Modelling multistatic sonar performance

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Abstract: *By including bistatic reception in a sonobuoy operation the ability to detect and track an underwater target is improved. Both when applying FM and CW sonar pulses, the added source/receiver geometry is beneficial for some target locations. The localization ability of the bistatic reception is highly dependent on the input errors as well as the source/target/receiver geometry. Sometimes bistatic detections should be disregarded because of high localization uncertainty, and should therefore be accompanied by an estimate of the localization error.*

Keywords: *Multistatic sonar, localization, detection, modelling*

INTRODUCTION

Active sonar operations have been performed since before the Second World War. Traditionally these operations are performed by use of one or several sources with co-located receivers, so-called monostatic operations. However, in the past decades there has been an increasing focus on bi- and multistatic sonar operations [1][6][7][8].

Let SR be the number of platforms equipped with both a source and an (almost) co-located receiver. Let S be the amount of platforms with only a source, and R the number of platforms with a receiver only. The different active sonar operation concepts may then be defined as follows:

- **Monostatic sonar operation**: The SR platforms equipped with source and receiver process their own receptions only, resulting in SR source-receiver pairs. The sonar data before tracking are not shared with the cooperating platform, but processed tracks are communicated.
- **Multi-monostatic sonar operation**: As monostatic sonar operation, but the processed sonar data are shared with the cooperating platforms by fusing sonar data.
- **Bistatic sonar operation**: Platforms process receptions from their own and other sources, resulting in a maximum number of (SR + S) * (N – S) source-receiver pairs. The sonar data before tracking are not shared with the cooperating sensor, but processed tracks are communicated.
- **Multistatic sonar operation**: As bistatic sonar operation, but the processed sonar data are shared with the co-operating sensor by fusing sonar data.

Figure 1 illustrates different active sonar concepts. Traditionally the left setup is used. In this paper we consider a sonar operation where all the sensors are of the SR-type. We will illustrate the benefit of including a bistatic reception (middle). The transmissions from the “yellow” sensors are omitted to keep the figure tidy.

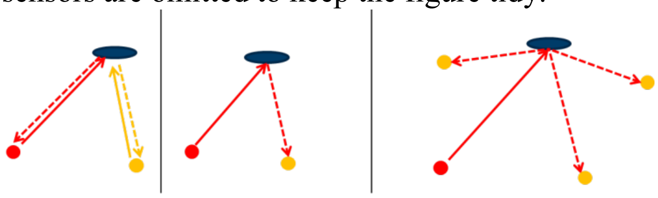

Figure 1: Illustration on active sonar concepts. Left: (Multi-)monostatic. Middle: Bistatic. Right: Multistatic

THEORY

Multistatic sonar operations may be performed by various assets; ships, helicopters, aircrafts with sonobuoys or a combination of different assets. Here we focus on active multistatic sonobuoy operations. We constrict ourselves to operations with sonobuoys that can both send and receive a sonar ping.

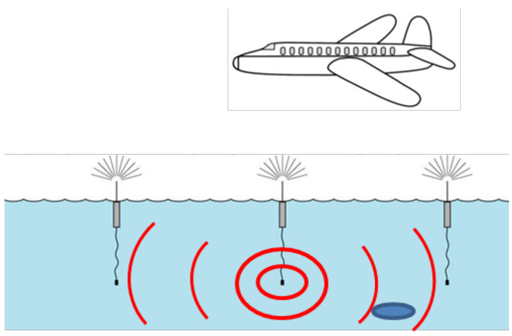

Figure 2: Illustration of active sonobuoy operation

In this type of sonar operation the buoys may be used in the same way as in a classical monostatic operation. But a ping that is sent from one buoy will be processed by other buoys as well as on the source buoy. Therefore the ping from one buoy can become useful for the other buoys instead of unwanted noise, as before.

Linear or hyperbolic FM-pulses and CW-pulses are widely used in active sonar. By including bistatic reception in addition to monostatic reception, we may have some benefits. When FM-pulses are used the so-called glint effect is a very important feature. Some angles of incidence will give a stronger echo than others. When operating monostatically, normal incidence on a tube-shaped target will provide a very strong echo, the glint effect. In bistatic operations the glint will occur when the angle of incidence equals angle of departure. As illustrated in Figure 3, one more target orientation will provide glint if bistatic reception is included.

