LOCALIZATION OF PARTIAL DISCHARGES IN POWER TRANSFORMERS BY COMBINED ACOUSTIC AND ELECTRIC MEASUREMENTS

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Abstract: This paper describes an advanced combination of electric and acoustic measurements for the localization of partial discharges in power transformers. The measurement of acoustic signals is triggered by an electric partial discharge signal. The distance between the partial discharge source and sensor is calculated from the time the acoustic wave needs to travel from the partial discharge source to the sensor. Different factors influencing the accuracy of the determination of the distances between the partial discharge source and the acoustic sensor are evaluated.

1 INTRODUCTION

Partial discharge (PD) measurement is a powerful tool to diagnose the condition of insulation of high voltage equipment. A well accepted method for localization of these PD in power transformers is given by the combination of electric and acoustic PD measurement [1]. For PD localization mostly time of flight analysis is used. The analysis is based on measurements with acoustic sensors spread around the transformer housing [2]. The accuracy of the localization strongly depends on the accuracy of the determination of the distances between the PD source and the acoustic sensors. These distances can be calculated from the time the acoustic waves travel from the defect to the sensors (time of flight). For calculation of the defect location different algorithms with different accuracy and reliability exist [5-7]. This paper will focus on showing different steps to enhance this accuracy.

2 MEASURING EQUIPMENT AND TESTING PROCEDURE

2.1 Measuring procedure

Acoustic and electric PD signals were detected synchronously. The electric measurement was used for comparison of PD activities. Additionally the electric measurement could also be used as a trigger for measuring and averaging of the acoustic PD signals. When triggered on stable electrical PD signals, averaging of acoustic signals leads to significant and often essential improvement of the signal to noise ratio (SNR).

The starting point of the electric signal and the acoustic PD signal were determined. It was assumed that the electric PD signal reaches the measuring system in the instance the PD occurs. With this arrival time, the time the acoustic wave took to travel from the PD location to the sensor was calculated. With known signal runtime and propagation velocity the distance from the sensor to the PD source was calculated. The propagation velocity in oil for all calculations was assumed to be 1410 m/s, as stated in [9]. The acoustic signals from different sensor locations were used for localization of the PD defect.

2.2 Measuring equipment

The acoustic PD signals were acquired with acoustic emission sensors of Physical Acoustics Corporation (P.A.C.). To improve SNR additional preamplifiers by P.A.C. with plug-in filters were used. The acquisition of the acoustic signal was done with a digital four-channel oscilloscope (DSO, LeCroy WavePro 725Zi). The data obtained via the DSO was exported to PC and afterwards evaluated using MATLAB®.

For electric measurements a coupling capacitor as well as a HFCT (High Frequency Current Transformer) were used. These sensors were connected to a OMICRON mtronix MPD600 PD acquisition unit. The acquisition unit on the other hand was connected to the PC as well as to the DSO. If in the acquisition unit a PD impulse with a higher charge than charge threshold level was registered, a voltage pulse was generated which was used to start the acquisition of the acoustic PD impulses on the DSO.

3 SYSTEM DEPENDEND RUNTIMES

The accuracy of the localization of the PD source extremely depends on proper determination of the signal runtimes from the site of the defect to the location of the sensor. Therefore it is important to know all inherent delays of the measuring system.

For further consideration, the term “runtime” is defined as the time that the acoustical or electrical wave needs to propagate from its source via different part of the measuring equipment to the oscilloscope. It consists of partial runtimes, related to parts of the measuring chain.

Figure 1 shows a simplified measurement setup with different smaller runtimes. The different acoustic and electric PD propagation paths are considered.

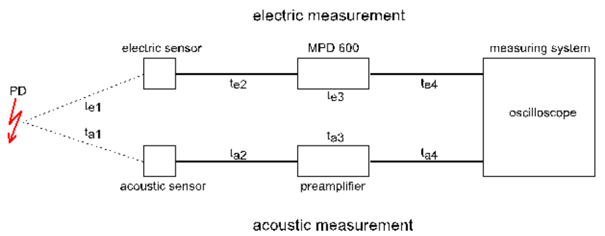

Figure 1: Signal runtimes indicated in the measuring setup

The runtimes t_{e2}, t_{e4}, t_{a2}, t_{a4} are propagation times of electric signals in signal cable. The runtime t_{e1} describes propagation of electromagnetic waves. These can be considered insignificantly small for further evaluation. The times t_{e3} and t_{a3} and accordingly all runtimes originating from the measuring equipment have to be determined.

