Comparison of Approximate and Simple Location Methods for AE-Sources on Dished Heads

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Abstract. Artificial AE-sources of type Hsu-Nielsen on a semi elliptical head according to DIN 28013 were located using a planar location algorithm and an azimuthal equidistant- as well as an orthographic projection of AE-sensor's mounting positions. These projections introduce distortion of distances from Hsu-Nielsen source position to mounting positions of AE-sensors. Distortions of distances are responsible for deviations of location results from actual source positions. In the course of gathering experimental data it could not be avoided that some measurement channels triggered on *S*0- while others triggered on *A*0-wave mode. This mismatch of using a speed of sound in the location algorithm that did not reflect the speed of sound of the wave front that triggered arrival time measurement introduced an even larger deviation than the distortion of distances. Controlling arrival time measurement turns out to be more important than reducing the distortion of distances due to a planar approximation. An equidistant projection delivered more reliable location results than an orthographic projection after arrival time measurement was tuned to A0 wave mode. This can be attributed to the overall small distortion of distances on the semi elliptical head due to an equidistant projection onto a plane.

1. Introduction

Locating Acoustic Emission (AE) sources is an important task of an AE-data analysis [1]. Point location algorithms based on arrival time measurement can deliver accurate information about a source's position. A number of analytical and iterative point location algorithms are available for planar surfaces such as a plane, cylinder or cone [2, 3]. A planar surface is any surface that can be unrolled onto a plane without distortion.

Often one is confronted with curved surfaces such as a dished head when testing pressure vessels. The surface of a dished head cannot be unrolled onto a plane without distortion. A dedicated point location algorithm for curved surfaces is not available that delivers location results online. One may note that a sphere is the only exception to this statement.

The author showed in a previous publication [4] that for spherical heads a planar approximation of the location problem of AE-sources on the head delivers reliable results if the distortion of distances between AE-source and AE-sensors is small. A distortion arises when a distance on the sphere is projected onto a plane leading to a shortening or lengthening of the projected distance. Especially for azimuthal projections a planar location algorithm delivers results with small deviations close to the osculation point of the projection.

In this publication artificial AE-sources on a semi elliptical head according to DIN 28013 are investigated. It will be examined if a planar location algorithm delivers reliable location results for AE-sources on a dished head. A location result is considered reliable if deviation from actual AE-source position is small and if events of an AE-source are located with small spread, i.e. events of an AE-source form a cluster.

2. Location on Curved Surfaces

Being able to calculate the shortest distance between two points is the key to any analytical or iterative point location algorithm. Planar surfaces are subject to Euclidean metric and the distance between two points, given by their x_i, y_i co-ordinate tuple, can be calculated by using the Pythagorean formula. On curved surfaces the Euclidean metric is no longer valid. The geodesic problem of finding the shortest distance between two points is not trivial. There are solutions to the geodesic problem applied to AE-data shown by Kus [5] and Prasanna [6]. These solutions do not qualify for online analysis because the geodesic problem cannot be solved in a timely way.

In some cases it may not be necessary to solve the geodesic problem in order to get an accurate location of AE-sources. For one thing it may be sufficient to distinguish between active AE-sources. A location algorithm may just do that because it interprets arrival time patterns and assigns locations to it. As long as the arrival time patterns are similar, the same location will be produced by the location algorithm. It may be true that this location is afflicted with a large deviation but for the task of distinguishing active AE-sources this does not matter. For other reasons, one may be interested just in rough location results. Choosing a suitable approximation for the AE-source location problem can deliver useful results in this case

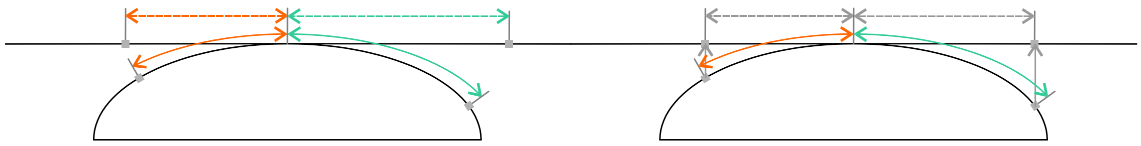

Fig. 1 depicts a schematic of an equidistant- (left hand side) and orthographic projection (right hand side) of a semi elliptical head onto a plane.