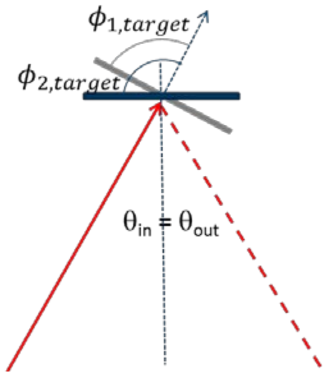

Figure 3: Illustration of FM-glint. Target orientation φ_1 provides glint in the monostatic operation. If bistatic reception is included φ_2 will also provide a glint.

CW pulses are (amplitude weighted) sine tones with short durations (typically 0.1 – 2.0 seconds). Due to the Doppler effect a moving target will return a frequency shifted echo. Thus the target may be detected despite unwanted reverberation from other reflectors such as rocks and seamounts. We may define Doppler speed as shown in Figure 4. The relative frequency shift will be equivalent to the Doppler speed divided by speed of sound. Figure 5 shows the Doppler speed for a target moving in 45 degree direction at different location near a stationary source/ receiver pair. The left and middle plots shows the monostatic and bistatic case, respectively. The right plot shows target areas where the bistatic setup will have higher Doppler than the monostatic setup. Yellow represents more than 2 kts and orange 4 kts. Although the benefit of including bistatic reception is not very big, it may be important in order to distinguish slow moving targets and echoes from static formations.

$$\text{Doppler speed}_{monostatic} \equiv 2\vec{v}\cdot\widehat{ST}$$
$$\text{Doppler speed}_{bistatic} \equiv \vec{v}\cdot\widehat{ST} + \vec{v}\cdot\widehat{TR}$$

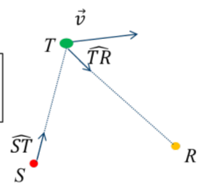

Figure 4: Definition on Doppler speed

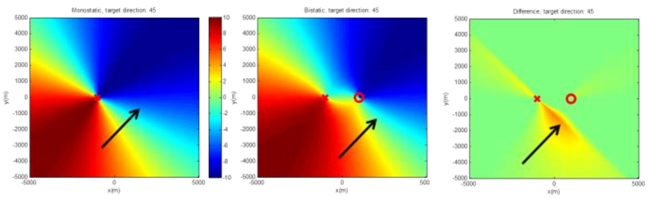

Figure 5: Doppler speed (in kts) for a target moving 5 kts in 45 degree direction (black arrow). Left: Monostatic case. Middle: Bistatic case. Right: yellow and red shows increased Doppler by including bistatic reception. Limits of the colorbar between the two leftmost plots are [-10, 10] kts.

LOCALIZATION ACCURACY

Additional glint opportunities and increased Doppler speed in some areas will make detection easier. However, there will also be a need for sufficiently accurate localization in order to associate detections from different receivers to the same target and to track the target. Coraluppi [1] has dealt with this problem and derived analytical expressions for the target localization standard deviations given standard deviations of source/receiver position, angle of echo, orientation of receiver, average speed of sound and time of sound propagation.

Figure 6 illustrates the geometry of the active sonar operation and Table 1 shows the standard deviations that we have used.

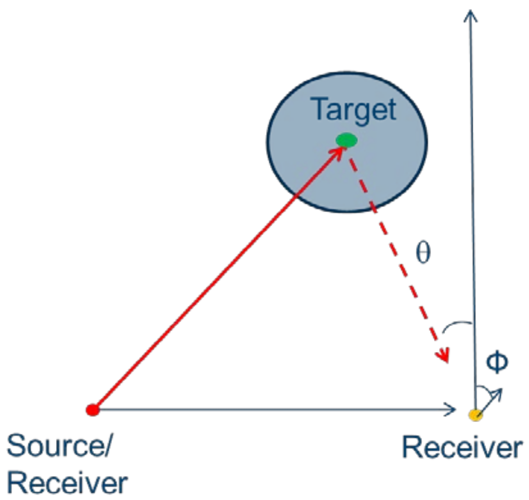

Figure 6: Illustration of source / target / receiver geometry.

Parameter	**Std dev, bistatic**	**Std dev, mono-static**
Source pos, x-dir/ y-dir	20 / 20 m	20 / 20 m
Angle to target from receiver (θ)	5 deg	5 deg
Receiver orientation (Φ)	5 deg	5 deg
Receiver pos, x-dir/y-dir	20 / 20 m	0 m
Average sound speed	15 m/s	15 m/s
Time of sound propagation	*0.02 s / 0.1s*	*0.02 s / 0.1s*

Table 1: Standard deviations for different parameters that influence the target localization error of the sonar.

