Fusion Concepts for Multistatic Sonar Systems

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Abstract: Multistatic sonar operation provides some well-known advantages compared to monostatic operation like enlarged detection areas and increased probability of detection. In order to gain the maximal profit from the information of different sources highly sophisticated fusion algorithms have been developed during the last years. Furthermore, today's processing power allows the application of modern algorithms in real time.

In the literature there are two general concepts for data fusion. One concept is the decentralised fusion, where each sensor has its own tracking system and the fusion of the data is performed on track basis. Another approach is the centralised fusion, where the contacts of all sensors are processed in a common tracker.

From the theoretical point of view the centralised fusion can provide the optimal performance concerning track stability and accuracy of the estimated target kinematics. However, in some applications the decentralised tracking is preferable, e.g. to overcome systematic measurement errors.

In this presentation evaluations of datasets recorded by two completely different sensor systems are shown. It turns out that each of these sensor systems requires its individual fusion concept.

1 Introduction

The performance potential of multistatic sonar operation has been investigated by several research institutes and proven in numerous international sea trials during the last years. The characteristics of multistatic sonar operation are the use of one or more spatially separated transmitters and receivers, the exchange of the contact or track information as well as the appropriate combination of all available data in order to optimise the detection and localisation performance.

erschienen im Tagungsband der INFORMATIK 2011
Lecture Notes in Informatics, Band P192
ISBN 978-3-88579-286-4
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http://informatik2011.de/519.html

One of the most important advantages of multistatic systems is the increased detection area in comparison to monostatic systems. Another important feature of multistatic systems is the growth of detection opportunity due to the diversity of available sound sources and pulse forms. The probability that a target will be detected increases with the number of sonar systems involved because every system faces a different target strength, reverberation, and noise situation. This property of multistatic systems improves system track holding. Gaps in the detection sequence of one sensor may be filled with detections of other sensors. Multistatic systems usually consist of bistatic detection geometries which have the additional advantage that targets can not choose an optimal course to reduce their target strength, since the targets usually can not be aware of the receiving position of the bistatic system. A target not knowing the receiver position may even not recognise that it is detected.

To draw the maximum profit from these advantages, it is necessary to combine all the information available from different sources, sensors and signals into a unified general view of the underwater situation. Therefore, highly sophisticated fusion algorithms have been developed during the last years. Furthermore, today’s processing power allows the application of modern algorithms in real time.

2 Fusion Concepts

There are two generally different concepts for the fusion of contact data from different sensors: centralised and decentralised fusion. In the first approach the contacts of all sensors are transmitted to a common tracking system and tracks are created from all available data. From the theoretical point of view this fusion concept provides the optimal performance with respect to the accuracy of the estimated target kinematics and track stability. Even weak targets, which can not be tracked by a single sensor alone (e.g. due to many detection losses), may be tracked by using the data of several sensors in combination with a centralised fusion system.

In the second approach each sensor is equipped with its own tracking system in order to create tracks from the respective sensor data. The sensor tracks are then transmitted to a fusion centre, where the data fusion is performed on track basis. An important advantage of this fusion concept is its enhanced robustness against systematic measurement errors. One origin of these errors can be compass misalignments. Furthermore, unrecognised failures in single sensors cannot degrade the complete system. Less data transfer is necessary because the number of tracks is usually lower than the total number of contacts. As this concept is more robust and the integration of additional sensors is straightforward, this concept is often preferred in operational systems.

Since each of the fusion concepts has its advantages and disadvantages none of them performs generally better than the other one. Actually, the choice of the preferable tracking approach depends on the sensor layout and the data situation in a specific application.

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In the following sections examples of two different sonar applications will be presented: the simulated Metron dataset [Or09] and the SEABAR'07 sea trial dataset [Eh08]. Both datasets were investigated by the Multistatic Tracking Working Group (MSTWG) which is organised under the auspices of the International Society of Information Fusion (ISIF). The aim of this group is to foster interaction among researchers in sonar and radar multi-sensor tracking, and to compare complementary approaches to fusion and tracking using common datasets. Due to the different nature of the sensor systems being responsible for the two datasets we propose to use two different fusion approaches, too. In order to gain the best performance we favour a decentralised fusion approach for the first dataset and a centralised fusion approach for the second one. In both cases a multiple hypothesis tracker (MHT), which is based mainly on [BP99], was used.