For a semi elliptical head according to DIN 28013 a simple planar approximation using an azimuthal equidistant- and orthographic projection is applied to demonstrate the effectiveness of this procedure. Properties of such projections are described in [7]. The schematic in figure 1 briefly outlines the idea behind such a projection. The most important characteristic of a projection in case of locating AE-sources is the distortion of distances. An azimuthal equidistant projection does not distort radial distances while it stretches longitudinal distances. It follows that distances measured in an equidistant projection will be overestimated, i.e. they will be generally larger than on the curved surface. An azimuthal orthographic projection conserves longitudinal distances but shortens radial distances. As a result distances in an orthographic projection are generally underestimated.

3. Measurement Setup

The test object was a pressure vessel with a capacity of 50m³. Data for evaluation was gathered on a semi ellipsoidal head according to DIN 28013. The diameter of the hull was

3000mm with thickness of 16mm. An equidistant projection of the dished head is shown in figure 2. The cross section of the dished head is shown in figure 3

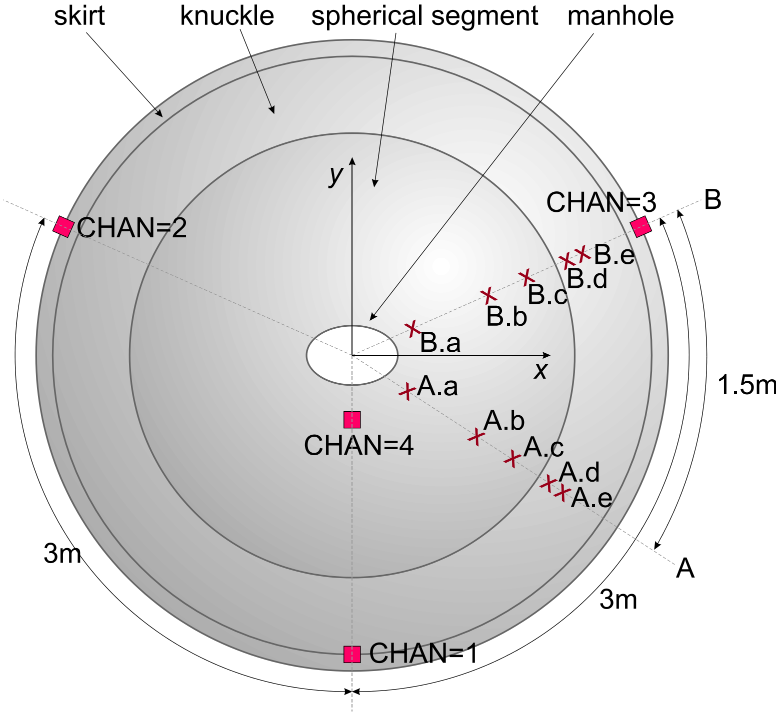

Fig. 2 shows a schematic drawing of dished head in azimuthal equidistant projection. Elements of semi elliptical head are indicated as skirt, knuckle and spherical segment. Manhole in the centre was elliptical. Line *A*, line *B* and positions of Hsu Nielsen sources from *a* to *e* on each line are indicated.

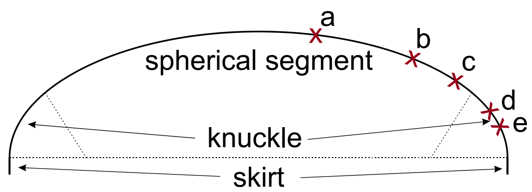

Fig. 3 shows the semi elliptical head in a cross section. Elements of a semi elliptical head as well as approximate source positions in this cross section are indicated

Four AE-sensors were mounted on the dished head. The position of three AE-sensors was on the circumference at almost equal distances from each other. The fourth AE-sensor was mounted close to a manhole that was located at the centre of the dished head. Mounting positions of AE-sensors for channel 2 and 3 were at the end of the dished head's skirt, whereby the skirt length was 100mm (see fig. 2). AE-sensor type was VS150-RIC, a sensor with an integral preamplifier and resonance frequency at 150kHz.