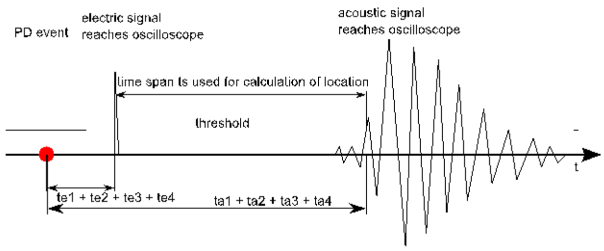

Figure 2: Runtimes of electric and acoustic signal in timeline

In figure 2 all runtimes of the electric and all runtimes of the acoustic signal path are shown on the time line for a PD event. It has to be emphasized that for a correct determination of t_{a1} all runtimes have to be known. The runtime t_s of the acoustic signal is the time difference between the arrival of the acoustic and the electric signal at the oscilloscope. All known runtimes in the acoustic signal path have to be subtracted from the time t_s whereas all known runtimes in the electric signal path have to be added to determine the correct signal runtime t_{a1}.

4 DETERMINATION OF SIGNAL STARTING POINT

A very important step is to determine the starting point of the acoustic signal, thus the arrival time of the acoustic signal to the sensor (t_{a1}). It can be difficult because the acoustic signals are oscillating and often not steep at the beginning. The arrival time and thus the runtime have to be determined automatically. For the work presented here the Energy Criterion was used for automatic determination of the signal starting point [1]. Other possible methods are described in [1, 3-4].

The determination of the runtime of the acoustic signals requires the elimination of noise at the beginning. In most cases good SNR is already reached by averaging of the measured acoustic signals. Investigations showed that in some cases also wavelet filtering brings an improvement [1]. For the work presented here the averaging method was successfully used.

In figure 3 for 53 acoustic signals with different distances from the PD location to the sensor the Energy Criterion graphs are indicated. A vertical blue line marks the signal starting point determined by the Energy Criterion for each signal.

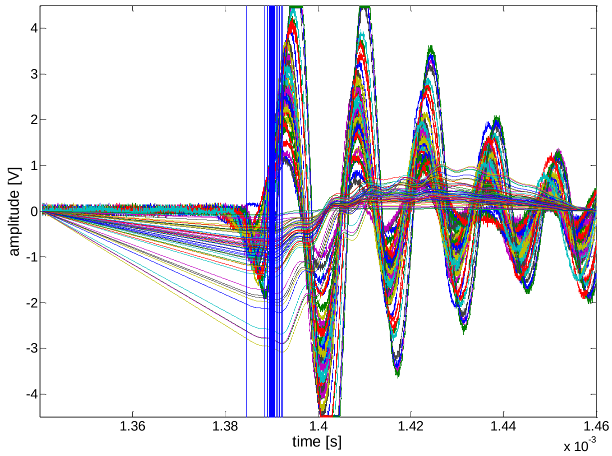

Figure 3: Energy Criterion on 53 acoustic signals

All signal starting points were correctly found in the beginning of the acoustic signal which shows that the minimum in the Energy Criterion marks the beginning of the acoustic signal. For acoustic signals with good SNR, the Energy Criterion is able to determine the signal starting point reliably at the beginning of the signal. For low SNR however, it can be seen that in most cases the Energy Criterion does not determine the signal starting point exactly where the signal amplitude begins to rise or rather fall in this case. The performance of the Energy Criterion can still be improved, especially for signals with low SNR.

5 FACTORS INFLUENCING THE DETERMINATION OF THE SIGNAL STARTING POINT

Since it is very important for the quality of the localization to determine the signal starting point with high accuracy, major parameters influencing the quality of the determination of the signal starting point using the Energy Criterion were investigated.

5.1 Influence of number of averaging sweeps

It was investigated how many averaging sweeps are necessary for the arrival time to be computed with required accuracy resulting in an error in distance of less than 10 cm.

