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Addendum

In this addendum, simulations and measurements not having been reported on in the main section will be presented. With the majority of techniques for propagation modelling and source localization already having been described in detail in that part, and the strategy used in the following investigations being similar, the experimental procedure will only be presented briefly. Consequently, it is recommended that the reader first familiarizes himself with the first part of this report.

Overview

1) Influence of ground unevenness
2) Adaptive grid search
3) Localization of multiple sources
   1. Partitioning of beamform power map
   2. Removal of sources from covariance matrix
4) Long-range measurements
   1. Repeatability
   2. Combination of vertical and horizontal arrays
5) Variability of position estimates
6) Summary

Influence of ground unevenness

In the first part of this study, simulations were done only for even ground. In addition, measurements were also limited to (mostly) flat ground. One can foresee that ground unevenness exceeding the wavelength or obstacles blocking the line of sight between array and source will influence of accuracy of the position estimation. On the one hand, if the array is (partly) in the shadow zone of an obstacle, the sound pressure level and SNR will be greatly reduced resulting in higher variability of the position estimates. This effect will not be considered in this study as it depends on the specific source level and background noise. Ultimately, one can not expect to localise sources behind barriers unless they have a high level (relative to the background noise).

We will concentrate on the effect ground unevenness has on the phase relation between the signals arriving at the array microphones, keeping the SNR constant.

Simulations were used to determine the effect of different ground profiles, maximum profile heights, source and array heights as well as frequency ranges on the error in the position estimates. Table 1 gives an overview of the parameters used. The source signal was pink noise, mixed with spatially white noise to obtain an SNR of 40 dB at the lowest microphone. Ground impedance was described by the two-parameter (2PA) model \[1\] with a flow resistivity of 100 krayl/m and \(\alpha = 25 \text{ m}^{-1}\) (grassland). The array consisted of 8 microphones with a 20 cm spacing.
Ground profile | Four different, see figures
Max. profile height | 0, 0.1, 0.2, 0.5, 1 [m]
Source height | 0.5, 1, 1.5, 2, 5 [m]
Height of lowest microphone | 0.5, 1, 1.5, 2 [m]
Frequency range | 100-500, 500-1k, 1k-2k, 2k-4k [Hz]

Table 1: Range of parameters used in modelling the influence of ground unevenness on the accuracy of source position estimates.

For each combination of ground profile, geometry and frequency range (100 Hz resolution), the propagation loss between the source and the array microphones was calculated using the Generalized Terrain Parabolic Equation (GTPE) method [2]. GTPE is an extension of CNPE allowing propagation over non-flat ground to be calculated as long as the local slope of the ground does not exceed approx. 30°. The method was implemented in Matlab following the formulation in [3]. It was tested by comparison with CNPE (flat ground) and, for a randomly selected ground profile, by comparison with a boundary element method (BEM) solution.

From the source spectrum, multiplied with the propagation losses and adjusted for SNR, the frequency dependent covariance matrices (100 frames of 10 ms length) were obtained and used for MUSIC based position estimated as described in the “ground effect inversion” chapter. In other words, propagation took the uneven ground into account whereas position estimation assumed flat ground.

The results for the four different ground profiles, three sin² shaped hills and one random profile, are shown in figs.1-8 in annex A. Independent of the specific ground profile, the following trends can be observed:

A decrease in accuracy with increasing profile height, which is to be expected.
A decrease in accuracy with increasing frequency, though there’s an improvement when switching from the 1k-2kHz range to the 2k-4kHz range. The effect of the frequency range is the result of two separate effects. On the one hand, the absolute effect of ground unevenness on the phase relation at the array depends on the relation between height of obstacle and wavelength, low frequencies are less affected. On the other hand, the phase differences used for position estimation are generally low at low frequencies, so even a small change can have a large effect. The simulations do, however, show that in case of uneven ground one can expect to lowest influence in the lowest chosen frequency range of 100 – 500 Hz.

The ground profile effect also changes with source and array height. While there’s no clear relation between source height and accuracy one can expect the best accuracy for an array height of 2 m, whereas an array height of 0.5 m resulted in the worst performance. In light of the good performance of the 2 m array when it comes to low SNR and uncertainties in the ground impedance, this height appears to be optimal for all situations considered in this study.

