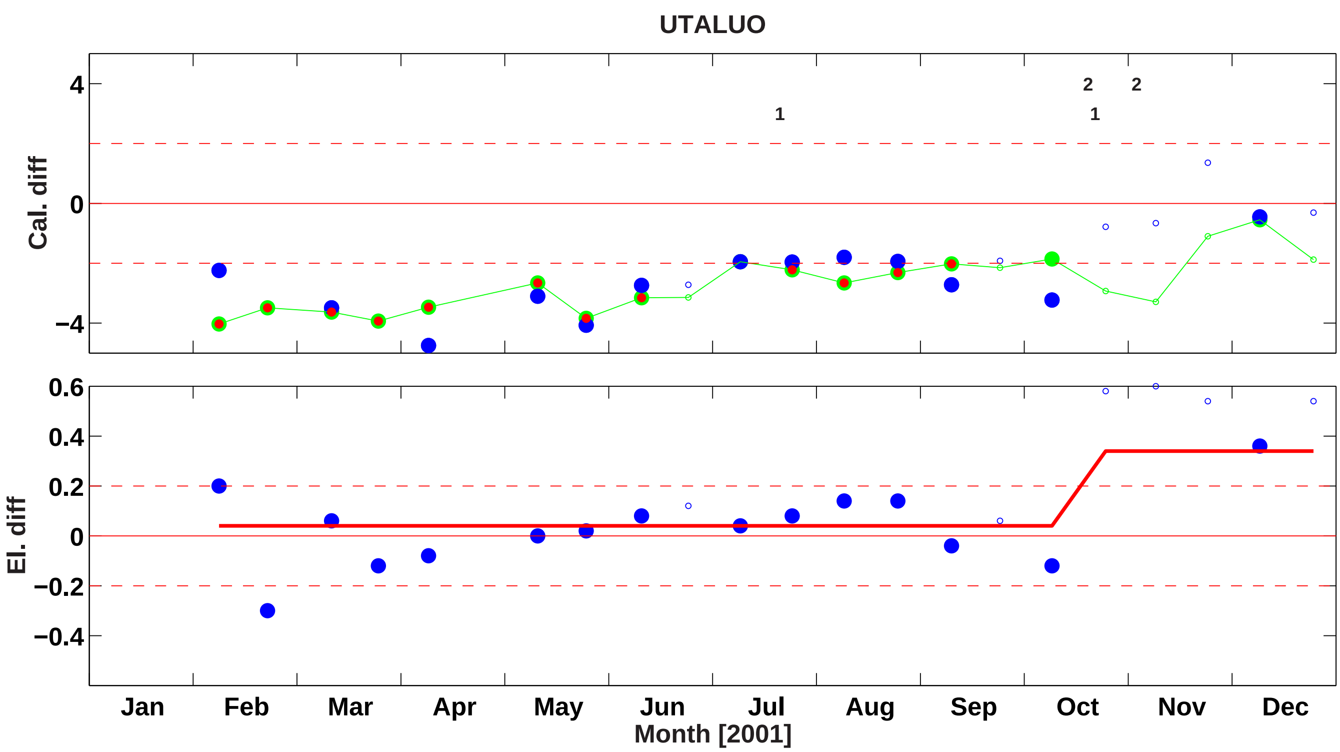
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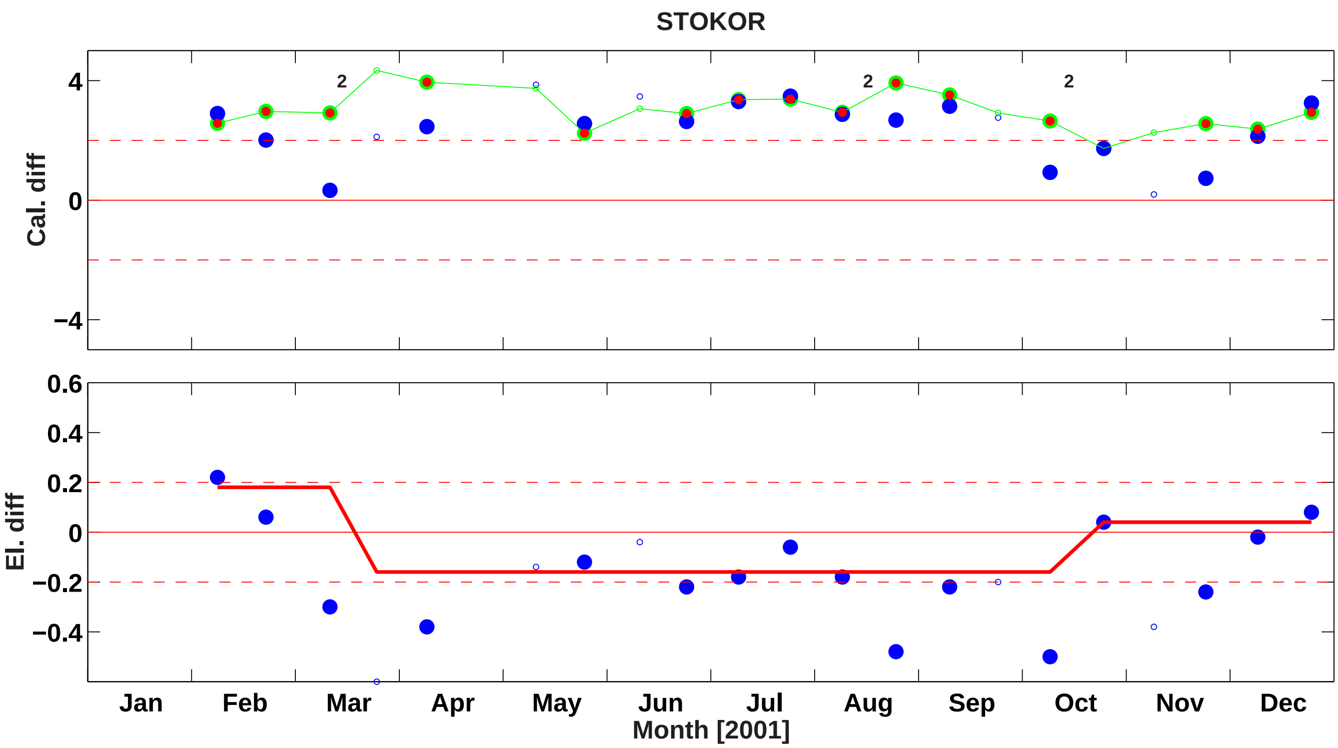
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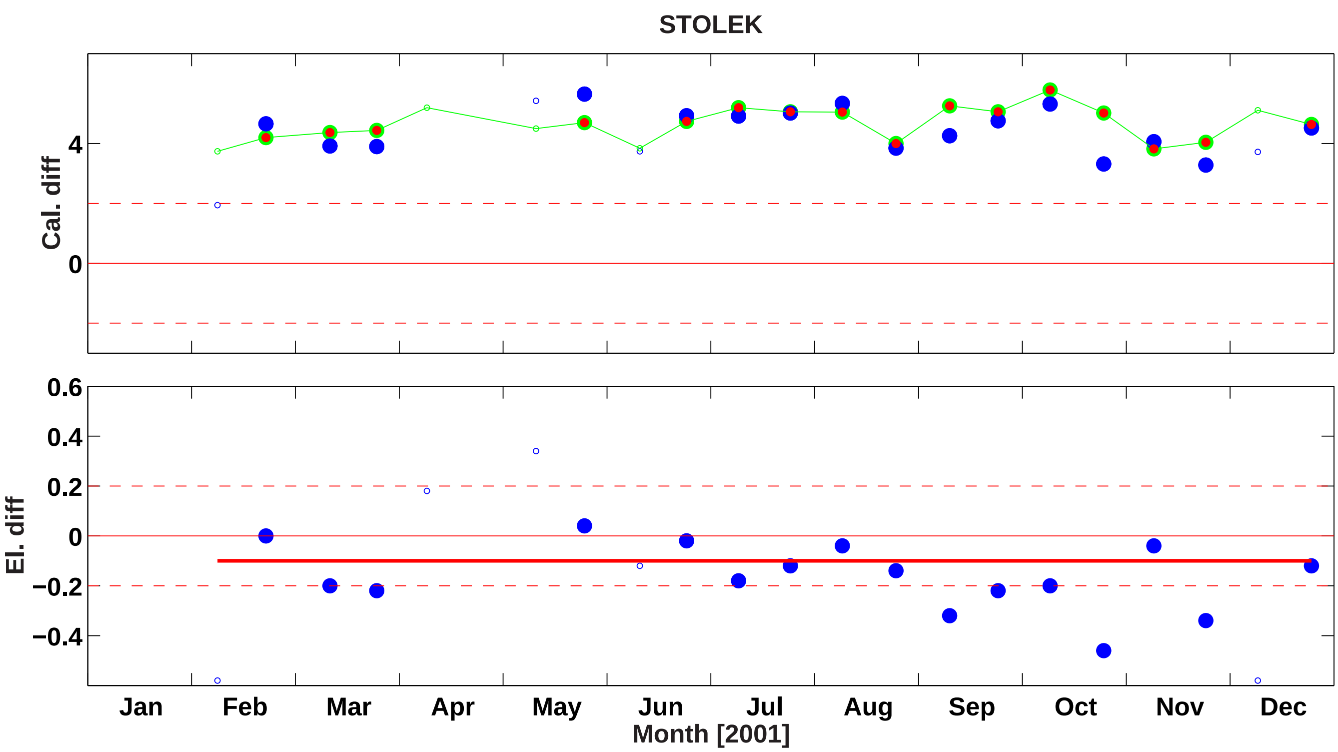
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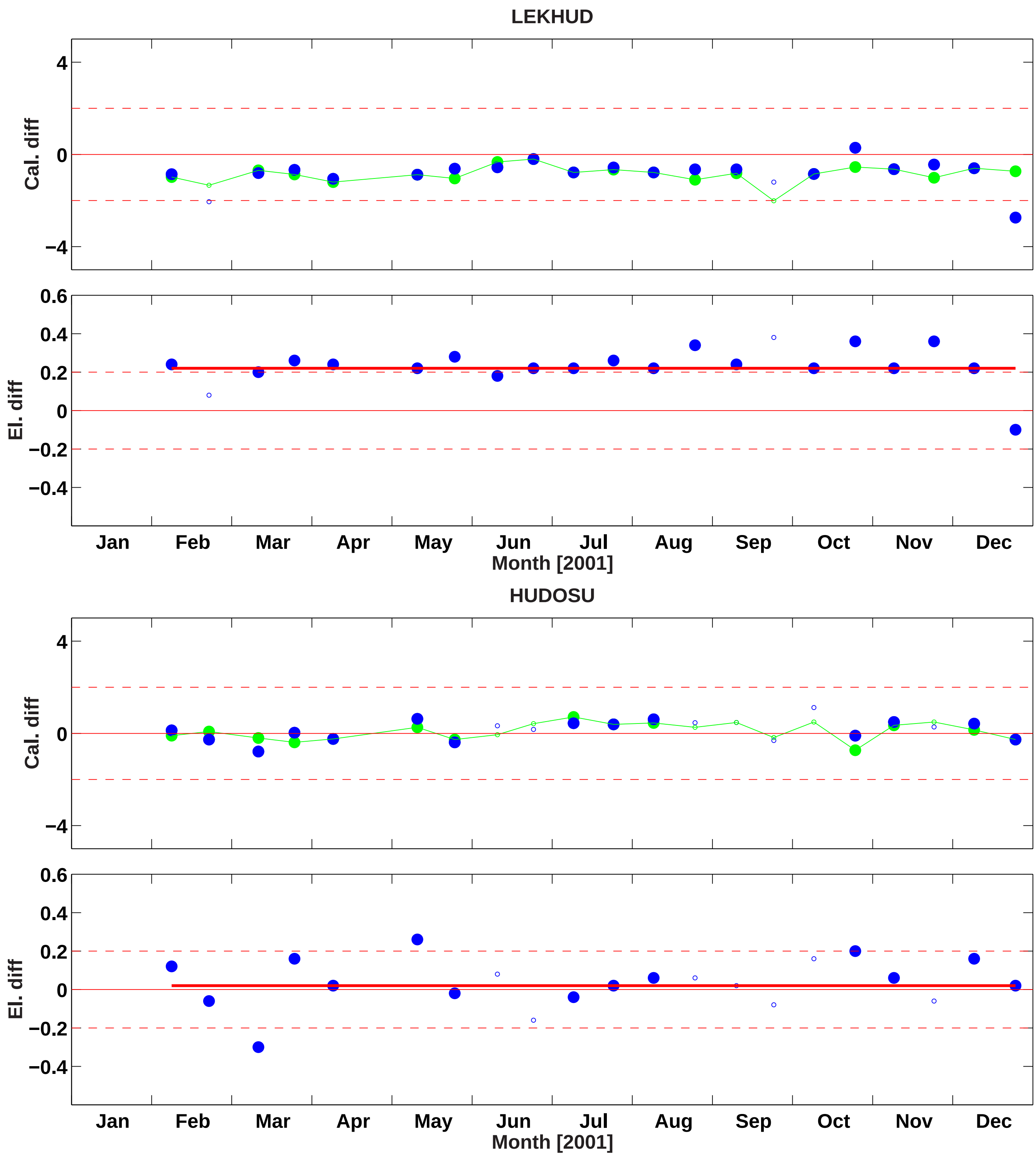
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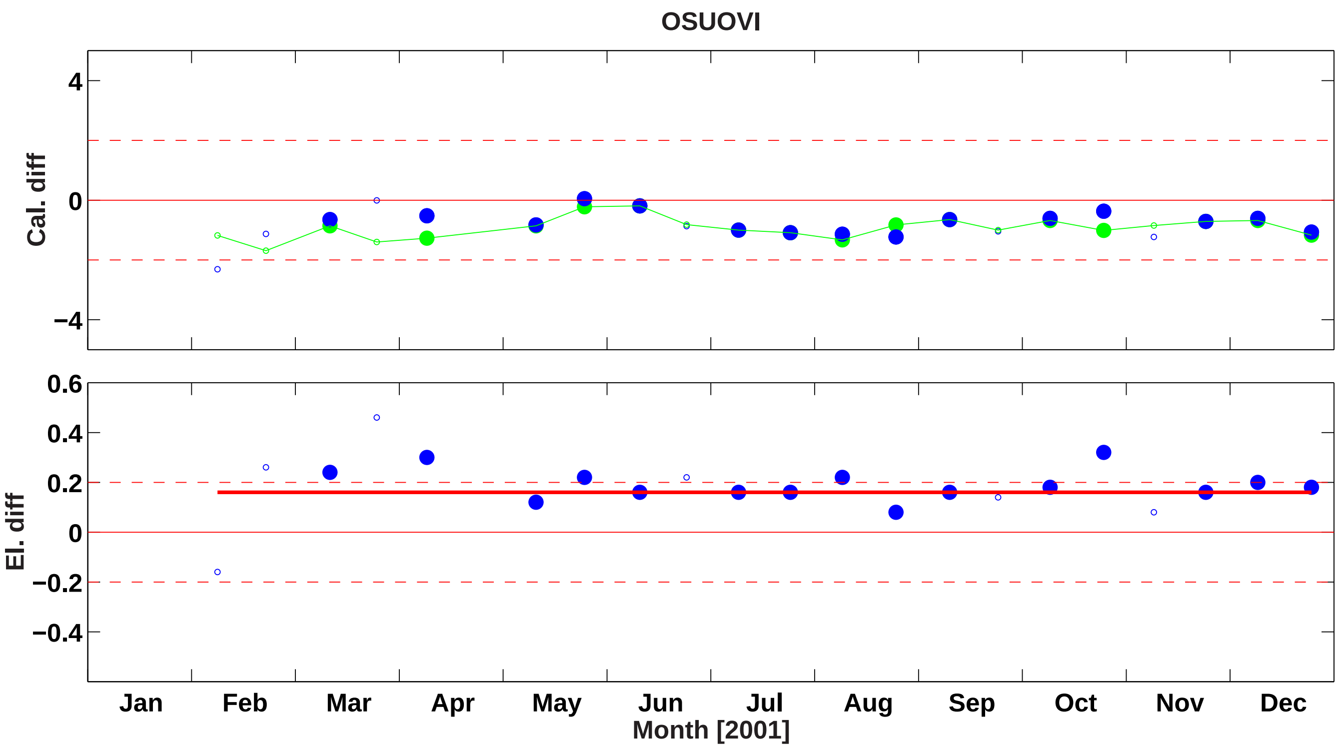