3 SEABAR'07 Dataset

The SEABAR'07 sea trial [Eh08] was a multistatic experiment conducted by the NATO Undersea Research Centre (NURC) on the Malta Plateau, south of Sicily, in October 2007. The experiment included a single source and three receivers. A sequence consisting of a CW and an FM pulse was transmitted at one minute intervals. The target was an echo repeater towed by a NURC research vessel. The geometry of run A01, which is investigated in this paper, is shown in Figure 1. The experiment was situated in a challenging shallow water area, with high levels of reverberation, clutter, and shipping noise.

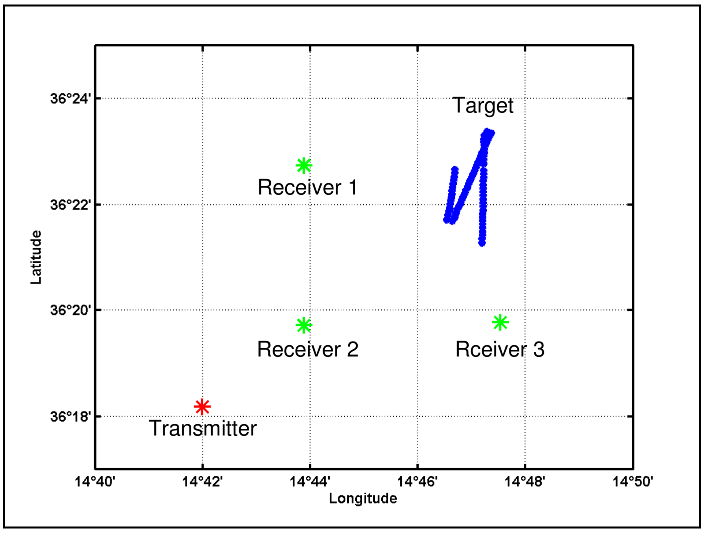

Figure 1: SEABAR geometry for run A01

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ISBN 978-3-88579-286-4
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The target was detected quite well by all of the three receivers, except for some temporal failures as will be shown later. An interesting feature of this dataset is the existence of large systematic errors in the bearing measurements. Although the systematic bearing errors were removed manually after the trials, in this paper the uncorrected data were used since alignment errors are realistic for operational systems and the data fusion system should be able to overcome this problem.

Due to the alignment errors and the temporary failure of single receivers a decentralised fusion concept was chosen in this case. The main advantage of this concept is that the systematic measurement errors affect the performance of the sensor tracker only marginally, and the association of sensor tracks is less sensitive than contact association in a centralised fusion.

The selected fusion concept consists of two stages. At the first stage, sensor tracks are created by the MHT using the CW and FM contacts of each of the receivers separately. The sensor tracks and the corresponding target contacts are passed to the second stage, where the association of the tracks of the different sensors is done by a global nearest neighbour approach (see [BP99]). Finally the estimation of a common target state is accomplished by a Kalman filter, working on the pre-associated contacts of all receivers. By this the estimation of the common target state can be performed in an optimal way as the contacts of the consecutive scans and the different receivers are independent from each other (see [Ch00] for more information).

In Figure 2 an overview of all sensor tracks of the three receivers is shown. An enlargement of the target of interest is shown in Figure 3. On the left hand side, the sensor tracks from the target of receiver 1 (blue), receiver 2 (red) and receiver 3 (green) are shown. The ground truth is marked with black crosses, where the target starts at the upper left corner. It is obvious that due to the systematic bearing errors the different tracks do not match. Furthermore, sensor track 1 exists only for a short time, and also sensor track 3 stops earlier than sensor track 2. In the middle of Figure 3, the fused target track without consideration of the systematic measurement errors is shown. It is visible that the alignment errors are compensated to some extent, as the different systematic bearing errors cancel out each other. However there are still deviations from the true target positions, especially at the end of the track, where only measurements from receiver 2 are available.

In order to overcome the localisation problems caused by the systematic measurement errors the Kalman filter in the second fusion stage was extended to allow for this kind of errors and to estimate the bias errors. It is assumed that the measurements of each sensor are corrupted by independent bearing errors and a common range error. The systematic range error may be caused by an error in the sound velocity which is assumed to be identical for all receivers.