In addition to common effects, there’re differences in the effect different ground profiles have on the localization accuracy. The lowest influence had the hill next to the source, followed by the hill centered between source and array. The random ground profile spanning the whole distance between source and receiver and especially the hill below the array had a large effect, with all but the smallest profile heights leading to unusable results.

This leads to the conclusion that both the total “amount” of unevenness between source and array as well as the height of the array relative to the mean terrain height are major factors influencing the accuracy of source position estimation when the ground is not flat.

Adaptive grid search

Calculation of the beamform power on a fixed grid, as used in all previous parts of this work, is a robust method. As long as the grid is fine enough, it is guaranteed that the global maximum and hence the most likely source position is found. Unfortunately, it is a time-consuming procedure, as both the propagation loss and the beamform power itself need to be evaluated at each grid point. On the 2.4 GHz Q8200 computer used, and after thorough optimization, the search over 4800 grid points (20 deg at ¼ deg resolution, 60 distances) took, on average, 2.1 sec for 75 frequencies.
Taking in mind that a finer grid, esp. for the elevation angle, will increase the accuracy of the method, that one is not always able to limit the search space to 20 deg and 60 distances and that one may want to track moving objects in real time, a faster method for finding the global maximum of the beamform power is desirable.

In case the search space (and possible other parameters like the ground impedance) are fixed, one solution is to pre-calculate the propagation losses for the whole search space and store the data in a database. If this was done for the analytical propagation model used, the time required for calculating the source map will be reduce to approx. one-half. Precalculation is necessary if more complex propagation models, e.g. CNPE, are used, as these are orders of magnitude slower than the analytical model, even if one exploits, by use of reciprocity, the fact that these models (PE, FFP) “automatically” provide the complex pressure on a grid spanning the search space.

Another approach is the use of adaptive searches. The strategy used in this investigation is coarse-to-fine grid contraction. First, the beamform power $\phi$ is calculated on a coarse grid. Then, the grid points with the highest $\phi$ are selected and a finer grid is created around these points. This process is iterated, and the position with the highest $\phi$ is considered to be the source position. Simulations for different geometries, frequency ranges, ground impedances and signal-to-noise ratios were done (see tab.2) to find an adaptive grid search with a reliability comparable to the fixed grid search and a maximum speed increase. The following parameters were varied:

- Size of the initial (coarse) grid
- Number of grid points selected from this grid
- Grid contraction factor
- Number of iterations.

A comparison of a fixed grid and an adaptive grid search in shown in fig.9 in annex B. One can see that the adaptive search starts with a very coarse grid but contracts around the global maximum near 60 m / -0.5 deg. It requires only a fraction of the time the static search needs.

From all parameter combinations considered, the following combination showed the optimum performance:

- Initial grid: 1 deg * 10 ranges (linear spacing)
- 5% of the grid points – with the highest beamform power – selected
- Grid spacing reduced by a factor of 2/3
- 10 iterations

In table 3, a comparison of the reliability of the fixed grid search and the coarse-to-fine grid contraction with these parameters is given. It shows the percentage of cases (geometry, ground impedance, frequency range) for which the estimates are within the given error margins, e.g. the estimated range doesn't deviate more than 10% from the actual one. It is evident that the adaptive search offers comparable reliability (not more than one percentage point worse) while yielding a speed increase by a factor of 5 to 6.

Aside from coarse-to-fine grid contraction, other techniques for global optimization, as provided by Matlab's global optimization toolbox, were considered. However, no method or setting could be found leading to a similar performance as the adaptive grid search proposed. Because of the high number of options it is, however, possible that methods even better suited to the specific problem of source localization exist.

Localization of multiple sources

In the first part of this study it has already been demonstrated, by simulation and measurement, that multiple (2) sources can be separated even if their separation in space is small. It was observed that for each of the measurements done, there always existed a value of the beamform power which separated the areas belonging to the individual sources.