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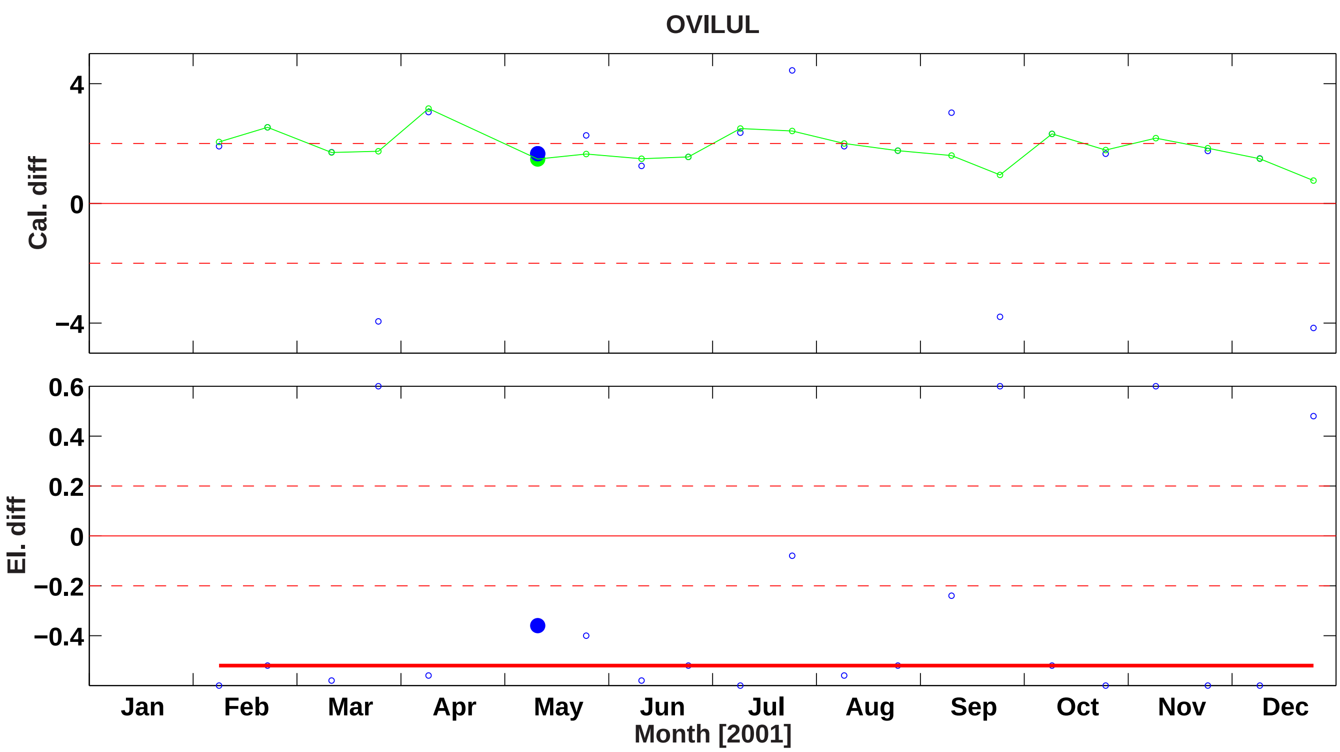
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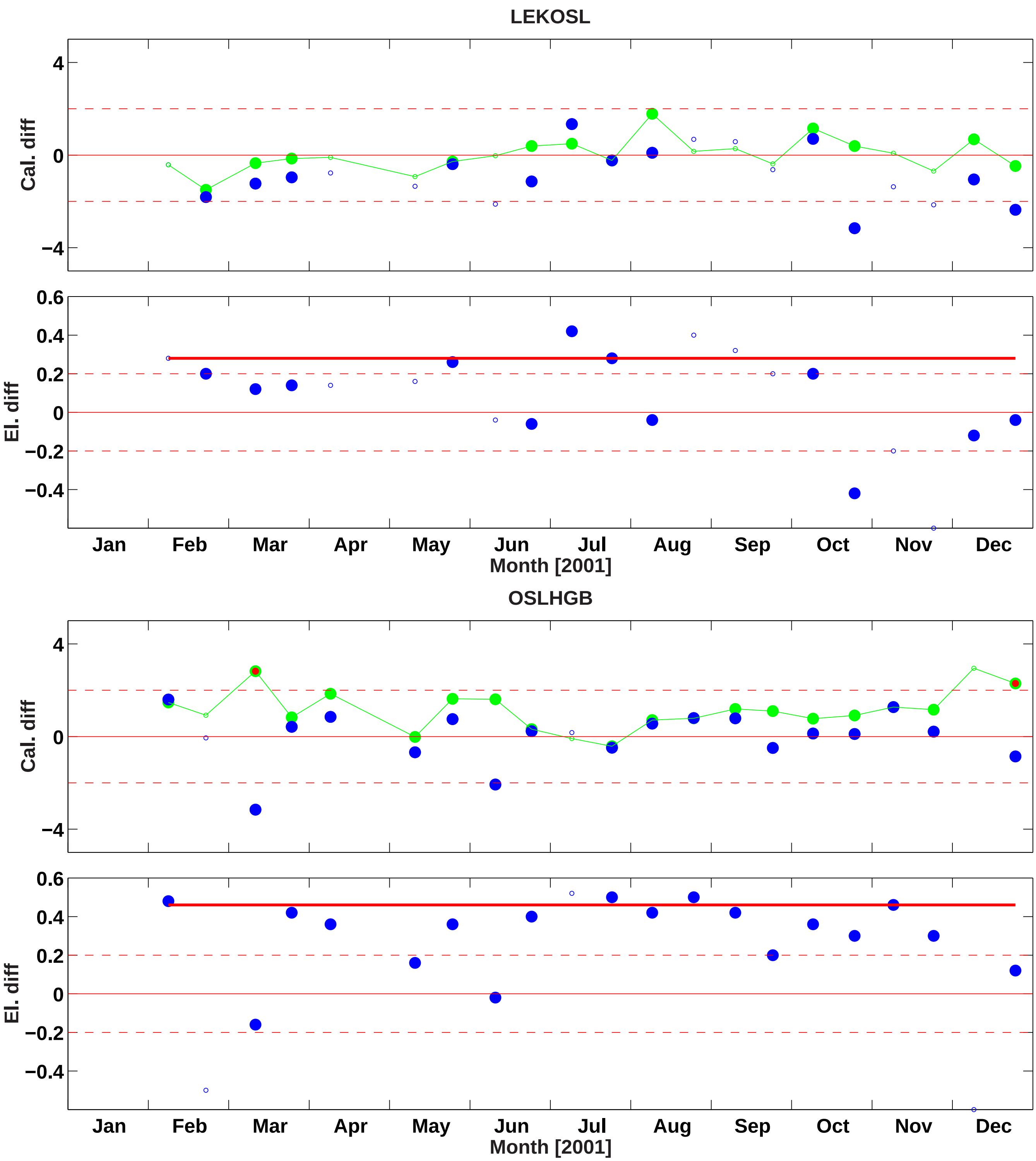
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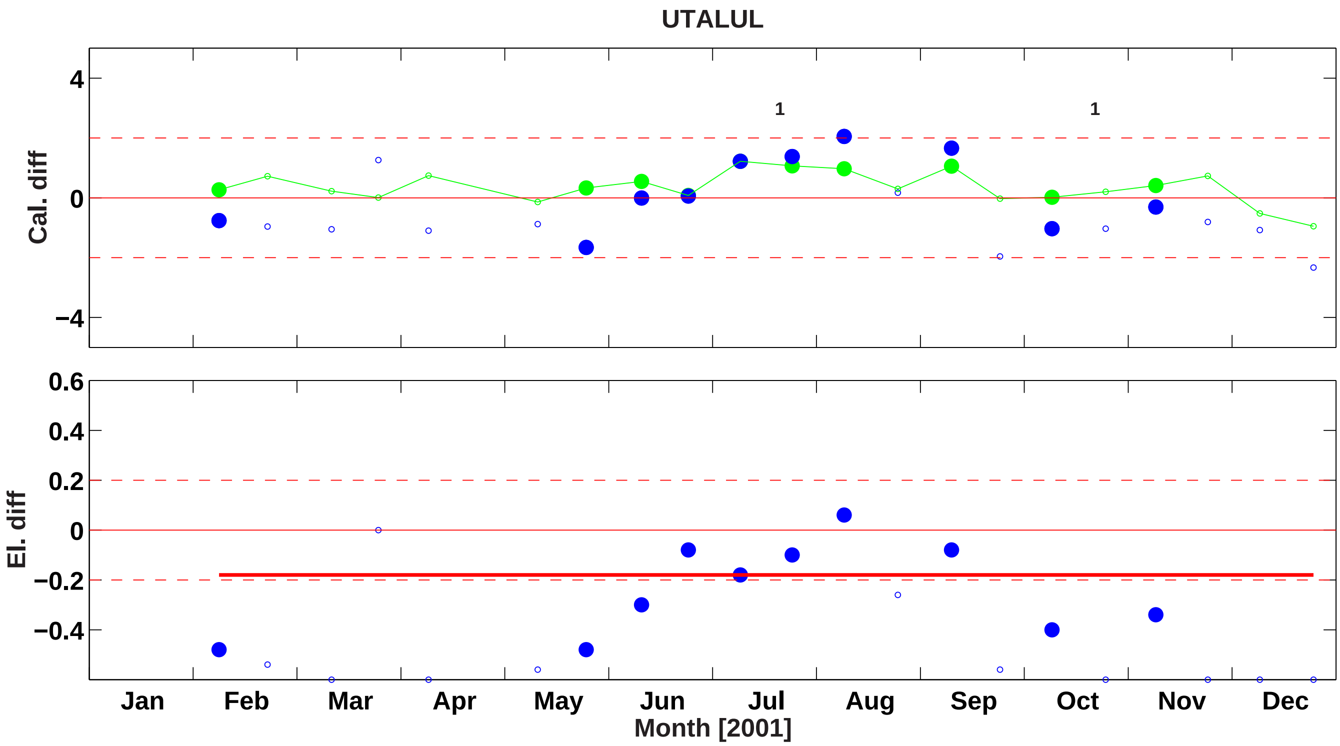
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4 Production of paired-radar images