Artificial AE-sources have been used to stimulate elastic waves. Artificial sources were of type Hsu-Nielsen with 0.5mm, 2H lead. Hsu-Nielsen sources have been placed along two virtual lines, labelled *A* and *B* in fig. 2. Line *A* is the intersection of the semi elliptical head and a plane bisecting the hull between position of AE-sensor 1 and 3. Line *B* connects centre of dished head with position of AE-sensor 3. Hsu-Nielsen sources were located at approximately 420mm, 920mm, 1220mm, 1520mm and 1620mm distance from centre of dished head (see fig. 2).

Data was acquired with an AMSY-6 in the frequency range from 95kHz to 850kHz. Threshold for data acquisition was determined based on peak noise measured during a noise test. It was set to 40dB$_{AE}$.

Mounting position of an AE-sensor was characterised by polar co-ordinates: radial distance r and longitude λ. An equidistant- and orthographic projection were used to convert the polar co-ordinates into Cartesian co-ordinates x and y. Since the mounting position of two AE-sensors was at the end of the skirt, skirt length of 100mm was also considered in the equidistant projection. The projected Cartesian co-ordinates of mounting positions of AE-sensors were used in the planar location algorithm.

Locations were calculated using the planar Simplex algorithm [3] as it is implemented in the Vallen AE-Suite software version of R2014.0414.1. Except for the speed of sound factory default settings were used for remaining setup parameters of the event-set building and location algorithm. The speed of sound was set to 3200m/s. This value was confirmed by an independent measurement on the cylindrical hull of the pressure vessel.

A clustering algorithm was applied to the location results. It shall cluster individual located events of Hsu-Nielsen sources at a certain position. Cluster size was 25cm².

4. Results

It turns out that 95kHz to 105kHz component of *S*0 wave mode caused first threshold crossing in channels 1, 3 and 4 for all burst signals of sources on lines *A* and *B*. Only channel 2 was triggered by *A*0 wave mode in case of sources on line *A* and by *S*0 wave mode for sources on line *B*. The speed of the *S*0 wave mode varies a lot in the frequency range of 100kHz to 300kHz (see fig. 4) and therefore arrival time measurement based on *S*0 wave mode is unfit for use in a location algorithm. Even worse is the case when different wave modes trigger arrival time measurement for individual hits of an event. This was the case for Hsu-Nielsen sources on line *A*. Taking into account the dispersion diagram in figure 4 the arrival time measurement should be based on arrival of *A*0 wave mode. Using the *A*0 wave mode for arrival time measurement has two big advantages: (i) its speed of sound in the frequency range of interest is nearly constant; (ii) its rise time is extremely short which allows determining arrival of it very exactly even if AE-source strength varies a lot.

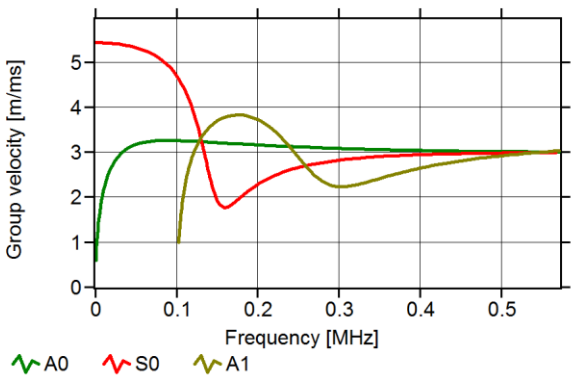

Fig. 4 shows a dispersion diagram of plate waves in 16mm steel plate. Depicted is speed of sound distribution for *S*0-, *A*0- and *A*1 wave mode

*A*0 arrival time has been determined for each burst signal per channel and event in an automated post analysis process considering transient recorder data. Results of it were fed into the location algorithm. This procedure should eliminate or at least substantially decrease a deviation of location results that is caused by using the wrong speed of sound in the location algorithm for the wave front that triggered arrival time measurement. The result of this analysis is shown in figure 5 and figure 6 when mounting positions of AE-sensors are projected equidistant and orthographic onto a plane, respectively. "Expected" location results indicate the position of Hsu-Nielsen sources in the projection. "Original" location result refers to the output of the location algorithm using arrival times of raw data. "Improved" location labels the output of the location algorithm when using arrival time of the *A*0 wave mode only. Location results depicted in figure 5 and figure 6 refer to an average of *x*- and *y* co-ordinate of up to 10 events.