The measurements were performed on: an oil tank (3 m in diameter) with simulated transformer tap changer, two different transformers and a GIS module. Taking the oil tank as an example the number of necessary averaging sweeps depends strongly on the defect type. Two different PD defects were simulated in the oil tank. When the PD were generated by HV protrusion, no averaging was required. For a void in an epoxy material, 120 averaging sweeps became necessary.

As a conclusion for the measurements in four different test setups (only one shown here) it can be stated that in a laboratory environment with little disturbances, 100 to 300 sweeps of averaging are sufficient for a precise recognition of the acoustic signal starting point.

5.2 Different propagation paths of acoustic waves

In most high voltage equipment the acoustic wave propagates through different media (gas, liquid and solid insulation, even metal). It has reflection and attenuation on different points of discontinuity on its propagation path and the direct / shortest path is usually not the fastest way of propagation. The propagation speed of the acoustic waves is different in different materials, e.g. 5920 m/s for longitudinal and 3255 m/s for transverse waves in steel, 343 m/s in air and 1410 m/s in oil, all at 20°C. Therefore it is of great importance to know the shortest propagation path for correct localization.

In power transformers there are two main acoustic propagation paths. One is the direct propagation path, where the acoustic waves propagate from the defect on the shortest way to the sensor. The waves travelling this propagation path wer assumed to travel mainly through oil. Thus the propagation velocity of these waves was assumed to be equal to the propagation velocity in oil.

The second typical way is the shortest way, or almost the shortest way in a certain angle depending on the propagation velocities, from the PD defect to the housing of the transformer. In this case the wave travels as a solid borne wave substantially faster through the metallic housing. For some materials, metal for instance, there are two ways of propagation, the longitudinal and the transverse waves. Usually the acoustic waves travelling this mixed propagation path are faster, while the acoustic waves travelling the direct way arrive later at the sensor. It is of major interest to know the length of time of the propagation on the direct way, since the calculation of the distance with mixed propagation paths is only possible if the exact construction of the device under test is known.

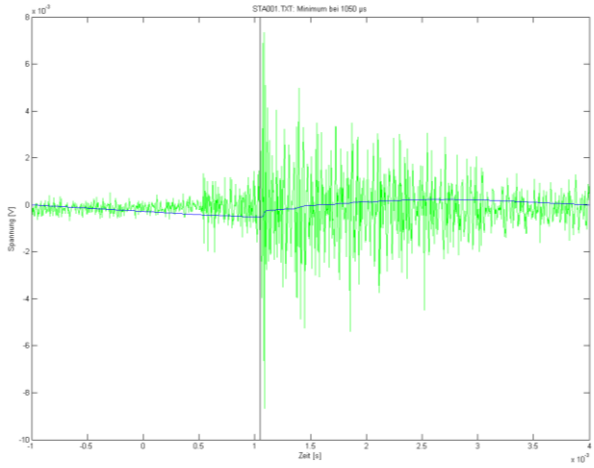

Figure 4: Averaged acoustic signal in 4.5 MVA transformer

Figure 4 shows an averaged acoustic signal, measured on a 4.5 MVA transformer. The PD originated from humidity in the transformer insulation. Two parts of the signal can be recognized. In the beginning, the signal has a smaller signal amplitude and later the signal amplitude rises suddenly. These two parts of the signal can be allocated to the fastest and to the direct propagation path. If the arrival time of the first part of the signal would be taken, and error in the calculated distance of about 70 cm would occur. Therefore it is important to distinguish the arrival time of the direct propagation path from the acoustic signal.

5.3 Angle of incidence

Previous tests, that are not described in this paper, indicated that the angle of incidence of the acoustic wave on the acoustic sensor influences the frequency spectra and thus the shape of the recorded acoustic signals. Thus a setup was built to examine this behaviour.

A sensor was placed on a rotating axis and measurements were recorded while the sensor was rotated from -80° to +80° with respect to the acoustic signal path. In figure 5 the acoustic signals for all measured angels of incidence are presented. It is shown that the signals vary a lot depending on the angle of incidence. It can also be seen, that the signal shapes are symmetrical depending on the angle of incidence. That means the signal with +35° angle of incidence looks similar to the signal with -35° angle of incidence, and so on. This was expected since the setup is also symmetrical.