4.1 The input data

The input data in the paired-radar analysis is the dBZ pseudo-CAPPI data projected on a polar stereographic area. Products are produced at regular 15 minute interval for each radar in the pair, and the products are named as follows:

```
rrpsc_z_anj0ika1_2000.d011121t0900
rrpsc_z_anj1ika0_2000.d011121t0900
```

The prefix `rrpsc_z` is the product indicator, `anj0ika1` tells that this data is for the radar pair `ANJIKA`, and that the products contains the Anjalankoski data. The other file contains the data of the Ikaalinen radar. The suffix `_2000` is a resolution indicator, and the date and time is given right of the period. The areas have been defined so that they contain the area which is covered by both radars in the pair, the radar sites themselves, and an additional safety margin, which is some 10 km in size.

4.2 Setting up the product area

A routine `nrd_twin_areas.pro` written for PV-WAVE is available to calculate the area. The program asks for codes of the radars, and for the central longitude. The projection latitude of 60° is always assumed. The results are written to a file, which e.g. for the Anjalankoski-Ikaalinen pair will have the name `nrd_twin_area_anj_ika.txt`, with contents

```
NORDRAD twin radar QA area definitions made at FMI on 22 Nov 2001 max.range: 240km
Filename   y-axis  SW lat SW long   SE lat SE long   NE lat NE long   NW lat NW long
qa_anjika  25.00  59.5011 22.6128  59.4956 27.6344  63.1459 28.0092  63.1523 22.2731
```

Of these the central longitude (`y-axis`) and the SW and NE corner points are given to the product generator. They are written to file `AREA.ASC`, together with the projection latitude, and converted to binary. For our example case the file reads:

```
-- QA-alue Anjala/Ikaalinen resoluutio 2km --
 AREA = ANJ1IKA0

   PROJECTION = POLARSTEREOGRAPHIC 60.0 25.0
   SOUTHWEST  = 59.5011   22.6128
   NORTHEAST  = 63.1459   28.0092
     SUBAREA  = FIANJ7  -- Anjalankoski
```

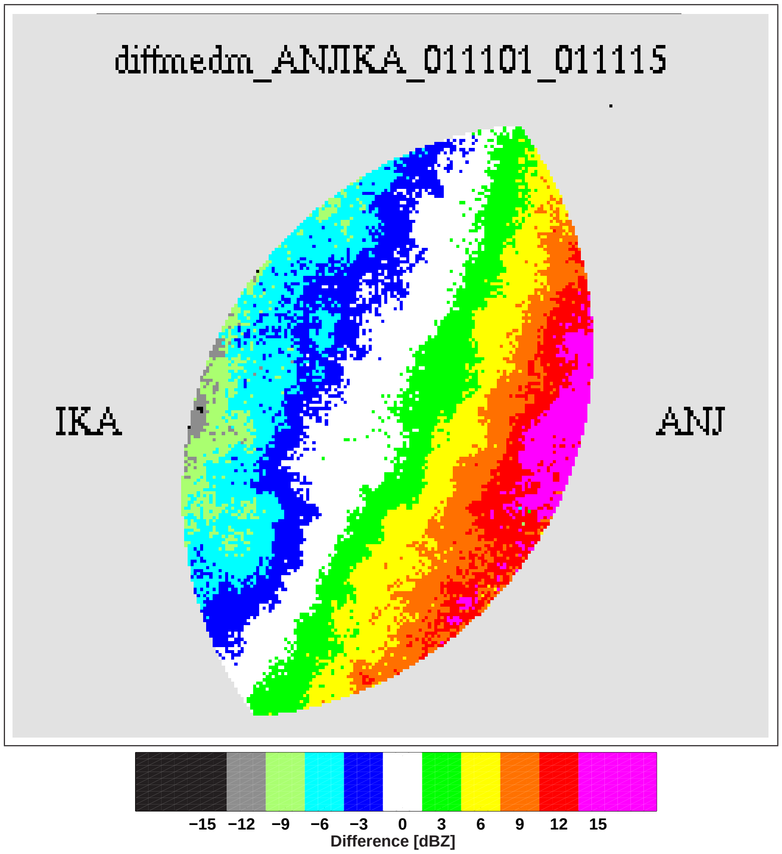

Figure 5: Difference data with labelling and colormap.