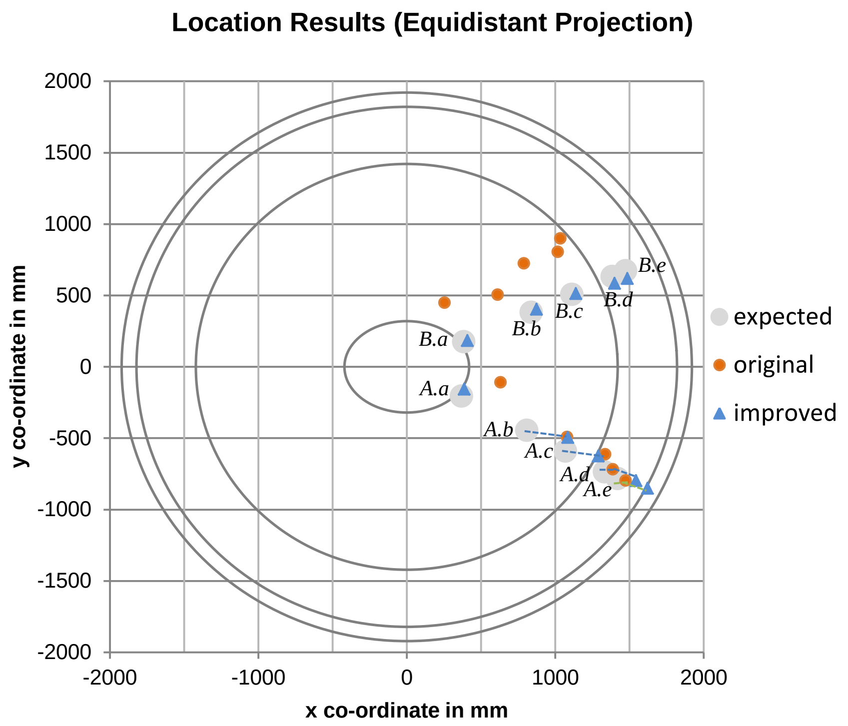

Fig. 5: diagram with expected-, original- and improved location results. For more clarity dashed lines have been added, that connect location results belonging to the same Hsu-Nielsen source position.