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To estimate these systematic errors, the state vector of the five targets marked in Figure 2, each given by

$$X_n = \begin{bmatrix} x_n & \dot{x}_n & y_n & \dot{y}_n \end{bmatrix}^T$$

and an additional state vector for the systematic error terms

$$F = \begin{bmatrix} \Delta\varphi_1 & \Delta\varphi_2 & \Delta\varphi_3 & \Delta C \end{bmatrix}^T$$

are combined to a common state vector

$$\tilde{X} = \begin{bmatrix} X_1^T & X_2^T & \cdots & X_N^T & F^T \end{bmatrix}^T$$

and a common covariance matrix. By updating this common state vector with the associated measurements in an Extended Kalman filter ([Ge74]) the target states and the measurement errors are estimated simultaneously. The result of this method is displayed on the right hand side of Figure 3. Here, the complete estimated track is very close to the ground truth. Figure 4 shows the estimated bearing errors (blue) for the three receivers, in comparison to the mean bearing errors estimated after the trial (red). The lower right picture shows the estimated range error resulting from the imprecisely estimated sound velocity.

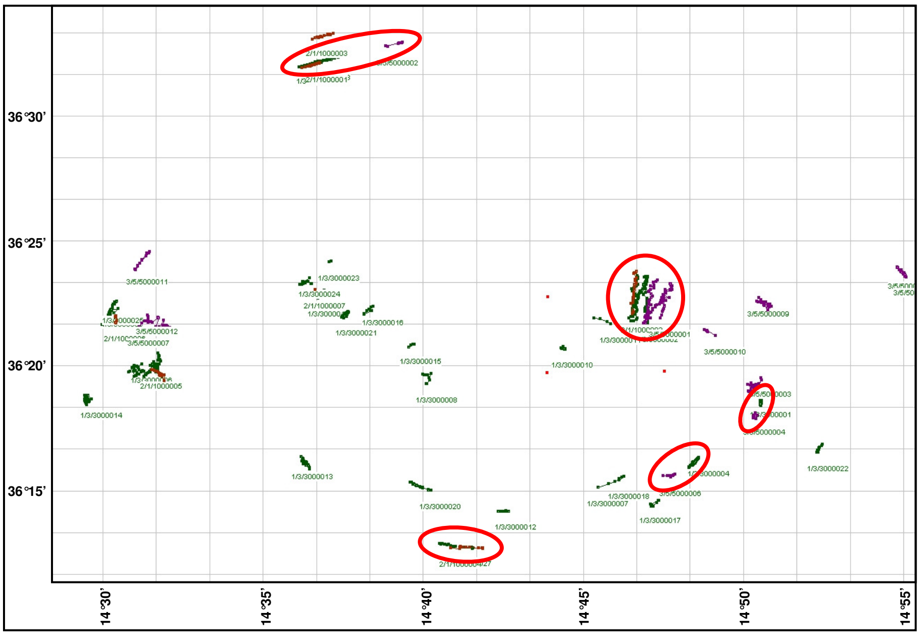

Figure 2: Overview of all sensor tracks

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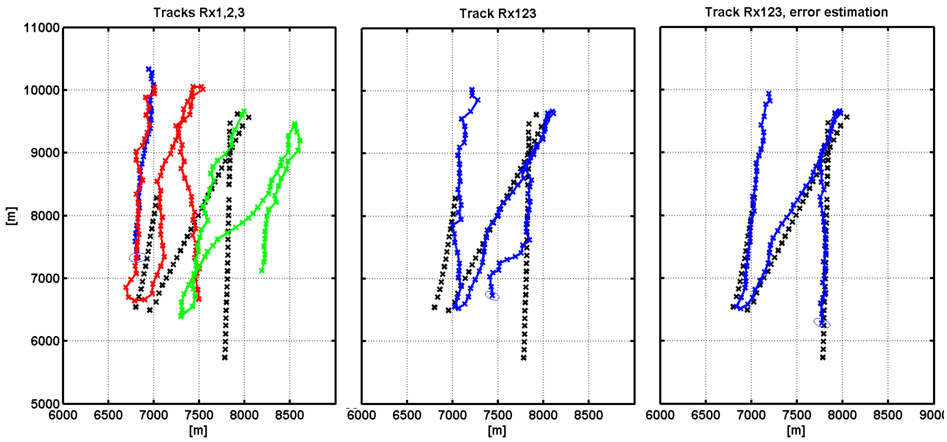