The other parameters can be read back. The listing gives e.g. the pixel map size.

```
Product type:  RRPSC_Z Height :   500 m Area : ANJ1IKA0
        POLARSTEREOGRAPHIC      Latitude:  60.0000      Longitude:  25.0000
        Lower left corner       Latitude:  59.5011      Longitude:  22.6128
        Upper right corner      Latitude:  63.1459      Longitude:  28.0092
SUBAREAS ( 1) FIANJ7 Resolution :  2000 m Time : 01-01-08 11:45:01
Quantity :  What=Q_REFL Unit=DBZ IntStore :  Ord=-32.00000 Slope=
0.50000 Offset=    0 PIXEL  Rows = 203 Cols = 143 StoreBits = 8
StoreMax = 255
       File offset =  513  StorePixels =   6765 Compressed = TRUE
BITMAP File offset =  7278 StorePixels =      4 Compressed = TRUE
```

4.3 Running NRDTOOLS

NRDTOOLS (Statistical Analysis Tools for NORDRAD Weather Radar Network) is a software package created during the NORDRAD continuation project in 1996-1998. The present version is 2.1, dated 1.9.1998. The software tools for analysis of single radar product files and for analyzing statistical differences of two adjacent radars. A set of Unix shell scripts is also included in the distribution version.

In the present project we have used the `Nrddiff` program to analyze the statistical differences between two adjacent radars. The program has been run with the following call

```
nrddiff -noise -min 10
```

which according to the documentation is equivalent to

```
nrddiff  -xls +pgm -noise -min 10 -and
```

Thus we have made the following choices:

- -xls No output in Excel readable form is created.
- +pgm Outputmap in pgm is created. This is the source for graphical output in gif-format. This file is also used as input to the numerical analysis program.
- -noise All echoes below the lowest detectable dBZ value are discarded. The limit depends on the range and is -45 dBZ at 1 km distance.
- -min All echoes below 10 dBZ are discarded. This option makes the previous one redundant, because this limit is always greater than the noise limit. If the minimum is less than 0 dBZ, the noise option is effective.
- -and Difference calculated only if both radars see echo. This is the only viable option of the three: -and, -or and -xor.

Two shell scripts are available for running the tools. The first one, `run_nrddiff`, is a modified version of the script included in the 2.1 release of NRDTOOLS. The main addition is made to the graphical output, which adds three letter radar names and the analysis interval to the picture. An additional call parameter is needed to get the radar names to right positions. A typical call is as follows:

```
run_nrddiff ANJ IKA 011101 011115 -lr
```

which takes the ANJ and IKA data for the first half of November 2001 for analysis. The last parameter tells that the three letter radar names shall be included in the final picture from left to right. The gif-file produced is seen in Fig 5.

The calls for all the radar pairs used in this study are included in `run_alldiff`, which can be called simply as

```
run_alldiff 011115 011130
```

to analyze all radar pairs for the latter half of November 2001.

The NRDTOOLS produce three different types of results. The mean difference is given either as the average value, median value, or the modal value. All these are produced.

Bugs found and corrected Two bugs have been found and corrected in the `Nrddiff` program of NRDTOOLS version 2.1. Firstly, the program did not process the data correctly, if the first radar in the pair is from the Finnish network. The analysis skips all the remaining data starting from the next 10^{th}, 20^{th}, or 30^{th} day of month, or if the analysis period extends to the next month. Secondly, it was found that the offset in the pgm-file was 200 instead of 100. This is the value in the file when the radars are in balance. The program was corrected so that 100 corresponds to a 0 dB difference between the radars.

5 Analysis of paired-radar images

5.1 Analysis procedure

In the following we try to make tractable the numerical method, by which the elevation angle and calibration differences are estimated based on the paired-radar data showed in the Fig. 5 on page 23. First of all, the appearance of the paired-radar picture is determined to a large extent by the vertical reflectivity profile. The profile can be determined from the measured data but, as our base data is in the form of differences of the reflectivities, it is better to build the analysis procedure so that the reflectivity profile is not needed in the procedure.

The key point to understand the procedure is Fig. 6, in which some sets of points are given. Each set includes points for which the height of the beam from the far away radar is at a fixed altitude. This altitude ranges from 2.0 to 5.0 km in steps of 0.5 km. The symbols are explained in the figure. Midway between the radars, at a line shown in the figure, the height from either radar is the same. Going from there the height of beam from the closer radar decreases by 0.5 km for each successive point. The points at which the far away radar measured at 5.0 km and the closer radar at 3.0 km are denoted by doubled open circles. We note that there are four points altogether, one pair in either side of the join line between the radars.

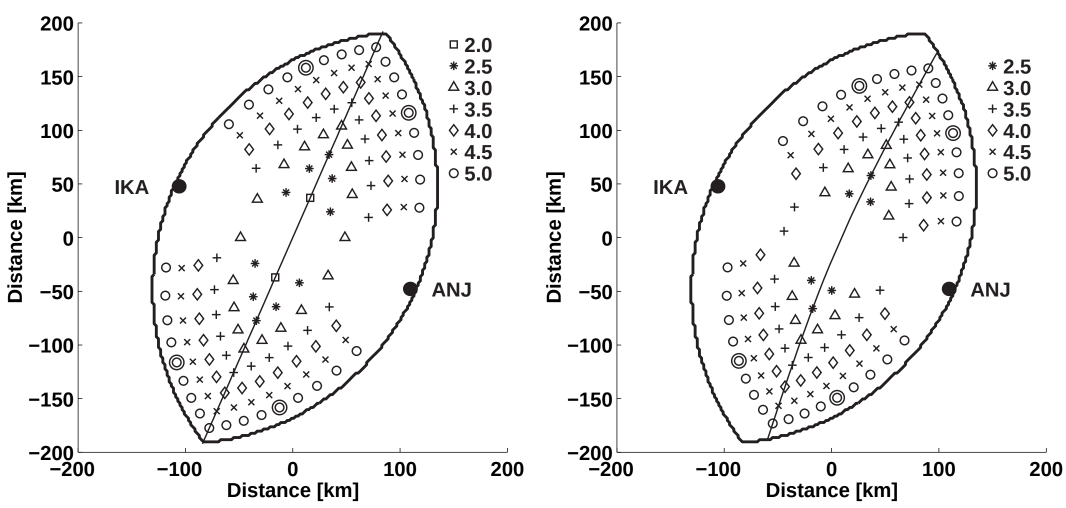

Figure 6: A selection of points for numerical analysis when both radars measure at an elevation angle of 0.5^{o} (left panel), and when one of the collection angles is 0.5^{o} and the other is 0.7^{o}(right panel). The solid line connects points equally far from both radars. Other symbols are explained in text.

For the data at these points, we get the following formulae:

$$m_l = \quad dBZ(5) - dBZ(3) + \Delta(\text{ANJ}) - \Delta(\text{IKA}) \tag{1}$$

$$m_r = \quad dBZ(3) - dBZ(5) + \Delta(\text{ANJ}) - \Delta(\text{IKA}), \tag{2}$$

where m_l and m_r refer to the measurement left and right of the dividing line, $dBZ(r)$

is the reflectivity at the altitude r, and Δ is the calibration error of the radar, which are assumed to be independent of the reflectivity. The ANJ signs are positive, because the IKA data have been subtracted from the ANJ data. Here we have made use of the fact that the precipitation is uniform and the vertical reflectivity profile the same at all locations. After addition and division by 2 we get

$$\Delta(\mathrm{ANJ}) - \Delta(\mathrm{IKA}) = (\mathrm{m_l} + \mathrm{m_r})/2. \tag{3}$$

which tells that we will get the calibration difference of the radars by taking the mean of the measurements m_l and m_r. This tells how much the reflectivity as measured by the two radars differ from each other.

In the above we have assumed that the collection angles are identical. This may not be the case. The right panel in Fig. 6 shows the point locations when the collection angles are 0.5$^{\mathrm{o}}$ and 0.7$^{\mathrm{o}}$, respectively. Comparison of figures shows that the points have moved considerably towards the Anjalankoski radar, the radar with the higher collection angle. Yet it is possible to find points which correspond to each other and to data from which the above formula can be used. It is easily seen that the location of the points is no more symmetric.

The determination of the collection angle is based on studying how much the calibration difference varies when we determine the difference for all the possible altitude pairs. If the assumption of the uniformity holds, each altitude pair should give the same answer for the calibration difference, to within the error fluctuations. Thus the collection angle, which produces the smallest variation of the calibration difference around its mean, is the most probable angle. We search through all elevation angle differences with a small step and find the minimum of the standard deviation of the calibration differences.

5.2 Numerical implementation of the analysis procedure

One can carry out the above procedure manually and, in fact, the first results were obtained by manual scaling of differences from the figures. In a numerical implementation one can process much higher amounts of data, and also make the grids denser than those in Fig. 6. Tests with data have shown that a grid having a step around 100-200 m is optimal. There are two contradicting things which affect to the choice. One is connected to the error estimation and the other to the homogeneity of the basic cell. The number of points has to be large enough that a reliable variance estimate for the mean is obtained, and the range bin should not be so large that the value of the difference changes too much. A typical grid ranges from 1 km to 5.5 km in steps of 0.15 km, which has 31 grids points, and 30 altitude bins for each radar. If this is denoted by M, the total number of bins is then given by

$$2(M-1)M + 1 \tag{4}$$

which amounts to 1741 in our example case. As the total number of measurements ranges from 10000 the 15000, the number of points is a range cell is between 6 and 9, which allows us to calculate reliable empirical variance estimates.

Thus the first step is to calculate the mean and variance for each range bin. The variance is calculated from the standard formula. However, the base data is rounded to the nearest integer by the NRDTOOLS software, and is thus accurate only to 0.5 dB. Thus the variance is not allowed to be smaller than $0.25/N$, where N is the number of points in the altitude bin. This is important because it might happen that all the observations in an altitude bin had the same value, and the empirical variance estimate would be zero.

The analysis goes then so that the elevation angle of the first radar in the pair is fixed, and the elevation difference is stepped through a number of values. We have found in our tests that fixing one angle to an incorrect value does not affect the angular difference significantly, if the other angle is correct to within 0.2^{o}. This also means that it is not possible to deduce the angles itself by the method, only the difference of the collection angles is obtained.

The following operations are done within the analysis program:

1. Calculate the elevation angle for the second radar in the pair.
2. Bin the observations to the range bins. This includes a number of operations, which finally give the height of the center point of the antenna beam for each pixel in the picture, allowing us to bin the observations.
3. Calculate the mean and variance for each bin
4. Calculate the calibration difference according to the Eq. 3. An error estimate is also calculated, based on the variance estimates of the binned data. Here we divide the data into two halves, treating data in either side of the line joining the radars separately. Thus, e.g. in the ANJIKA case, points on the Northern side and on the Southern side of the joining line are not averaged together, even though they belong to the same range bin according to the Fig. 6. We can thus relax the assumption of the uniformity to some extent.
5. Calculate the mean $\overline{m}$ of all calibration differences m_i, weighting the differences by inverses of their variance estimates σ_i^2.

   $$\overline{m} = \frac{\sum_i m_i \sigma_i^{-2}}{\sum_i \sigma_i^{-2}} \qquad (5)$$

   The goodness of fit is determined in a standard manner by looking at the fit residual or variance

   $$\xi^2 = \frac{1}{M} \sum_i \frac{(m_i - \overline{m})^2}{\sigma_i^2} \qquad (6)$$

   where M is the number of range bins after applying Eq. 3.