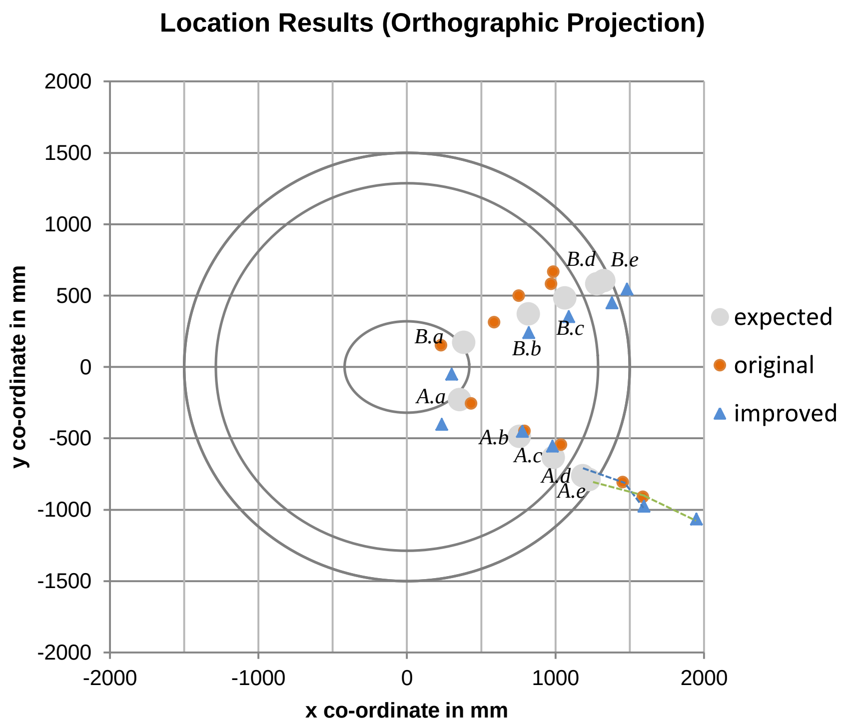

Fig. 6 diagram with expected-, original-, and improved location results. For more clarity dashed lines have been added, that connect location results belonging to the same Hsu-Nielsen source position.

In case of an equidistant projection (see fig. 5) it is obvious that location results labelled original deviate from expected source positions except for sources *A.d* and *A.e* in the knuckle region of line *A*. Improved location results correspond well with Hsu-Nielsen positions on line *B* in case of an equidistant projection. For an orthographic projection (see fig. 6) original location data deviates quite a lot from expected source positions except for Hsu-Nielsen sources *A.b* and *A.c* in the spherical region of the dished head. Improved location results show a similar deviation as original location results. Only sources *A.b* and *A.c* correspond well with actual source positions.

Deviation from expected location of Hsu-Nielsen sources can be expressed as deviation in radial distance and deviation in longitude referring to the origin of the used co-ordinate system. Using a polar co-ordinate system has the advantage that deviation results do not suffer from a distortion because of the mapping onto a plane. While the equidistant projection conserves radial distances and the longitude an orthographic projection just conserves longitude but shortens radial distances, especially in the knuckle region.

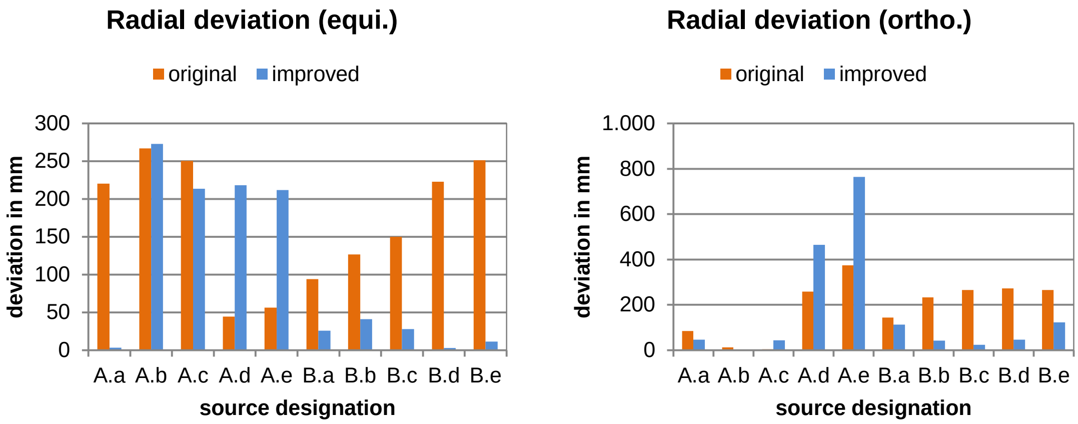

Fig. 7: radial deviation for equidistant- (left hand side) and orthographic (right hand side) projection.

The radial deviation of original and improved location results is shown in figure 7 for equidistant- and orthographic projection. In case of an equidistant projection improved location results on line *B* exhibit a substantial smaller deviation than original location data. The deviation of location results for sources on line *A* is mixed. Source designated *A.a* was located with very small deviation. As Hsu-Nielsen sources tend outward the deviation in radial distance becomes larger, even exceeding the deviation of original results by a factor of 4 in case of sources *A.d* and *A.e* in the knuckle region. The maximum radial deviation is 273mm, the minimum 3mm, the average 103±35mm. With a largest distance of 3520mm between mounting positions of two AE-sensors, the average deviation is about 3% of this distance. For comparison, the average deviation of original location results is 168±27mm. A similar behaviour can be observed for the radial deviation when an orthographic projection is applied. The difference between both projections is that absolute deviations are generally larger for the orthographic projection than for the equidistant projection. Again the largest deviations are observed for sources *A.d* and *A.e* in the knuckle region. A similar analysis can be done for deviation in longitude but the Simplex algorithm is very good in determining the direction. While there is some deviation compared to expected results it appears that original and improved location results line up well.