Visual inspection of the beamform power map is not an option when one wants to automatically detect / track sources. Two methods for computerized localization of multiple sources were tested.
Partitioning of beamform power map

After observing that there exists a value of the beamform power $\Phi$ that will separate the sources it is a straightforward approach to have a program do the partitioning of the $\Phi$ map. This includes the following steps:

- Calculation of the map on a fine grid, using MUSIC based ground effect inversion.
- For each threshold value $\Phi_{\text{min}}$ between 0.1 and 1 (step size 0.02), convert the map to binary by setting each grid point with $\Phi > \Phi_{\text{min}}$ to 1.
- Find the (8-way) connected areas (“islands”). This is done with the Matlab command `bwlabel`.
- Find the position with the maximum $\Phi$ within each island. Store it for each value of $\Phi_{\text{min}}$.
- After doing this for each threshold value, find all unique combinations of distance and elevation (potential source positions) from the total list of positions.
- Count for how many threshold value each position has been found to be the maximum of an “island”.
- Sort list by this number. We will consider the frequency to be a measure of likelihood that this position is actually a source position and not an artefact.
- If one expects $n$ sources, select the $n$ positions with the highest likelihood.

This strategy was found to be a robust method for detecting multiple (in this case 2) sources. It has been able to separate the two sources for all the measurements reported on in the first part of this report. Speed is determined by the time needed to create the beamform power map, as the partitioning procedure requires only a negligible amount of time.

In addition to the measurements, simulations – with the same parameter combinations used for testing the adaptive grid search (table 2) - were done, with a second source of same strength added either

1) at a 20% higher distance and same elevation
2) at a 3 deg. higher elevation and same distance
3) at a 20% higher distance and 3 deg. higher elevation.

Unfortunately, the success in locating the two sources by partitioning the beamform power map has been less successful compared to the outdoor measurements. While the first source has been located correctly (distance error less than 10%, elevation error less than 0.5 deg.) in more than 90% of all cases, the second source has been located with this accuracy only in approx. 50% of all cases. This being severely different from the measurement result further measurements with multiple sources are recommended.

Removal of sources from covariance matrix

An alternative solution, which allows the (fast) adaptive grid search to be used, is the removal of sources from the covariance matrix, similar to the CLEAN algorithm [4]. If one expects $n$ sources, and removes all but one of them from the covariance matrix, one expects a single maximum of the beamform power where the respective source is located. In practise, the following procedure has been used:

- Calculate the eigendecomposition of the covariance matrix (as needed for MUSIC). The eigenvectors corresponding to the $n$ highest eigenvalues represent to $n$ sources.
- Remove all but one source eigenvector / eigenvalue combination. The eigenvectors belonging to the noise subspace remain unchanged.
- Recalculate the covariance matrix from its reduced eigendecomposition.
- Use the reduced covariance matrix for MUSIC based source localization in conjunction with the coarse-to-fine grid contraction.
• Do this for all expected sources from 1 to n.

Time required is n times the time needed for the adaptive grid search. Consequently, there’s a speed advantage of this method compared to partitioning of the beamform power map as long as the number of sources is low (n < 5).

Reliability of the method was verified using the same measurement data as for the partitioning procedure. Performance was less good as in 2 out of 24 cases, one of the sources was not localized with same accuracy (distance error less than 10%, elevation error less than 0.5 deg.).

Just as for the partitioning, same same simulations were done to check the reliability of the CLEAN like approach. Results were comparable, with the first source being detected correctly in approx. 95% of all cases while the second source was only located correctly in approx. 45% of all cases.

Long-range measurements

The measurements reported so far were all limited to a maximum source-array distance of 40 m due to constrains regarding the available test sites and the equipment. Additional test have been performed with a range of 80 m.

Measurements were done on pasture land. The ground was dry, the ambient temperature 25°C with a clear sky. Wind speed varied significantly with maximum speeds of approx. 6 m/s. The ground, though mostly flat, was slightly sloped. Background noise as a result of the wind and nearby trees was present.