The most probable elevation angle difference is the one producing the smallest fit residual according to Eq. 6.

The expected value of the residual at the minimum is 1. If the residual deviates significantly from unity, either the variances σ_i^2 of the binned data are incorrect, or the model of the data is not correct. In our model we assume that we are able to find an elevation angle difference such that the calibration difference estimated by Eq. 5 does not depend on the altitude difference of the measurements. Then all altitude pairs will give the same calibration difference within the error fluctuation. If the error fluctuations of the binned data are correct, the expectation value of the residual is unity.

5.3 Practical analysis

5.3.1 The software

The analysis procedure has been programmed in the Fortran 90 language. The software does not use any non-standard features or external libraries. The program is named `QAcalc`. The program asks for the file containing the difference data in pgm-format. It reads from the file name the radar pair name. The control parameters are given in a self-explanatory configuration file with name `QAcalc.config`:

```
! QAcalc.config
! This file contains the configuration parameters of the
! QAcalc-program
!
! The parameters are explained in the following
! Asko Huuskonen, FMI, 2001-11-05
!
! PS. You may add as many comments lines starting with  !
! But the order of the parameters must not be changed
!
!!!!!!!!!!!!   The configuration parameters start from here !!!!
!
! The elevation angle of the first radar in the pair
! Note that this is a scalar value and given in degrees
!
   0.4
!
! The next line specifies the elevation differences which are used
! The elevation values for the second radar is obtained by
! adding the difference vector to the elevation of the first radar
!
! first difference, last difference, difference step:
!
  -0.6 0.6 0.02
!
! The altitude binning specifies how the data is handled
! We give the lowest altitude, the highest altitude and the altitude step
! All are given in kilometers
!
 1.0 5.5 0.150
!
! End of config
```

Some Unix shell scripts are available for running the program. The script `run_qacalc` takes as arguments the radar names and the start and end date of the analysis period, e.g. `run_qacalc ANJ IKA 011101 011115`. The analysis for all the radar pairs can be run by call `run_allqa 011101 011115`. The shell script `run_alldiff`, used to run the `Nrddiff` program, makes a call to the script `run_allqa`. Thus the analysis program is executed automatically whenever a new period is processed by `Nrddiff`.

5.3.2 Interface to NORDRAD

The analysis program needs to know the radar coordinates, as well as the projection parameters of the paired-radar data. The radar coordinates are read from file `Nordrad_radars.txt`, and the projection coordinates of the paired radar data are read from file `Nordrad_radar_pairs.txt`. The module `Nordrad_radars.f90` handles the input.

5.3.3 Blocked sectors

The blocked sectors are specified by giving the azimuths of the left and right edges of the sector and the distance where the blocking occurs. There can be any number of the sectors and they may be overlapping. The sectors for the Hægebostad radar are specified in file `HGB_blocked_sectors.txt`, with contents:

```
List of all blocked sectors for HGB
leftedge rightedge   range (edges degrees from North clockwise, range in km)
     353.      18.      71.    %  0.2 degree elevation
     327.      24.      91.    %  0    degree elevation
     300.      49.    116.    % -0.2 degree elevation
```

The data entered to this file has been scaled manually from a diagram showing the horizon of the Hægebostad radar.

5.3.4 Result file format

The `QAcalc` program write the output to file `QAresult`, which contains two lines, the header line and the result line:

```
  Pair  START FINISH   angle  diff   err   res  Nobs  angle:  0.60  0.58  0.56  0.54  0.52  0.50  ...
OSLHGB_011101_011115    0.44  1.17  0.44  2.33  3083   diff:  1.78  1.77  1.74  1.67  1.60  1.51  ...
```

The lines are much longer and have been cut in this example. The first line contains explanatory text for the results on the second line, as well as all the elevation angle differences following the `angle`-tag. The tag and the angles are repeated twice. The second line gives the radar pair and analysis interval, the most probable elevation angle difference, the calibration difference, an error estimate for the calibration difference, the residual of the fit, and the number of pixels that contributed to the result. Next follow the calibration differences for all the elevation angle differences, as well as the residuals of the fit for all the elevation angle differences.

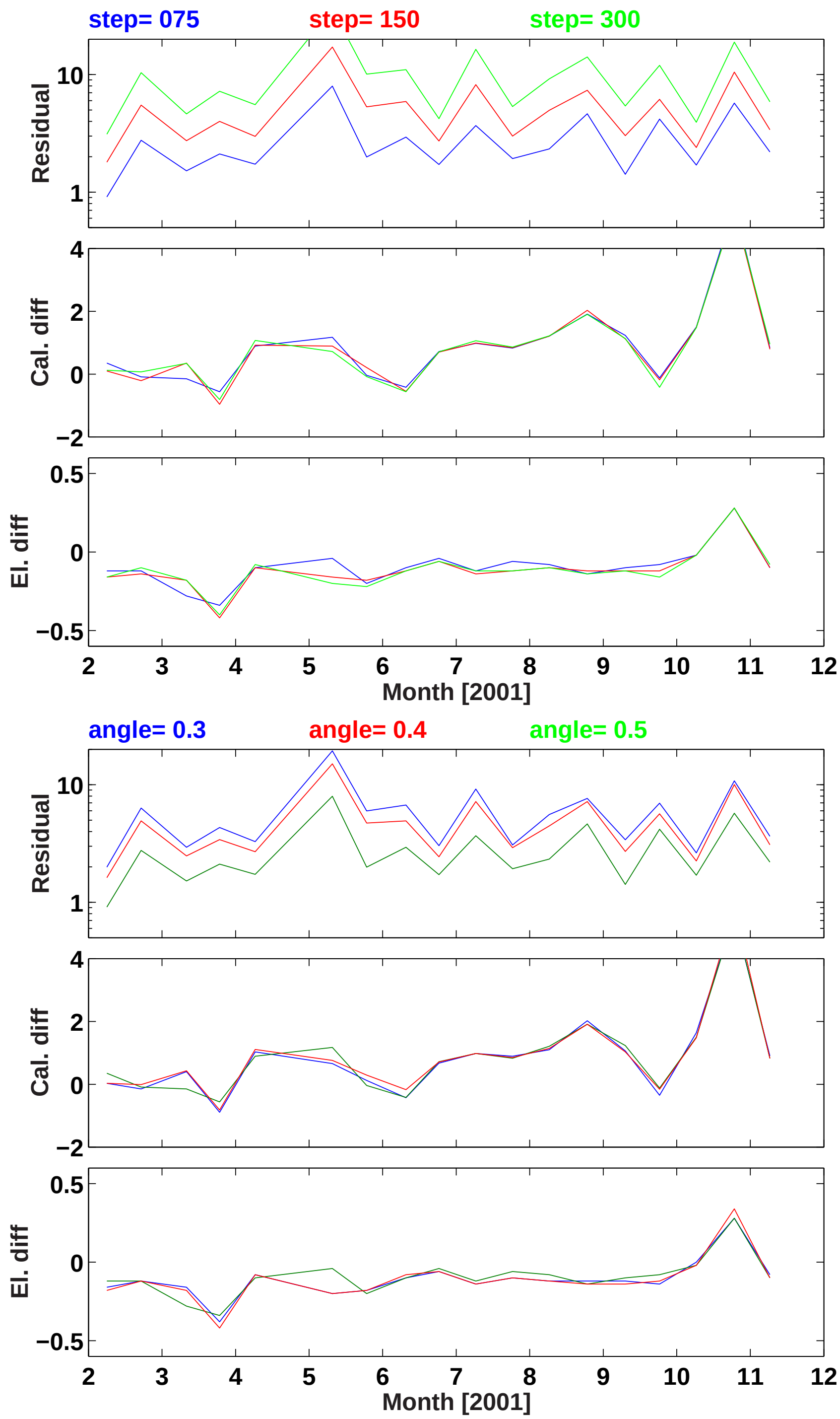

Figure 7: Upper panel: Residual of the fit, the calibration difference, and the collection angle difference for range steps of 75 m, 150 m, and 300 m. The elevation angle of the first radar is 0.4° in all cases. Lower panel: The range step is fixed to 150 m, and the elevation angle of the first radar has values of 0.2°, 0.4°, and 0.6°.

5.3.5 Justification for the parameters

We have run a series of tests to find out the best combination of the configurable parameters. The first run was done to find out the optimal altitude step. Three steps were tried, namely 75 m, 150 m, and 300 m. The results are seen in the upper panel of Fig. 7. First of all, we can note that the calibration difference is within 0.5 dB in all cases, and mostly within 0.2 dB. Thus the calibration difference is obtained equally well by all the step sizes. The elevation difference is mostly within 0.05^o, but at two cases the extremes differ by more than 0.1^o. We can conclude that all the steps give identical results on the average. The upper panel shows that the smallest residual is obtained by using the smallest step size. This is, however, obtained at the expense of not using all the data. The total number of points is lower by roughly 30 %, when compared to the two other cases. The lower residual thus is some kind of an artifact, and the residual should only be used to determine which analysis periods are better than the other.

Based on the above we have chosen 150 m as the standard altitude step size. Thus the smallest step size is adopted, which makes use of all the observations. This limits the effects of vertical gradients within an altitude cell. The test has been done for the ANJIKA pair only, but there is no reason to believe that they would not be representative for all the pairs.

The lower panel of Fig. 7 shows the effect of changing the elevation angle of the first radar in the pair. One should always use the true angle in the configuration, but the curves on the figure show that an incorrect value by 0.1^o does not hamper the determination of the calibration difference. The influence on the elevation difference is considerable occasionally.

Yet another configuration parameter was tested during the development but, as it was found to have a negligible effect on the results, it was given a fixed value. This factor is related to the variance estimation. When the calibration differences are averaged in Eq. 5, the variance estimates can be modified with an ad-hoc factor. It is probable, although not certain, that points representing smaller altitude differences are actually more reliable than points representing larger altitude differences. We have to assume that the vertical reflectivity profile is identical at the two corresponding locations. Locations with a larger altitude difference are further apart than locations with a smaller altitude difference, and thus the assumption of identical vertical profiles is less reliable in the first case. This theory error can be compensated for by multiplying the variances with a factor

$$\max(1, |h_i - h_j|)^y \tag{7}$$

where $h_{i,j}$ are the altitudes of the beams in the range bin in kilometers, and y is a constant. The value of the parameter has been fixed to 1, which means that the weight of altitude differences exceeding 1 km is reduced.