Location results generally deviate from actual source positions. Causes for a deviation can be: (a) inaccurate measurement of sensor mounting positions and Hsu-Nielsen source positions; (b) using a speed of sound for location calculation that does not match the speed of sound of the wave front that triggered arrival time measurement; (c) inappropriate approximation of dished head geometry by a plane inside the location algorithm.

The contribution of an inaccurate measurement of distances is estimated to be 20mm in radial direction. Longitude is measured as arc length on the circumference. In this case an error of 20mm is estimated as well. Under such assumption a longitudinal deviation accounts for 0.013rad. This means that determination of AE-sensor mounting positions and Hsu-Nielsen positions are afflicted with a deviation of 20mm and 0.013rad in radial and longitudinal direction, respectively.

Location results labelled original in figures 5 and 6 contain all three sources of deviation. For location results labelled improved the contribution of source (b) has been eliminated or at least substantially decreased. Based on the estimation of deviation of inaccurate distance measurement the remaining two contributions to a deviation can be assessed. This procedure is just an approximation since the weighting factors of each deviation source are unknown. In principle but being rather complex, the weighting factors of sources (a) and (b) can be determined based on how the Simplex algorithm works but weighting factor of source (c) cannot be determined at all but has to be estimated. For sake of simplicity, weighting factors are approximated by 1. The result of this assessment is shown in figure 9. Label "operator" indicates the deviation introduced by the operator when measuring the mounting positions of AE-sensors and Hsu-Nielsen sources. Label "wrong c" indicates the contribution to overall deviation when the speed of sound used in the location algorithm does not correspond to the speed of sound that triggered arrival time measurement. Finally "algorithm" indicates the contribution to deviation that is caused by using a planar location algorithm for locating AE-sources on the curved surface of the dished head. The last column in each plot is a sum over each deviation contribution for all AE-sources that have been considered.

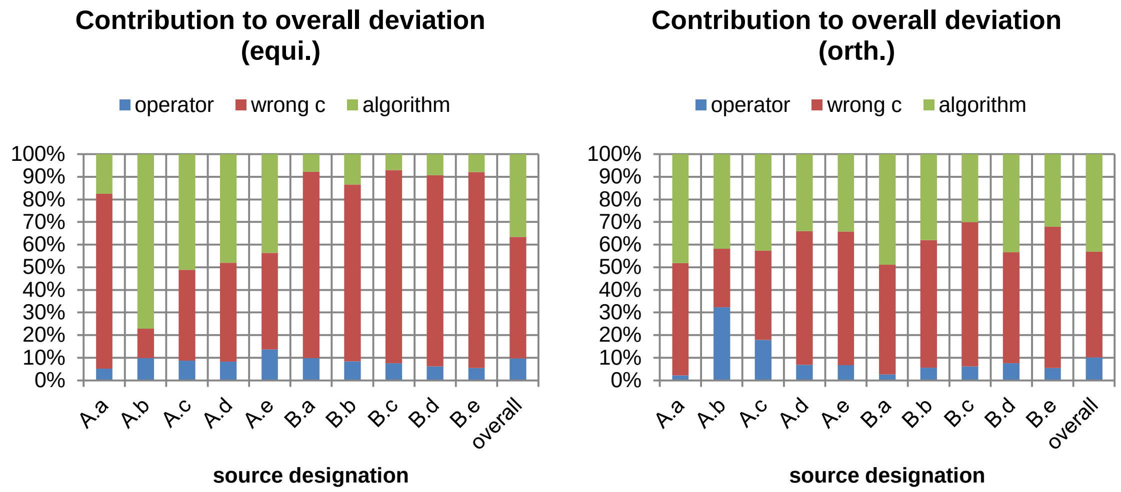

Fig. 9 shows how the overall deviation is divided into the individual contributions inaccurate measurement of distances ("operator"), using arrival time that does not reflect the speed of sound used in location algorithm ("wrong c") and inappropriate approximation of dished head ("algorithm").