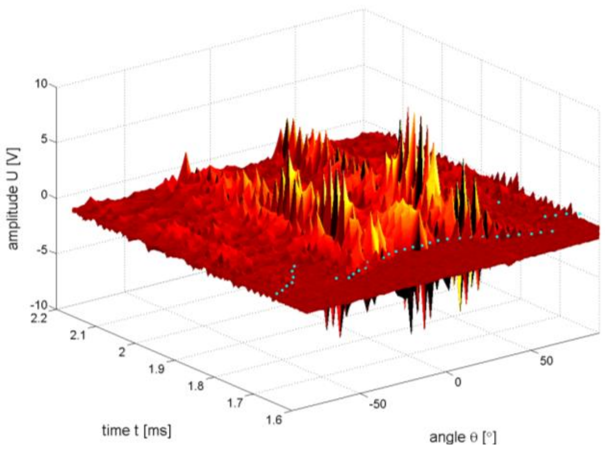

Figure 5: Acoustic signal with different angles of incidence

The signal starting point changes significantly with changing angles of incidence (blue points). In this setup the maximum difference between the recognized signal starting points is 158 µs, which results in a change in the computed distance of about 22 cm.

5.4 Bandwidth filtering

Filtering is a commonly accepted tool for improving the SNR. The measuring chain itself behaves like a filter due to its limited bandwidth or resonant behaviour. Therefore the influence of filtering on the determination of the signal starting point was investigated.

An acoustic PD signal was taken as a reference and various bandwidth filters were applied to this signal. A narrow band filter with gradually shifted centre frequency and with a bandwidth of 4 kHz was used. Figures 6 and 7 show typical signals for two applied centre frequencies, f_c = 15.5 kHz and f_c = 19.5 kHz. In both figures in the upper part the time domain and in the lower part the frequency domain is shown.

The upper part of the signal (blue colour) is the original acoustic signal. In the same colour the frequency spectrum of this signal is printed in the lower parts of figure 6 and 7. The green curve in the lower part is the filter window and the frequency spectrum of the filtered signal is drawn in red. The time domain of the bandwidth filtered signal is shown by a green curve in the upper part of the figures. There also the calculated Energy Criterion Curve for the filtered (green) signal is drawn in red. The vertical red line marks the starting point of the signal calculated by the Energy Criterion.

It can be seen that even in this example the recognized signal starting point shifts about 1.3 µs, which results in a change in the computed distance of about 18 cm. That means filtering the signal has a big influence on the determination of the signal starting point.

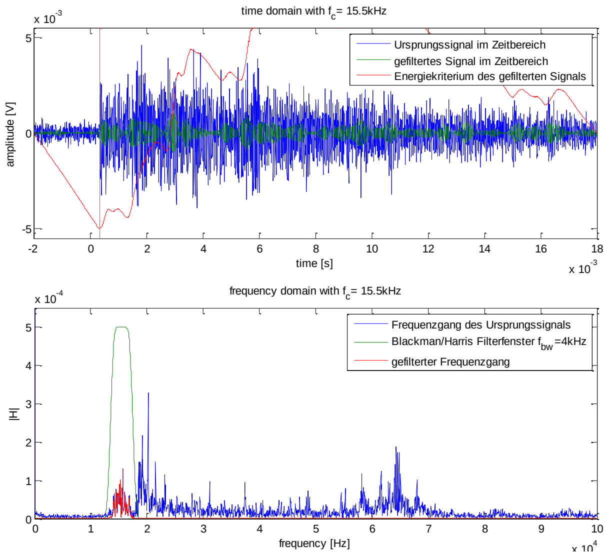

Figure 6: Acoustic signal and its frequency spectrum with applied bandwidth filter f_c = 15.5 kHz