5.3.6 Future tasks

Radar coordinates and projection parameters: Inputting these from a text file is only a temporary solution. The program should read this information directly from a source within the NORDRAD system.

Result format: The result file format is rather trivial, and does not contain e.g. the configuration parameters of the run. A proper data structure containing all the necessary parameters need to be defined later.

Blocked sectors: Some of the radars in the NORDRAD network have large blocked sectors. They must be taken into account in order to obtain reliable results. Presently the blocked sectors are only defined for Hudiksvall, Hægebostad and Oslo radars. In the future the text files should be replaced by a direct access to the corresponding data existing within the NORDRAD system.

6 List of appendices

1. Project proposal, April 15, 1999.
2. Interim report, May 10, 2001.

APPENDIX 1: Project proposal

Finnish Meteorological Institute
15.4.1999

Revised proposal for a NORDRAD quality-assurance project

Name of the project: NORDRAD QA project

Active project period: 1.5.1999 - 30.4.2000

Overall project leader: Robin King, FMI

Project management group: Robin King FMI, Madelene Nilsson Swedish Armed Forces, Oddbjörn Thoresen DNMI, Jan Svensson SMHI

Impetus for the project: approval by the NORDRAD Steering Group (in Oslo, 20.4.1998) of the conclusions of the Final Report of the NORDRAD Continuation Project, and in particular the Executive Summary recommendations 9.9, 9.12, 9.13 and 9.14.

Aims of the project (summary): to improve the intensity level harmonisation of C-band radars in the NORDRAD network to within +/- 2dBZ on a monthly basis by the completion of the project, and to establish workable and efficient quality assurance and maintenance practices.

Sub-projects:

SP1: Monitoring of all NORDRAD radars using the NRDTOOLS software (both single and paired-radar data being used)
SP2: Investigation of angular pointing accuracy of all NORDRAD radars and implementation of improvements to achieve an agreed level of performance
SP3: Investigation of calibration and radar parameter value accuracy at all NORDRAD radars, and implementation of improvements to achieve an agreed level of performance

Reporting:

The project leaders, supported by the contact persons, shall produce
a) an interim report covering all aspects of the QA project before 31.12.1999
b) a final report including country-specific SP2 and SP3 reports before 31.5.2000.
The reports shall be prepared for,and finally approved by, the NORDRAD Steering group or its corresponding responsible body.

The final report of the project will contain a summary of agreed calibration and other maintenance practices, based on the work done in the three sub-projects in the three countries. Sub-projects SP2 and SP3 shall provide a report on the work on a country-specific basis, including detailed documentation of methods and problem-solving. These sub-project reports, prepared by their project leaders, shall be included as an integral part of the final report of the project (i.e.1 report for SP1 and 3 reports for SP2 and SP3).

Funding:

SP1 will be carried out by the FMI on behalf of SMHI and DNMI with their cooperation. Funding will be divided proportionately between the Institutes, using an agreed division scheme (see SP1 proposal).

SP2 and SP3 will be funded by each Institute separately for work carried out in its own country. If e.g. a calibration expedition is arranged to a given country, the costs will be agreed between the participating countries on a case-by-case basis (as in e.g. the expedition to Hudiksvall in the NORDRAD Continuation Project). Contributions to the final report shall be drawn up by the individual project leaders in consultation with the participant Institutes and other involved parties.

Proposal for a NORDRAD quality-assurance project: sub-project 1

Name of sub-project: NORDRAD intensity level operational monitoring (NORDRAD QA SP1)

Project leader: R. King, Observational Services, FMI
Contact person DNMI: Oddbjörn Thoresen
Contact person SMHI: Jan Svensson

Aim of sub-project: to carry out analyses (using both single radar and paired-radar data) of the NORDRAD network using the software package NRDTOOLS, and to produce regular reports of the relative intensity levels of the participating radars to support other activities in the NORDRAD QA project (i.e. antenna angle, calibration and radar constant parameter investigations).

The single radar analyses will use the standard NORDRAD pseudo-cappi (0.5 km level) product with a range of 240 km and a resolution of 2*2 km^2. This should involve very little or no new product definition or production. In the case of the paired-radar data, the requisite areas will be defined by the project (see attached example of Finland's areas). They will contain both radars, with an extra area of about 10 km behind each. The resolution will be 2*2 km^2. Each composite area product is made at 15 minute intervals, once for each radar separately. The data from these two products are compared and combined in the analysis image. Additionally, the composite containing both radars of the pair is run monthly, or whenever elevation angles or other definitions are changed for either radar. This third product provides the NORDRAD dividing line between the radars as used in the other composites. In order to minimise the number of extra products required for the analysis, it is proposed that, as far as possible, each radar shall be compared with a maximum of only two neighbouring radars (in special cases, this may be 3). To share the burden of the production of these paired-radar "composites", each country may be asked to produce its own paired-radar data, with cross-border areas being shared. These products will then be picked up by FMI for analysis using the normal NORDRAD facilities. Even with this arrangement, the number of extra NORDRAD products is quite considerable, as can be seen from the following table:

Single radars	paired with	number of products
VAN	KOR, ANJ	2
ANJ	VAN, IKA	2
IKA	ANJ, KUO	2
KUO	IKA, UTA	2
KOR	VAN, STO	2
UTA	KUO, LUL, ROV	3
ROV	UTA	1
LUL	KIR, OVI	2
HUD	OST, LEK	2
OVI	LUL, OST	2
STO	HUD, NKP	2
NKP	STO, GOT	2
GOT	KKR, NKP	2
KKR	GOT, GBG	2
GBG	NKP, KKR, OSL	3
LEK	HUD, STO, OSL	3
	(alternatively only HUD, STO)	
KIR	LUL	1
OST	OVI, HUD	2
OSL	GBG, LEK	2
	(alternatively, only GBG)	

Total numbers of (new) products to be run in NORDRAD: Finland: 14
Sweden: 23 (22)
Norway: 2 (1)

Chains of comparison:

1) KKR->GOT->NKP->STO->LEK->HUD->OST->OVI->LUL->KIR
2) KKR->GBG->OSL
3) STO->KOR->VAN->ANJ->IKA->KUO->UTA(->ROV)
4) LUL->UTA(->KUO->IKA->ANJ->VAN->KOR)
5) OSL->LEK (may be omitted)

The chains would be much more secure if multiple-pairing could be considered. However, it is probable that the extra loading on the national nodes brought about by the production of the abovementioned extra products may be the maximum permissible. The chains are designed so that they consist of radars with good overlaps, and have a double link between Finland and Sweden (STO<->KOR and LUL<->UTA) for more robust use. The double link between Norway and Sweden may not be thought necessary, although desirable. Because the Rovaniemi radar is exceptional in the network (an X-band radar using EWIS 1 software), its comparison is only made with Utajarvi, although in principle it could be also compared with Lulea and Kiruna. During the course of the project, the Rovaniemi radar will probably be replaced by the new Luosto radar, in which case comparisons with this will replace those with the old radar.

The actual relative levels between neighbouring radars will be determined not only from the levels obtained from the paired-radar data, but also from the levels of the single-radar analysis products, both in map and graph form (see examples in the Final Report of the Continuation Project). The determination will be made subjectively using the available data analysed over approximately 2 - 3 week rainy periods. Experience from 1997 shows that typically one usable period occurs monthly. More frequent analysis will be made if weather permits.
As the wet weather will probably not affect all parts of NORDRAD simultaneously, the levels found throughout the chains will probably be an average over about a month.

The results will be placed on FMI www pages which are accessible from authorized internet addresses in SMHI and DNMI. In this way the results (including all the single and paired-radar images for all radars in NORDRAD) will be immediately available to users in the three Institutes. A mailbox will also be provided for feedback. The relative levels of the radars will be shown on a diagram which contains +/- 2dBZ warning levels on each side of the average level for the whole network. After a period of time it will also be possible to compare the average level from month to month using as a reference a radar (or several radars) which are found to be particularly stable with respect to the whole group of radars. It is to be hoped that the Institutes will, in the light of the results obtained, take prompt steps to reduce the scatter, probably by changing a parameter in the radar equation at the radar stations which are persistent outliers: the project year is in this respect also a period of working towards a model of agreed operational cooperation in this respect between the NORDRAD countries.

The analyses will be run in FMI computers. In view of the large amount of data generated, FMI will not guarantee to keep the whole year's data on-line on disk. If felt desirable, the data may be archived on CD, and distributed to the participant NORDRAD countries.

Towards the end of the 1-year period the situation will be reviewed: FMI may be asked (but may also refuse) to continue the analyses on behalf of the other NORDRAD countries. In either case the software extensions that FMI has made to carry out the analyses and their visualization will be available for use in the other NORDRAD countries free of charge, although FMI will not install or guarantee the use of such software on other systems than its own.

Estimate of required resources at FMI

In the initial stages of the sub-project, the following tasks will be carried out:

- definition of paired radar areas
- setting up of www pages for results
- automatising of data selection and processing (mainly Perl scripts)
- standardizing of data output image format (Perl and PV-Wave graphics)
- writing of output chain comparison graphics program
- testing and trial runs

It is estimated that this phase will require 14 working days at senior research scientist level.

In the operational phase of the sub-project, it is estimated that somewhat more than one rainy period per calendar month will be used (14 occasions for the year of the project), and that each occasion will require 2 working days of analysis covering the 19 single radar analysis results and the 39 (or minimum 37, see above) paired radar comparisons. The year's total for the operational phase is therefore estimated as 28 working days at senior research scientist level.

The total personnel resources are therefore estimated as 28 + 14 = 42 working days for the year of the project. Costs are estimated using the standard FMI rate for the staff grade concerned, including infrastructure costs that cover the use of computer resources as required. This cost is 291 FIM/hour, or 2110 FIM for a 7.25 hour working day. Total costs for this sub-project are therefore 88620 FIM.

If we use the same principle to divide these costs that we use with e.g. the AU maintenance costs then they would be split between FMI, SMHI and DNMI according to the number of operational radars, i.e. 7, 11, 1 respectively. To these figures is added a standard "1 radar" overhead for each institute. The above sum would therefore be divided in the ratios 8/22, 12/22 and 2/22, respectively. Final cost allocation would be as follows:

FMI uses staff resources to the sum of 32226 FIM SMHI disemburses FMI to the sum of 48338 FIM DNMI disemburses FMI to the sum of 8056 FIM

Total costs: 88620 FIM

If data from the new Norwegian radar, planned to be brought on line in the summer of 1999, is included in SP1, then the division of costs may be changed to reflect this.