Considering location results for sources *A.d* and *A.e* in case of the equidistant projection shows that original results are afflicted with less deviation than improved results. It is just by coincidence that individual deviation contributions did not add up but almost cancelled each other out in case of these two sources in the knuckle region. Reducing one error leads to an increased deviation because the other errors were not balanced any more. However this should not be an argument against arrival time correction, because form a physical point of view the location calculation was based on wrong assumptions about the speed of sound and distances.

Up to now deviations of cluster centres have been evaluated. Inter cluster spread that is the spread of individual location results in a cluster is an indication of how sensitive a location algorithm reacts to sources of deviation. The intra cluster spread is a measure of how well a certain arrival time pattern is located at the same position by a location algorithm. Figure 10 shows that the intra cluster spread is reduced for all improved location results but one located on line *A* in the knuckle region (designated *A.d*).

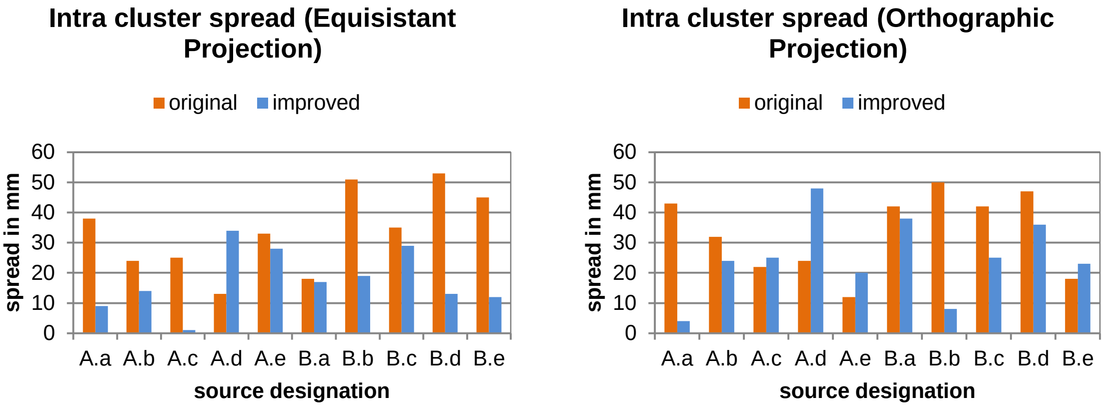

Fig. 10 shows intra cluster spread of original- and improved location data.

4. Discussion of Results

One remarkable result is that in case of the equidistant projection improved location results for Hsu-Nielsen sources on line *B* are afflicted with less deviation than the ones for sources on line *A*. The reason for location results on line *B* being better than on line *A* is related to the distortion introduced by the projection. The distances to AE-sensor mounting positions are less distorted for Hsu-Nielsen sources on line *B* than on line *A*. Comparing original- to improved data of Hsu-Nielsen sources on line *B* indicates that a large error is introduced if speed of sound used in the location processor does not match the speed of sound of the wave front which triggered arrival time measurement. Considering location results of Hsu-Nielsen sources on line *A* indicates that when distortions of distances because of a projection increase, the location algorithm reflects that with a larger deviation from expected results. Conclusion of this observation is that for Hsu-Nielsen sources located on line *B*, the largest contribution to a deviation is because of using the wrong arrival time in the location algorithm. Distortion of distances is small in this case and as a result improved location results correspond well with expected locations. Contrary are location results for Hsu-Nielsen sources of line *A*. In this case improved location results are not necessarily the ones with smaller deviation. While arrival time measurement matches the speed of sound used in the location processor the distances from Hsu-Nielsen source- to mounting position of AE-sensors are largely distorted.