A single vertical array, consisting of 8 microphones with a spacing of 20 cm, the lowest microphone 1.65 m above the ground, was used. Tests were done with one or two sources. For the single source trials, the loudspeaker was placed at a distance of 80 m at heights of 1.7, 2.0 or 0.3 meters. For the two source trials, an additional loudspeaker was placed at a distance of 44 m and a height of 1.2 m. The source signal was pink noise, whose level was varied by approx. 24 dB from clearly audible to far below the threshold of hearing (bearing in mind the background noise). Figure 10 shows an example of the power spectra at the lowest (1) and highest (8) microphone for one measurement with a single source at a distance of 80 m and a height of 1.7 m. One can see that the source signal was never above the background noise below 500 Hz, and even at higher frequencies only the loudest signal (“0 dB”) was clearly above the background. With the -12 dB setting being similar to the background noise, one can expect the SNR of all measurements to be not higher than 10 dB.

Reliability of the source localization by ground effect inversion, either with the Bartlett or the MUSIC cost function, was poor. Only for approx. 40% of all combinations of geometry and source level, at least one source could be detected with a maximum error of 20% for the range and 1 deg. for the elevation. Only in isolated cases could the two sources be separated.

Repeatability

One symptom of the poor reliability of ground effect inversion under the given conditions is the lack of repeatability. Even measurements with the same source level and geometry, done one after the other, resulted in largely different source position estimates. An example is shown in figure 11: five measurements with two sources, one at 80 m distance and 2 m height and one at 44 m distance and 1.2 m height, with the sources still audible at the array and with one minute between the measurements. Only two of the measurements have detected one of the sources close to their actual position: the 1st measurement source 2 (44 m) and the 5th measurement source 1 (80 m). None of them revealed two sources.

The likely reason for the poor performance is turbulence, possibly in conjunction with relatively low SNR. The wind speed were significantly higher than during the previous measurements, making, for example, the use of the large array with 50 cm spacing impossible. In addition, the high insolation on that day created additional turbulence. As has been discovered in the first part of this work, by numerical simulation, vertical arrays can be severely affected by turbulence due to modulation of the ground effect. While these measurements confirm the simulations the turbulence effect greatly reduces the usefulness of the proposed source localization by ground effect inversion.

Combination of vertical and horizontal arrays
In order to increase the reliability of source distance and height estimation by ground effect inversion, a combination of the vertical array with a large horizontal array was used. The horizontal array, on the one hand, is affected much less by turbulence, and, on the other hand, can easily be made very large whereas for vertical arrays this is generally impractical.

Measurements were done over a compacted, dry lawn. Air temperature was 20°C with a cloudy sky. Wind speed at 2 m height were between 3 – 4 m/s.

Six microphones, spaced 30 cm apart, with the lowest one at a height of 1.5 m, were used for the vertical array. The horizontal array consisted of three microphones, spaced 5 m apart. Both arrays shared one microphone (microphone 1).

Measurements were done with a single source at a height of 1.94 m and a distance of 40 or 78 m. As in the previous measurement, pink noise was used and its level varied over a large range.

When using only the vertical array for position estimation, only in 19 out of 52 cases (combination of level and distance) the source was localized close to its actual position. This is comparable to the results of the measurements over pasture land.

In a second step, the 3-microphone horizontal array was used to get an estimate of the source distance. This was done using (free field) TDOA based position estimation as described in the first part of this report. This time, the delays between the microphone signals were not estimated by use of cross correlation in the time domain but by generalized cross correlation (GCC) in the frequency domain, using the cross spectra [5]. This has the advantage that frequency dependent weighting functions can be used; in this case, phase transform (PHAT), the normalization of the cross spectrum, turned out to be the most reliable method. The effect of PHAT is that equal weight is put on all frequencies, thereby eliminating the influence of strong spectral components on delay estimation: (partly) periodic signals can cause non-uniqueness of the estimated delay. Whereas PHAT is generally used for periodic source signals like speech, it is, like in this study, also useful in reducing the influence of (non-random) background noise, e.g. originating from vehicles or other rotary machines.