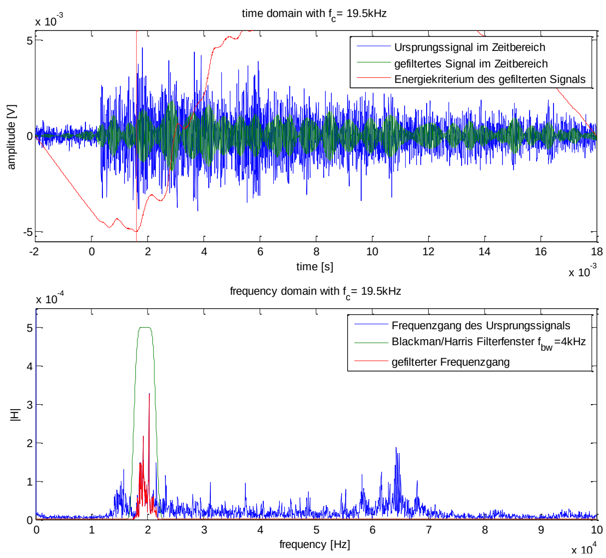

Figure 7: Acoustic signal and its frequency spectrum with applied bandwidth filter f_c = 19.5 kHz

As a second example the influence of the bandwidth on the determination of the signal starting point is shown. Acoustic sensors were placed in a rectangular grid in 80 positions on a test object. For a known PD defect position the acoustic signal runtimes to all 80 sensors can be calculated.

A map with the calculated acoustic signal runtimes is presented in figure 8. The x and y-axis show the coordinates of the sensor grid. The colour indicates the signal runtime. Here the shortest signal runtime shows the defect position. This means the defect is located where the colour is the darkest blue.

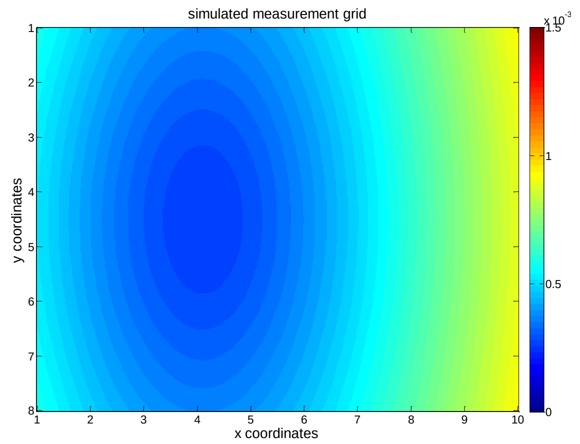

Figure 8: Calculated map for acoustic signal runtimes

The same maps were built from the signals measured in every point in the grid. These signals were filtered with filters of different bandwidths. As an example the maps for a filter centre frequency of 20 kHz and the bandwidths 0.1 kHz, 4 kHz, 12 kHz and 28 kHz are shown in figure 9.

None of these maps matches the simulated map exactly but the maps with smaller filter bandwidths show a strong divergence from the simulated maps. For acoustic signals filtered with a narrow band filter the recognized signal starting points vary a lot from the calculated actual signal starting points. From these maps it is not possible to determine the correct PD location.

In the map with 0.1 kHz bandwidth the differences between the simulated and the measured signal runtimes were up to about 125 µs, which results in a change of the computed distance of about 17.6 cm. The wider the filter bandwidth the more the maps of the filtered signals matched the simulated map. The map with a filter bandwidth of 28 kHz has a good correlation with the simulated one.

6 LOCALIZATION ALGORITHMS

Five localization algorithms were implemented and tested. Four algorithms by Bancroft, Kleusenberg, Abel, Wiline are described in [5-8]. The fifth algorithm (Dual) is a further development based on the other algorithms. All 5 algorithms were based on the GPS-like equations and needed four acoustic sensors and an electric trigger signal.

The algorithms Bancroft, Kleusenberg and Wiline calculate two different defect locations for each combination of acoustic sensors. The algorithms Bancroft and Kleusenberg give exactly the same results. The results given by the Wiline algorithm differ a little bit from the results given by Bancroft and Kleusenberg. The main disadvantage of these three algorithms is the inability to distinguish the