Location results for sources in the knuckle region generally show a larger deviation than location results in the spherical region of the dished head. Reason is that for these sources a large part of the propagation path to mounting position of AE-sensor 1 and 3 is across the skirt. Paths across the skirt are highly distorted by both projections. The distortion of the skirt is much larger than distortion of knuckle- and spherical region. With the measured arrival time and the distorted path lengths the location results tend outward of the AE-sensor perimeter.

In general arrival time measurement deviations have a bigger impact in case of the equidistant projection of AE-sensor mounting positions than the planar approximation made by the location algorithm (see last column in figure 9).

Intra cluster spread is a measure of how well a similar arrival time pattern is interpreted with the same location result. This property is important if one is more interested in distinguishing individual AE-sources from each other than in accurate location. Intra cluster spread is generally decreased by applying the equidistant projection. Only in one case of a Hsu-Nielsen source in the knuckle region is the intra cluster spread of improved location results larger than original location results. Intra cluster spread of clusters in orthographic projection does not show a clear tendency as in case of the equidistant projection. While in some cases the intra cluster spread of improved results increase, the inter cluster distance increases as well. For all clusters in the orthographic projection the inter cluster distance increase outweighs the increase in intra cluster spread. This means that cluster centres are farther apart from each other and can be resolved well.

5. Conclusion

The reliability of location results is chosen as basis for valuation of approximate location procedures. As defined in the introduction, a location result is considered reliable if deviation from actual AE-source position is small and if events of an AE-source are located with small intra cluster spread. Improving arrival time measurement leads to location results that generally deviate less from actual source positions than location results based on original data. Whether an average radial deviation of 103±35mm (3% of largest distance between mounting positions of AE-sensors) is considered small may be a subjective judgment of an operator. The author tends to attach greater importance to the fact that individual events form cluster very well than to an absolute deviation. In the light of this improved location results derived by an equidistant projection are considered reliable in the sense of the definition above. However, it became also evident that a large distortion of distances because of a projection leads to large deviations in absolute position. The intra cluster spread however, did not change remarkably. This means that the location algorithm interprets similar arrival time patterns very stable with the same location. Therefore a procedure of approximating the semi elliptical head by a plane should not be neglected a priori because it is unfit to remove all deviations.

The most important factor for producing reliable location data is related to arrival time measurement and if the correct speed of sound is used in the location algorithm. Any mismatch between speed of sound of wave front that triggers arrival time measurement and speed of sound used in location processor leads to large deviations in location results. Accuracy and reliability of location results can be greatly increased if all AE-channels trigger on the same wave mode. Recommended is to use the wave mode which speed of sound is nearly constant in the frequency range of interest.

For increasing reliability of location results, distortion of distances should be decreased where possible. Therefore AE-sensors on the circumference of the dished head should be mounted on the skirt right at the transitions zone of skirt to knuckle region. Then overall distortion of propagation paths are reduced because elastic waves do not have to transverse the skirt before being picked up by AE-sensors.

Results indicate that in some cases a more exact approximation of the curved surface will lead to more reliable location results. Adapting a metric for dished heads will help to minimize the contribution of the inappropriate approximation by a plane to the total deviation. It may not be necessary to rigorously solve the geodesic problem on the dished head but to approximate the dished head by a semi elliptical surface of best fit.

With given tools of planar location and equidistant projection of the dished head, increasing the number of AE-sensors on the circumference could help increasing the accuracy of location results. Reason for this is that only these AE-sensors should contribute their arrival time to a location algorithm that show the least distortion of distance to the AE-source. Such AE-sensor triplets can be found more easily when a lot of AE-sensors are available.

Finally one may note that Hsu-Nielsen sources are high energetic sources. In this investigation the *S*0 wave mode carried enough energy to cause threshold crossings in up to 2500mm distance when threshold is set to $40dB_{AE}$. Plastic deformation- or crack propagation sources usually emit less energy and arrival time measurement is most often triggered by the *A*0 wave mode which somehow should relieve the issue of using the wrong speed of sound in the location algorithm. However, the practice of confirming location results by Hsu-Nielsen sources should account for this fact, otherwise Hsu-Nielsen sources will deviate quite much from actual AE-source position.

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