Figure 3: Results for the SEABAR data, sensor tracks (left) and fused track without (middle) and with error estimation (right)

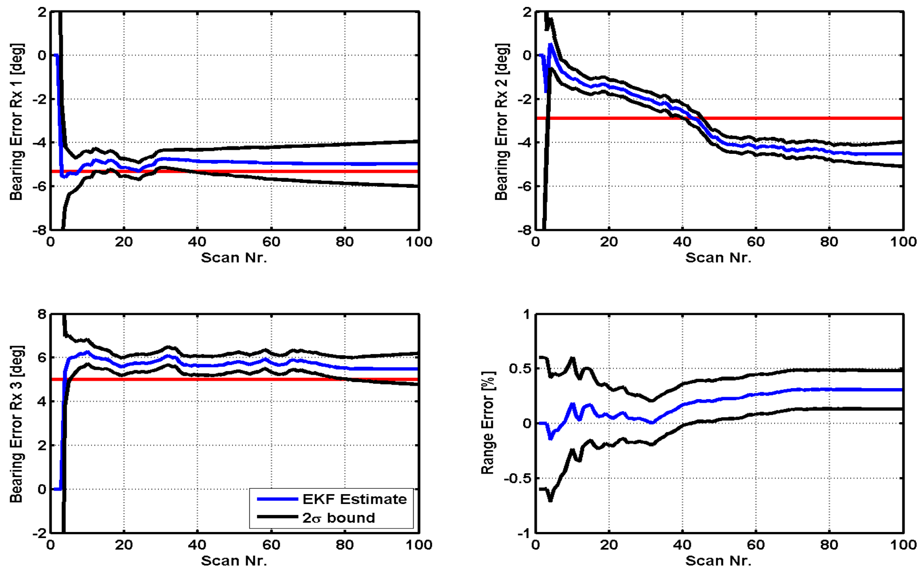

Figure 4: Estimated bearing and range errors

In summary, by using the detections of several spatially separated receivers an automatic online estimation of unknown bias errors is possible and the target state estimation can be improved essentially.

4 Metron Dataset

The Metron dataset [Or09], which consist of five distinct scenarios, was simulated by Metron, Inc. for the Multistatic Tracking Working Group (MSTWG) to evaluate their tracking algorithms. The sensor layout is the same for all scenarios and consists of 4 sources and 25 receivers located in an observation area of $72 \times 72\ \text{km}^2$ (see Figure 5). All sensors are stationary. A pulse is transmitted by one of the sources every 180 s and each source alternates between CW and FM pulses.

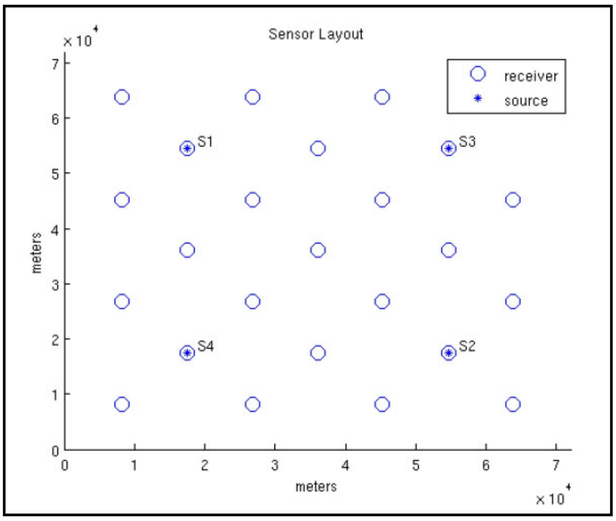

Figure 5: Metron sensor layout

One of the challenges of this dataset is a very low probability of detection of about 12.5% for each receiver. In combination with the high pulse repetition time of 180 s this leads to an average detection rate of approximately once per 24 minutes for each receiver. A target with a speed of 6 m/s, as given in the first scenario, will move more than 8 km in that time and can totally change its course and speed. Under these circumstances a decentralised tracking approach seems to be very challenging. However, centralised tracking, in which the contacts of all receivers are available, seems to be much more promising in this case. Because of this and due to the fact that these simulations contain no systematic registration errors which could trouble the centralised fusion we propose to use a centralised tracker to overcome the difficulties of this dataset.