Proposal for a NORDRAD quality-assurance project: sub-project 2

Name of sub-project: investigation of angular pointing accuracy of NORDRAD radars (NORDRAD QA SP2)

Project leader in Finland: R. King, Observational Services, FMI.
Project manager Sweden: Madelene Nilsson
Contact person DNMI: Oddbjörn Thoresen

This sub-project aims at investigating the azimuth and elevation angle pointing accuracy achieved operationally by radars in the NORDRAD network, and implementing improvements to achieve an agreed level of accuracy. The continuation project coupled with operational experience of the radars has shown that in particular the variation of the true elevation angles achieved by the radars plays a significant role in producing visible differences between the data of neighbouring radars in a composite image. Additionally, such inaccuracies obviously cause errors in products using height determinations, such as CAPPI and ECHO TOP. Although small azimuth errors may be less visible, nevertheless a quality assurance system should also include regular checking of azimuth angles, too.

Because of the differences between the Ericsson and Gematronik radars and their associated radar data and control systems, it will not be possible to carry out identical project programmes in Finland on the one hand, and in Sweden and Norway on the other. The overall aims of the sub-project in each country are, however, the same:

1) To carry out on several occasions throughout the project period at each radar an investigation of the azimuth and elevation pointing angle accuracy, repeatability, resolution and control linearity using primarily the sun and also other aids, such as echoes from masts and in-situ mechanical measurements of antenna position.

2) To devise suitable operational versions of these measurements for routine use.

3) To propose acceptable levels of variation of achieved antenna behaviour within NORDRAD, with action limits leading to servicing/overhaul.

4) To analyse the causes of inaccuracy and variability and make recommendations for structural and/or electrical modifications. These analyses shall also lead to the proposal of a (radar-specific) code of practice including diagnostic methods and documentation.

5) To carry out such electrical/mechanical repairs, overhauls or modifications as suggested by the results of the investigation.

During the active period of the project (one year), the member countries will intensify cooperation in exchanging information on methods used and experiences gained, and will document their work thoroughly for future reference.

The working methods of FMI to be used with its Gematronik/SIGMET radar systems which may be considered include, for example, the following:

1) Determination of the elevation and azimuth angle accuracy using the sun at as many angles as necessary for each radar using the IRIS ascope utility.

2) Determination of the elevation movement accuracy with a direct mechanical angle measurement with respect to the vertical using a sensitive angle-measurement instrument (goniometer) affixed to the antenna.

3) Checking of the beam for true direction and pattern at certain radars where this is possible (e.g. Vantaa) using the IRIS beam facility, which constructs the beam pattern from a 3D sector scan of an external signal generator and horn radiator. This will also provide a check on the beam widths and on-axis gain figure employed in the radar equation (see also sub-project 3).

Proposal for a NORDRAD quality-assurance project: sub-project 3

Name of sub-project: Investigation of calibration and radar parameter accuracy (NORDRAD QA SP3)

Project leader in Finland: R. King, Observational Services, FMI
Project manager Sweden: Madelene Nilsson
Contact person DNMI: Oddbjörn Thoresen

This sub-project is a follow-up of the work done by the balloon group in the NORDRAD continuation project. It builds on the experiences of that group and extends the scope of checks to other related areas.

The resources required to carry out a standard-reflector check on all radars in the network would be prohibitively large. The main remaining difficulty in reflector measurements is the accurate sampling in space, i.e. how to get the reflector in the middle of the contributing volume sampled by the radar. It seems reasonable to wait until the operational radar software and signal processors are capable of performing very dense spatial sampling in a sector volume scan before applying this method further. This kind of enhancement would make the actual measurements much easier than was the case during the winter 1997-98. It is strongly recommended that the radar systems should be enhanced to allow such measurements in the future.

The reference feed horn measurements, however, showed a very good accuracy and repeatability in the calibration of the receiver chain. There is also good evidence that measurements of the microwave emission of the sun could provide a fast quality check of the receiver calibration. Discussions at the QA Workshop in March 1999 confirmed that all NORDRAD countries are actively interested in devising operational methods of performance checking using solar microwave emissions. Both feed horn and sun measurements are quite easy and quick to perform in the field. These measurements should be made at all NORDRAD radars, at least at those radars which are outliers in the analysis carried out in sub-project 1.

In addition to the calibration procedures above, it was found during the NORDRAD calibration tests that the actual parameters (e.g. various losses) used in determining the radar constant should be carefully and critically checked and documented on-site at each radar. This re-checking will be carried out in all three NORDRAD countries throughout the project period.

A workshop was held in Finland (March 1999) for technicians and experts from all three countries, in which the emphasis was on exchange of experiences and hands-on comparison of techniques in the fields of calibration (SP3) and antenna control (SP2), also using data collected and analysed in SP1. The workshop provided additional information to help all NORDRAD countries in specifying in detail their own corresponding SP2 and SP3 projects. In addition, Sweden presented a preliminary phase report, giving details of investigations in SP2 and SP3 already carried out.

Work contents of SP3:

1. Workshop on calibration methodology prior to the actual field measurements (already held)

2. Re-checking and documentation of the radar parameters determining the radar constant and parameters affecting the measured dBZ values in the processing chain (including calibration constants) at all NORDRAD radars.

3. Feasibility study as to how the radar systems could be improved in order to achieve good sampling density in standard-reflector measurements.

4. Performance of identical reference feed horn measurements at all NORDRAD radar systems, at least at those systems which exhibit the largest inhomegeneities in sub-project 1.

5. Performance of identical and simultaneous sun measurements at overlapping radar pairs (NOR - SWE, SWE - FIN). Comparison of results to simultaneous reference feed horn measurements. Again such radar pairs have the largest priority, which show anomalies in sub-project 1.

APPENDIX 2: Interim report

Interim report of the NORDRAD quality assurance project (QA project)

May 10, 2001

Project period: 1.8.2000 - 31.10.2001

Project management group: Asko Huuskonen (FMI, project leader), Ingemar Carlsson (Swedish Armed Forces), Oddbjørn Thoresen (DNMI), Jan Svensson (SMHI, until 31.3.2001), Daniel Michelson (SMHI, from 1.4.2001)

Summary

Aim of the project: The aim of the project is to improve the intensity level harmonisation of the NORDRAD network to within ±2 dBZ, and to establish workable and efficient quality assurance and maintenance practices. The project is divided into three sub-projects:

- SP1 Monitoring of all NORDRAD radars using the NRDTOOLS software.
- SP2 Investigation of angular pointing accuracy of all NORDRAD radars, and implementation of improvements to achieve and agreed level of performance.
- SP3 Investigation of calibration and radar parameter value accuracy at all NORDRAD radars, and implementation of improvements to achieve agreed level of performance.

Sub-project SP1 is carried out by FMI on behalf of all parties with their cooperation. Sub-projects SP2 and SP3 are carried out by each Institute separately.

General remarks: The project started in March 1999 with a QA Workshop in Helsinki, where experts of the participating institutes and invited guests from Germany and Estonia met to discuss the project plan. The agreed active project period was from May 1999 until April 2000. However, the project was at standstill at FMI until August 2000, when the project was finally started. First results were presented to NOCORD at its meeting on October 18-19, 2000 in Helsinki. The project management group met in Helsinki on November 21, 2000, in conjunction with the NORDRAD Operations Group meeting. At the meeting the project management group members confirmed their interest in the project, despite the delay in the active project period. It was agreed that the work concentrates to SP1 in the beginning, because work on that project is carried out by FMI, which has already started active work. Other Institutes need time to allocate resources to the project and will start active work towards the latter half of the project.

Work done by April 2001: During the first half of the project the work has focused on SP1. Within SP1, the NRDTOOLS software has been taken into use, a set of radar pairs has been specified, a number of rainy periods has been selected and the tools used to obtain single and paired radar pictures, and web pages have been created to display to pictures. Finally, an analysis software has been created to get numerical estimates of the calibration difference and the difference in the collection angles. Details are given in the report of SP1.

Work plan: The work in SP1 has advanced according to the project plan and the work will be finalized in September 2001. Details are given in the report of SP1. Towards the end of the project period the work shall focus on SP2 and SP3. At FMI the work on SP2 has already been started. It is expected that the work will provide precision pointing observations which will complement the results of SP1. On the other hand, the advances in SP3 will most probably be limited during the active project period. The active project period ends in October 2001 and the final project report will be ready by the end of 2001.

On behalf of the management group

Asko Huuskonen
project leader

Sub-project 1, SP1

Organization The sub-project leader is A. Huuskonen (FMI) and the contact persons are Oddbjørn Thoresen (DNMI) and Daniel Michelson (SMHI, from 1.4.2001). Jan Svensson was the contact person for SMHI until 31.3.2001.

Aim of sub-project To carry out analyses (using both single radar and paired-radar data) of the NORDRAD network using the software package NRDTOOLS, and to produce regular reports of the relative intensity levels of the participating radars to support other activities in the NORDRAD QA project (i.e. antenna angle, calibration and radar constant parameter investigations).

Work done in SP1

Selection of radar pairs Altogether 15 radars and 15 radar pairs were selected from NORDRAD. These are given in Table 1. Each radar pairs requires the specification of two products, and thus the total number of radar pair products is 30. Only 16 of these are fully new, because data for seven radar pairs has been collected since January 1999. These seven pairs form a chain from Stockholm through Finland to Luleå. The additional eight radar pairs form a chain through Sweden from Stockholm to Luleå, and a chain from Stockholm to Hægebostad in Norway. These radars do not cover the whole NORDRAD network. The aim has been to include all three types (Gematronic/Sigmet, Ericsson, Gematronic) of radars in the comparison, and to limit the number of pairs so that the data processing is manageable with the resources available to the project.

The paired radar data for all these pairs, and the single radar data for all the radars is produced at FMI regularly at 15 minutes intervals and is stored to disk. Presently data for the last 3 months is kept on-line, which gives ample time to find promising rainy periods for the analysis. After the 3 month period the data is discarded. Data for the selected analysis periods is copied to a different location for analysis. The data from the selected analysis intervals is stored for a possible reanalysis.

Selected analysis periods Data from five periods have been analyzed so far. These periods and the radar pairs analyzed in each are given in Table 2. Of the 15 pairs, eight were specified in October, and therefore QA products for these pairs is available only for the last three analysis periods. The last of the five periods is from November 2000. The main reason is that we have tried to find periods where data from all radars would be available. The problems with some radars, explained below, have meant that no such periods have been found from December, January and February. Also, a lot of the resources allocated to the project, i.e. of the working days of the project leader, were spend in the creation and testing of the analysis software. As data is stored for at least 3 months, rainy periods in January-March 2001 can still be analyzed.