An example of the combined use of the two arrays is shown in figure 12. It shows the beamformer power maps for the vertical array only, using two different methods. On the one hand the already described ground effect inversion with the MUSIC estimator. On the other hand, the (inverse of the) sum of squared differences between the level differences (in dB) between the five microphone pairs and the level differences predicted by the sound field model. In this case, the use of the vertical array alone together with the MUSIC estimator already located the source close to its actual position, whereas the level difference based estimator predicted an almost constant beamform power along one line; it is important to note that this line passes through the actual source position, although the maximum is somewhere else.

The horizontal 3-microphone array gave very accurate estimates of the source distance, as should be expected due to its large aperture. For this array, either ground effect inversion with MUSIC or (free field) time difference of arrival based position estimation was used.

In the next step, both beamformer power maps were combined. First, the maximum beamform power for each distance was extracted from the horizontal map. Then, these values were added to the vertical map at each point corresponding to these distances. In other words, vertical and horizontal array were weighted equally. The results are presented in the same figure. It demonstrates that especially the combinations using level difference (magnitude) based localization for the vertical array provided precise source height and distance estimates. Keeping in mind that the TDOA based method is also the fastest one, combining it with level difference based localization seems to be the preferred solution.

Another example is given in figure 13. In this case (with a much lower source level), the vertical array alone did not find the source close to its position. The horizontal array with the MUSIC estimator did also not result in an acceptable distance estimate, while TDOA/PHAT based estimation did. Again, the combination of TDOA for the horizontal array and magnitude difference based estimation for the vertical array proved to be the best solution.

It is still far from perfect: while for 71% of all combinations of geometry and level the distance was estimated with an error of less than 20%, only in 50% of all cases the elevation was, in addition, determined with an error of less than 1%.
Variability of position estimates

The combination of vertical and horizontal array, as described in the previous chapter, was used to assess the variability of the position estimates for a fixed source position at a distance of 80 m and a height of 1.77 m. 60 measurements of 4 second length were done at an interval of one minute, each measurement with 4 source levels, starting with a clearly audible signal (“0 dB”) and then reducing the level by 6 dB. The source signal was white noise filtered to obtain a traffic noise spectrum. The test site was a ruderal area with an uneven, slightly sloped surface; the ground was soft and wet. The temperature was approx. 20 °C, with a cloudy sky and wind speeds below 2 m/s. The results, expressed as mean ± standard deviation, are shown in figure 14 for the four different source levels and eight different range (resp. 6 different height) estimators. Part of them use only the vertical (V) array, part the horizontal (H) array, others use a combination of the results. The average source distance estimate of approx. 65 m is lower than the actual distance (80 m), most likely due to ground unevenness (vertical array) and slight misalignment of the microphones (horizontal array). Use the the magnitude LMS estimator and the vertical array resulted in estimates far too low, use of the horizontal array and the MUSIC estimator also gave lower than average range estimates. Variability of the estimates was lowest for the time-difference-of-arrival (free field) estimator due to the large size of the horizontal array and the high robustness of the GCC-PHAT TDOA calculation.

The source height also showed a tendency to be underestimated, with the combination of vertical array based magnitude LMS height estimation and horizontal array TDOA based range estimation showing the lowest variability and indicating a height of 1.2 - 1.8 m. This underlines the good performance of this combination of the two arrays as already observed during the initial measurements.

In addition, it can seen that the variability of the estimators increases clearly with decreasing source level, as shall be expected.

Summary

In the second part of the study on the influence of environmental conditions on source localisation, the effect of additional factors on localization accuracy has been investigated. Ground unevenness can significantly degrade the performance of the ground effect inversion, especially if a large part of the area between source and array is uneven or if the array is raised above the mean terrain height. This is in addition to the possible decrease in SNR due to shadowing of the source. A height of the lowest array microphone of 2 m has been found to offer the best tolerance against uneven terrain as well as low SNR and uncertainties in the ground impedance. Outdoor measurements over distances up to 80 m, with one or two sources, were done during medium to high turbulence conditions. Turbulence led to a decrease in the localization accuracy, as predicted by the numerical simulations in the first part of this study. To improve the reliability of the new method even under adverse conditions, a combination of vertical and horizontal array has been investigated. The large aperture horizontal array was used to estimate the distance of the source by (free field) generalized cross correlation with phase transform (GCC-PHAT), while the source height was determined using a vertical array and a LMS estimator based on the level differences between the microphone pairs.