Another interesting characteristic of this dataset is a very large measurement error with respect to the bearing. The bearing error is normally distributed with a standard deviation of 8°. As the centralised data fusion requires a common coordinate system for the contacts from all receivers it was decided to transform all contacts into Cartesians.

ISBN 978-3-88579-286-4

But the large bearing errors lead to imprecise transformation of the error covariance as shown in Figure 6. On the left hand side of Figure 6 the correct measurement covariance is shown in red and the transformed one in blue. It is obvious that the true position (green) is far outside of the uncertainty region. On the right hand side of Figure 6 it is visible that the filtered estimated position (red) is also far away from the true position.

This problem was solved by decomposing the normal distributions with respect to the bearing into a sum of N normal distributions (see [DK10]) as shown on the left hand side of Figure 7. The resulting parts of this sum are then transformed separately to Cartesians. The predicted tracks are filtered separately with each of the decomposed measurements and finally the filtered track states and covariance matrices are fused to a common result as shown on the right hand side of Figure 7. In this way the filtered estimated position (red) and the true position fit very well.

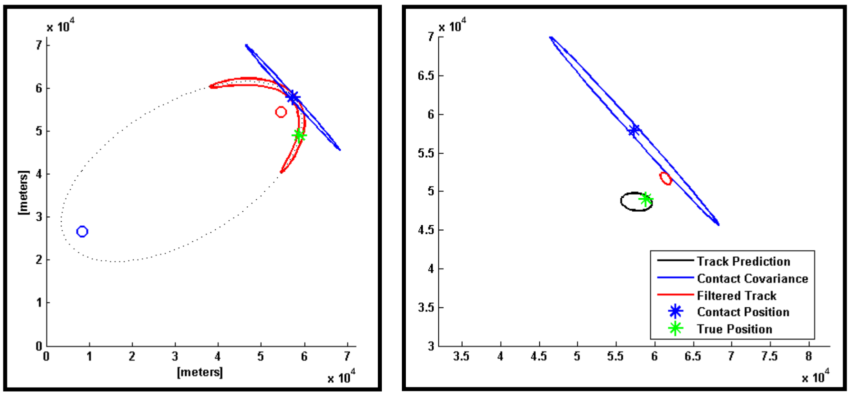

Figure 6: Estimation errors due to transformation to Cartesians

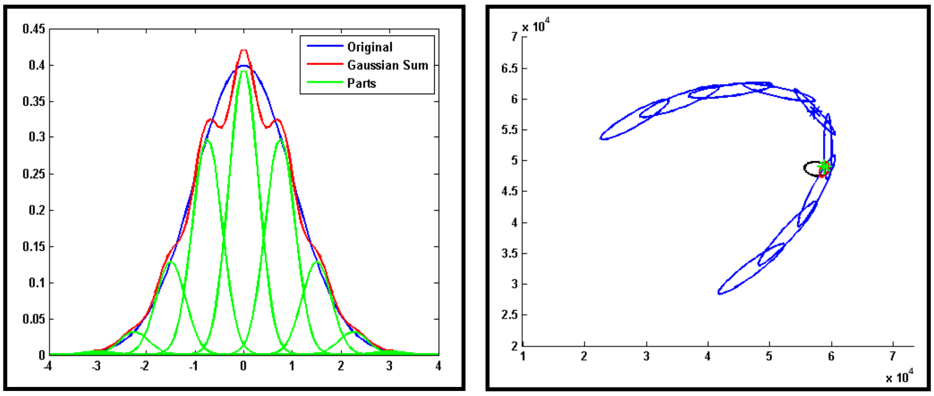

Figure 7: Decomposition of the covariance with respect to the bearing

An additional challenge of this dataset is the very low amount of information gained in each scan. This is because of the low probability of detection, the high false alarm rate and especially because of the large measurement errors. Therefore it is of special importance to use all information available. Especially the Doppler measured by the use of CW pulses is valuable in the Kalman filter to estimate the target kinematics. We used the Doppler also in the likelihood ratio test to extract and terminate tracks. Finally even the distribution of the Doppler of the false contacts contains important information. As the Doppler of the false contacts is normally distributed with a standard deviation of 0.5 m/s, it is very unlikely that a contact with a high Doppler is a false alarm. Another feature that should be used in the data fusion is the signal-to-noise ratio of the contacts.