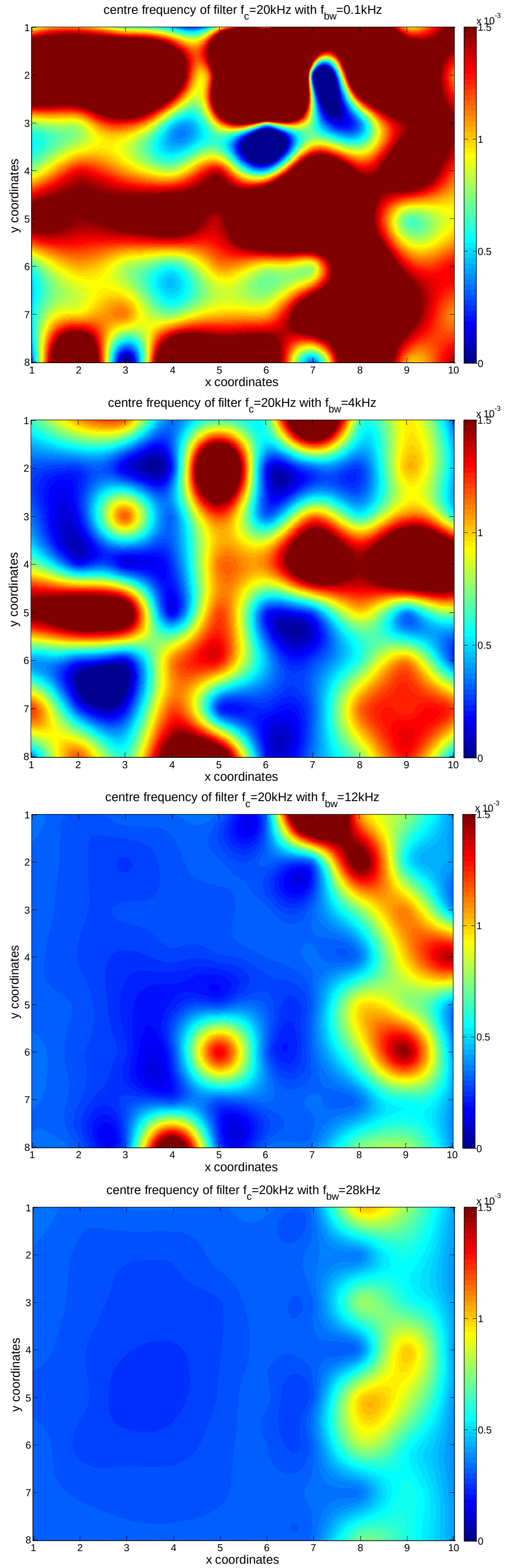

Figure 9: Maps of filtered signals for 20 kHz centre frequency and bandwidth (top to bottom) of 0.1 kHz, 4 kHz, 12 kHz and 28 kHz

right location out of the two results. The algorithms Abel and Dual calculate only one defect location per combination of acoustic sensors.

In all tests the 5 localization algorithms gave almost equally good results. At least one solution was found within a 10 cm sphere around the defect location.

The influence of the chosen sensor positions was researched. It was found that the algorithms Bancroft and Kleusenberg are most independent of the sensor positions. The other three researched algorithms do not lead to any results if all sensors are placed in one plane. At least two different tank walls should be used when positioning the sensors.

7 CONCLUSION

As concerning the determination of the signal starting point:

- For automatic detection of the signal starting point the Energy Criterion was chosen.
- The number of steps taken for the averaging process of the acoustic signal influences the determined signal starting point. In an environment with little disturbances 100 to 300 sweeps of averaging are sufficient for a precise recognition of the acoustic signal starting point.
- Different propagation paths can influence the determination of the signal starting point.
- The angle of incidence of the acoustic signal waves also leads to differently recognized signal starting points. In the presented example differences in the recognition of the signal starting point of up to 158 µs were found.
- Concerning bandwidth filtering it was found that narrow band filters lead to high differences between the computed and the real signal runtimes. With broader bandwidth the differences get smaller.

As concerning the localization algorithms:

- Five localization algorithms (including the new developed on) based on the GPS-like equations were implemented. First tests lead to promising localization results with errors in the determination of the PD location of less than 10 cm.
- Algorithms by Bancroft, Kleusenberg and Wiline gave two localization results for each PD location, while Abel and Dual gave one localization result.
- The localization results given by Bancroft and Kleusenberg are less depended on the positioning of the sensors.

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