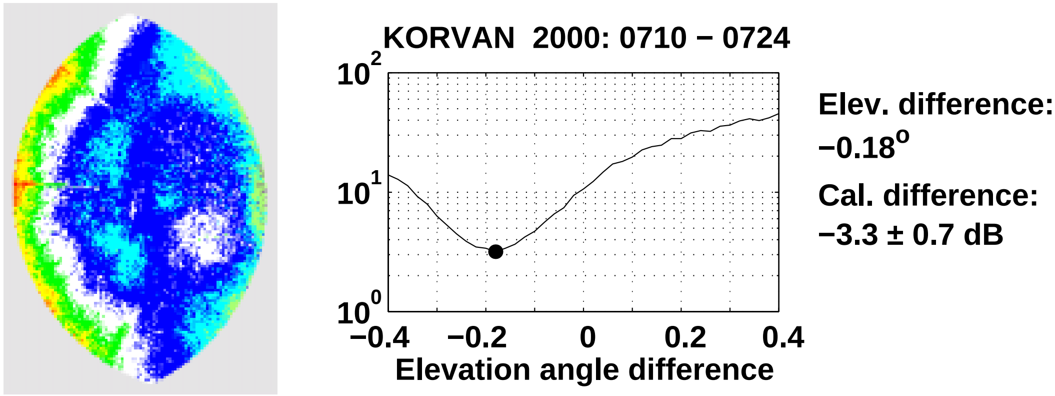

Figure 1: Paired radar result for the Korpo-Vantaa pair (left panel), the residual of the fit as the function of the collection angle difference (right panel). Results are seen on the right.

Data from three pairs have appeared faulty or impossible to use:

- OSUOVI and HUDOSU: Data which was collected during year 2000 cannot be used because the coordinates of the Östersund radar were found wrong. Correct coordinates have been used since December 28, 2000 in the production of the paired radar products. It then appeared that the product generator could not produce correct data for the new area defined. The problems were solved by January 25, 2001, after which correct data has been available.
- UTALUO The product generator problems made the data useless until February 25, 2001.

Analysis results The immediate results are the images produced by the NRDTOOLS software. These include single radar results, which are averages or medians of the radar reflectivity for the analysis period, and paired radar results, which simply stated are averages (or median) of the differences of the reflectivities. These are available at the QA web-pages at nordrad.fmi.fi/qa/qaindex.html. The user name is nordrad and the password is known by the management committee members.

Secondly we have numerical estimates, which are based on the results from the NRDTOOLS software. Presently only the paired radar data is analyzed numerically, and an analysis program has been made, which gives the calibration difference and the difference in the collection angles of the radars. The analysis procedure is explained in a separate document. An example of the results in seen in Figure 1. A summary of the results about the angular difference is presented in Table 3 and for the calibration difference in Table 4 .

A best guess estimate for the collection angle difference is given for 7 of the 12 cases. We see that best guess estimates based on the data and the nominal values for the differences deviate by less than 0.1°, except for ones case. This is KORVAN, where the analysis gives a -0.2° difference, although the difference should be zero.

The calibration differences are mostly less than 2 dB, except in two cases. The

OSLHGB shows a calibration difference of about -5 dB. This is in agreement a 5 dB error in the calibration of the Hægebostad radar, found in December 2000.

Resources The sub-project is done by FMI for all the parties. Most of the work is done by the project leader, supported by the computing branch of FMI. The total amount of working hours is estimated at 200+40=240 hours by the end of March 2001. Three months of QA products is stored permanently on disk, requiring some 4 GB of disk space. Also, the production of the QA products used some 50 % of the resources of a workstation. The computer resources needed for running the NRDTOOLS and the numerical analysis program are negligible.

Work summary and work plan for SP1

The following table summarizes the work carried out and the work planned in sub-project 1:

	Task	Time period	STATUS
1.	Specification of a set of radars and radar pairs for calculation of the QA products	00/08–00/08	DONE
2.	Setting up NRDTOOLS and creating scripts for copying of data and running the tools	00/08–00/09	DONE
3.	Running the NRDTOOLS software for a number of selected rainy periods	00/08–	ONGOING
4.	Setting up web pages to present the single radar and paired radar pictures	00/10–00/10	DONE
5.	Creating software to obtain calibration differences and collection angle differences from paired radar data	00/10–00/12	DONE
6.	Running the analysis software to get calibration and collection angle difference estimates	00/10–	ONGOING
7.	Improving the numerical analysis software, e.g. to take into account the blocked sectors	01/04–01/09	ONGOING
8.	Specifying graphical output of results on the web server	01/05–01/05	T.B.D.
9.	Analysis of the single radar pictures. This task is carried out time permitting.	01/05—	T.B.D.
10.	Final report of SP1	01/10–01/12	T.B.D.

Sub-projects 2 and 3, (SP2, SP3)

Organization The sub-project leader in Finland is A. Huuskonen (FMI). The contact person in Norway is Oddbjørn Thoresen (DNMI). Presently no contact person for Sweden is nominated.

Aim of SP2 Investigation the azimuth and elevation angle pointing accuracy achieved operationally by radars in the NORDRAD network, and implementation of improvements to achieve an agreed level of accuracy.

Aim of SP3 Investigation of calibration and radar parameter accuracy.

Work done in Finland A work has been started to establish a regular procedure for checking the antenna pointing during each maintenance trip. This includes checking the antenna azimuth pointing by using the sun. The antenna elevation readings are checked against a precision inclinometer to check the linearity of the elevation scale and the changes with time.

Work done in Sweden The work done in Sweden prior to the active project period has been summarized in "Preliminary phase report from NORDRAD QA-project phase 1: 1999-01-01 — 1999-03-31" by Madelen Nilsson.

Table 1: The single radar sites and the radars to which each is paired with. The last column gives the number of paired radar products and the number of new products added during the project period (in parenthesis)

Radar		paired with	# of products
Stockholm	STO	LEK, KOR	2 (1)
Korpo	KOR	STO, VAN	2 (0)
Vantaa	VAN	KOR, ANJ	2 (0)
Anjalankoski	ANJ	VAN, IKA	2 (0)
Ikaalinen	IKA	ANJ, KUO	2 (0)
Kuopio	KUO	IKA, UTA	2 (0)
Utajärvi	UTA	KUO, LUL, LUO	3 (1)
Luleå	LUL	UTA, OVI	2 (1)
Luosto	LUO	UTA	1 (1)
Örnsköldsvik	OVI	LUL, OSU	2 (2)
Östersund	OSU	OVI,HUD	2 (2)
Hudiskvall	HUD	OSU, LEK	2 (2)
Leksand	LEK	STO, HUD, OSL	3 (3)
Oslo	OSL	LEK, HGB	2 (2)
Hægebostad	HGB	OSL	1 (1)
		Total	30 (16)

Table 2: The availability of paired-radar images. Successful cases are denoted by x and unsuccessful ones with o. An empty space denotes that the QA data was not available at all.

	000710 000724	001010 001016	001024 001029	001104 001109	001120 001129
STOKOR	x	x	x	x	x
KORVAN	x	x	x	x	x
VANANJ	x	x	x	x	x
ANJIKA	x	x	x	x	x
IKAKUO	x	x	x	x	x
KUOUTA	x	x	x	x	x
UTALUL	x	x	x	x	x
UTALUO			o	o	o
STOLEK			x	x	x
LEKHUD			x	x	x
HUDOSU			o	o	o
OSUOVI			o	o	o
OVILUL			x	x	x
LEKOSL			x	x	x
OSLHGB			x	x	x

Table 3: The collection angle difference for the analysis periods. Highly suspicious values are given in parenthesis. The last two columns give an expert guess on the most probable angle, when such a guess can be made, and the nominal angle difference. When two values are given, the latter is valid for the last period. The value is different for that period because some radars in Finland have a higher lowest collection angle in the Summer period and the angles were changed between periods 4 and 5.

	000710 000724	001010 001016	001024 001029	001104 001109	001120 001129	Expert guess	Nominal value
STOKOR	0.08	-0.18	-0.06	(-0.40)	(0.40)	- /-	-0.1/0.1
KORVAN	-0.18	-0.22	-0.22	-0.18	-0.22	-0.2	0.0
VANANJ	0.18	0.22	0.18	0.20	0.12	0.2/0.1	0.1/0.0
ANJIKA	-0.12	(0.20)	-0.08	-0.04	0.06	0.0	0.0
IKAKUO	0.12	(0.34)	0.16	(0.40)	(0.30)	0.1/-	0.1/0.0
KUOUTA	0.08	-0.08	0.02	(-0.24)	0.04	0.0	0.0
UTALUL	(0.40)	0.22	(-0.36)	(-0.40)	(0.40)	-	0.1
STOLEK			0.08	-0.18	-0.08	-0.1	0.0
LEKHUD			-0.06	0.18	(0.38)	-	0.0
OVILUL			(0.36)	(-0.40)	(0.40)	-	0.0
LEKOSL			0.04	0.06	(0.38)	0.0	0.0
OSLHGB			(0.40)	-0.10	0.06	-	0.0

Table 4: The calibration difference in dB for the analysis periods. Highly suspicious values are given in parenthesis. The last column gives the average value of accepted results. Two values are given for KORVAN and VANANJ, due to the re-calibration of the Vantaa radar between periods 3 and 4.

	000710 000724	001010 001016	001024 001029	001104 001109	001120 001129	Average value
STOKOR	1.9	1.6	2.0	(-0.1)	(3.5)	1.8
KORVAN	-3.3	-2.6	-3.0	-0.8	-1.6	-3.0/-1.2
VANANJ	1.2	1.0	-0.3	-1.1	-0.7	0.7/-0.9
ANJIKA	1.7	(3.6)	1.3	2.0	0.5	1.4
IKAKUO	0.4	(0.4)	0.3	(3.9)	(3.0)	0.4
KUOUTA	-0.1	-3.3	-1.2	(-3.8)	-0.8	-1.4
UTALUL	(0.2)	6.1	(-1.3)	(-1.1)	(3.2)	-
STOLEK			6.6	4.9	4.6	5.3
LEKHUD			-2.7	-0.9	(-0.3)	-1.8
OVILUL			(8.3)	(3.3)	(3.4)	-
LEKOSL			-0.4	-0.4	(-0.0)	-0.4
OSLHGB			(-1.9)	-7.3	-4.2	-5.6