Efforts have been made to improve the efficiency of the ground effect inversion. An adaptive search – a coarse-to-fine grid contraction - offered the same reliability as the search on an fixed grid but required only 1/5th of the time.

Finally, two methods for the automatic localization of multiple (2) sources have been tested. Partitioning of the beamform power map by use of a threshold separating the areas corresponding to the individual sources correctly identified the sources in all the outdoor measurements (up to 50 m distance). Removal of all but one source from the covariance matrix showed a slightly worse reliability but a higher computational speed. However, simulation with a high number of geometries, ground impedances and SNR indicate that both methods will only be able to separate the sources in approx. 50% of all cases, if sources are separated by not more than 3 deg. in elevation or 20% in distance. Further measurements with multiple sources are recommended to verify these simulation results.
References


Annex A Influence of ground unevenness

Figure 1: Ground profile 1: Hill centered between source (Distance = 0) and array (Distance = 80 m). Maximum height 1 m.

Figure 2: Effect of ground profile 1 on source position estimates. Shown are number of parameter combinations (in %) which fulfil the limits chosen for distance R and elevation α as stated in the legend.
Figure 3: Ground profile 2: Random profile (maximum slope 20°) between source and array. Maximum height 1 m.

Figure 4: Effect of ground profile 2 (random heights) on source position estimates.
Figure 5: Ground profile 3: Hill next to the source (left). Maximum height 1 m.

Figure 6: Effect of ground profile 3 (hill next to source) on source position estimates.
Figure 7: Ground profile 4: Receiver array on top of hill (right). Maximum height 1 m.

Figure 8: Effect of ground profile 4 (array on hill) on source position estimates.
Annex B Adaptive grid search

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<tr>
<td>Source-array distance R</td>
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<td>Elevation α</td>
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<td>Microphone spacing</td>
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Table 2: Parameters used for the simulation of source localization over flat ground in order to compare the fixed grid search with various adaptive search types.

Figure 9: Comparison of search on a fixed grid (left) and an adaptive search / grid contraction (right). Search on fixed grid (4000 grid points) took 2.5 sec., grid contraction 0.3 sec.

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<th>Percentage / Adaptive grid</th>
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Table 3: Comparison of the reliability of source localization using a fixed grid and an adaptive grid / grid contraction for 1620 combinations of geometry, frequency range and ground impedance. Average time for a single fixed grid search was 2.1 sec, for the adaptive search 0.37 sec.
Figure 10: Power spectra of the signals received by the lowest (1) and highest (8) microphone for measurements over grassland with a single source at a distance of 80 m and a height of 1.7 m. The source emitted pink noise, which at the highest level (“0 dB”) was clearly audible.
Figure 11: Beamform power maps for two sources, one at 80 m / 0.3 deg. elevation and one at 44 m / -0.6 deg. elevation. Measurements over grassland, single vertical array of 8 microphone with 20 cm spacing. Pink noise, 500 – 4 kHz frequency range used for position estimation. One minute between the five measurements.
Figure 12: Combination of vertical and horizontal arrays. “MUSIC” and “Magnitude LMS” use only the vertical array (map shows beamform power vs. distance and elevation angle), “Horiz. MUSIC” and “Horiz. TDOA” only the horizontal one (distance and azimuth). The other 4 diagrams show all combinations these position estimation methods. Actual source position is marked by circle, estimated one by asterisk.

Figure 13: Combination of vertical and horizontal arrays. “MUSIC” and “Magnitude LMS” use only the vertical array (map shows beamform power vs. distance and elevation angle), “Horiz. MUSIC” and “Horiz. TDOA” only the horizontal one (distance and azimuth). The other 4 diagrams show all combinations these position estimation methods. Actual source position is marked by circle, estimated one by asterisk. Low SNR situation.
Figure 14: Mean and standard deviation of estimated source distance (top) and height (bottom) versus relative source level and type of estimator. 60 measurements at 1 min. intervals. Vertical array of 6 microphones plus horizontal array of 3 microphones. Actual source position is 80 m / 1.77 m height.