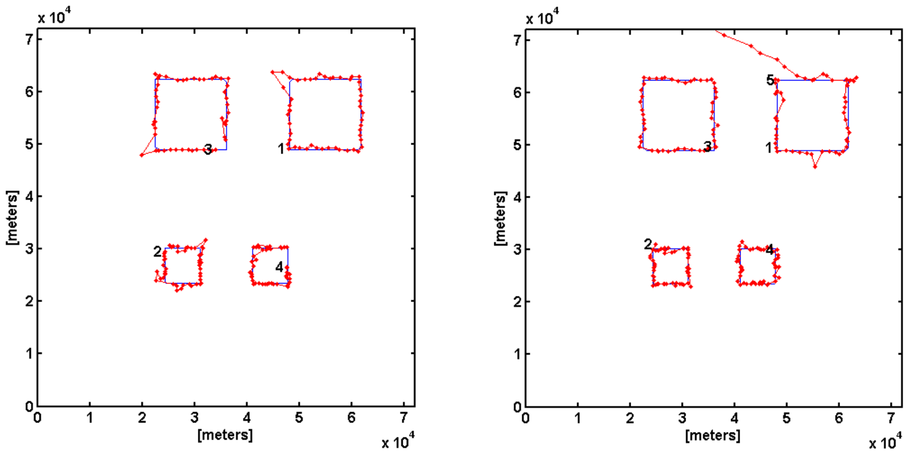

Figure 8: Metron data, scenario 1, scans 1-50 (left) and scans 51-100 (right)

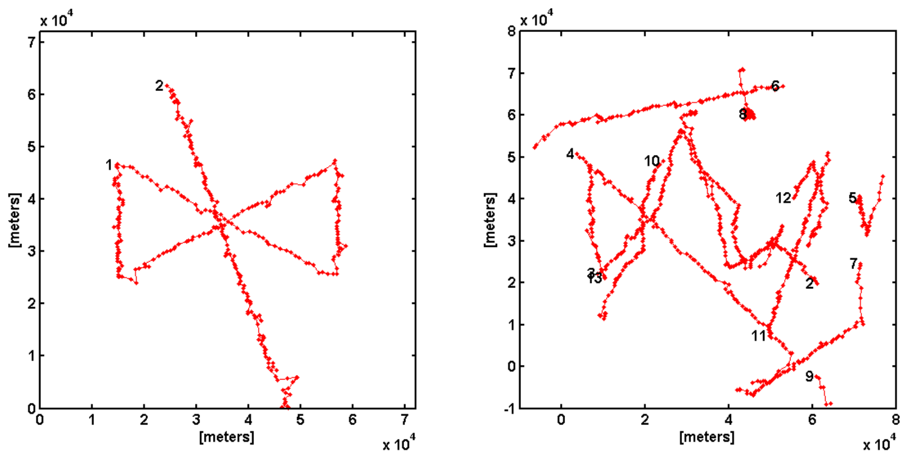

Figure 9: Metron data, scenario 3 (left) and scenario 5 (right), scans 1-200

Some of the tracking results achieved with the Metron dataset are shown in Figure 8 and Figure 9. For the shown evaluations, the ground truth (blue) is known only for scenario 1. The other two scenarios are 'blind', meaning that the true target locations and the numbers of targets are unknown. In spite of the described difficulties very good results could be achieved. Tracks for all targets could be extracted, there are only few fragmentations and nearly no false tracks.

5 Conclusions

In this paper evaluations of two datasets recorded by completely different multistatic sonar systems are presented. It turned out that each sensor system requires its individual fusion concept depending on the layout and performance of the single sensors. In both cases excellent tracking results could be achieved by an appropriate data fusion. For the first dataset a decentralised solution was applied because of its robustness against systematic measurement errors. However, for the second dataset a centralised fusion concept is more advantageous. As in this concept the contacts of all sensors are processed simultaneously a higher probability of track extraction and track stability can be achieved. In summary, depending on the individual situation at hand one has to decide which fusion concept is most suitable for a multistatic operation.

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