If the sonobuoys are fitted with a GPS sensor, a standard deviation of 20 meter in x- and y-direction is realistic, even though the submerged sensor may be horizontally displaced from the buoy.

The chosen bearing accuracy is realistic assuming that an optimal beamformer is used, the target is detected with a sufficiently high signal-to-noise level, and the buoy has a sufficiently large aperture relative to the wavelength. The latter is obtained by buoys that fold out a big planar aperture in the water.

The orientation of the buoy is decided by a compass onboard the submerged receiver. Temporal or geographical variations in the magnetic field may increase the receiver orientation error.

The average speed of sound propagation may be estimated by a sound speed measurement and calibrated by measuring the time of the direct pulse reception between two buoys.

The sonar system must handle data from different sonobuoys with adequate time synchron-ization. This puts requirements on the accuracy of the time of sound propagation (*time of flight*). The latency between a ping command and the actual ping time should be measured in the raw data of the sender buoy. Then the time resolution of the matched filter of the sonar pulse is the dominating factor. The time resolution depends on the sonar pulse. According to [5] the typical time resolution of a weighted CW pulse is 0.6*T, where T is the pulse duration. Long CW pulses result in large standard deviations of *time of sound propagation*.

For the standard deviations in Table 1 we have plotted uncertainty ellipses (Figure 7) for the target localization using Coraluppi's expressions [1]. Note that the orientations of the "bistatic and monostatic error ellipses" tend to differ. Thus the added contribution of a bistatic reception may improve the target localization, even though the bistatic error ellipse is greater than the monostatic error ellipse.

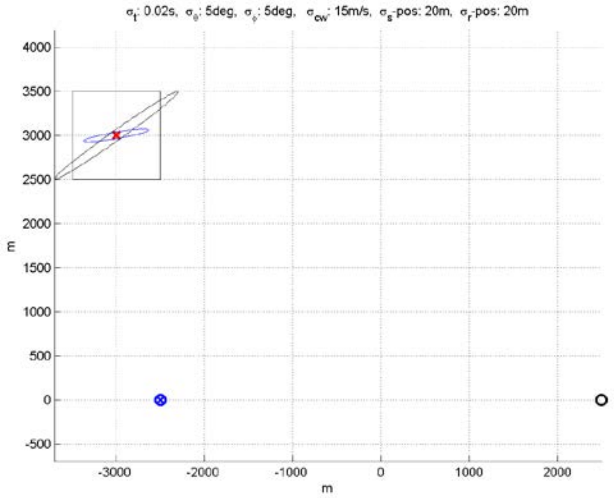

Figure 7: Target localization error ellipses when all the input errors in Table 1 are included. Input propagation time standard deviation is 0.02 s. Blue ellipse for monostatic reception, black for bistatic reception.

Figure 10 shows the total localization uncertainty $\sqrt{\sigma_x{}^2 + \sigma_y{}^2}$, where σ_x and σ_y are the standard deviation for the target localization in x- and y- direction, respectively. Note the asymmetry of the plot. For target positions near the receiver the standard deviation tends to be smaller. This is because the bearing uncertainty contributes substantially to the total target localization uncertainty. All the other input uncertainties tend to result in a symmetric contribution to the target localization uncertainty [1].

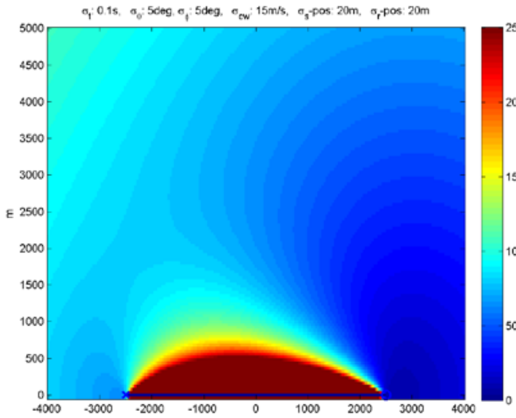

Figure 8: Representation of the target localization error when source is placed at [0,-2500] m and receiver at [0, 2500]. Input propagation time standard deviation is 0.1 s.

MODELED SONAR PERFORMANCE

Consider a network of five sonobuoys shaped as a cross and separated by 5 km. Let a single underwater target try to circumvent the network in order to avoid detection. The positions of four buoys and the target are shown in Figure 11.

The total sonar performance of the buoy network is estimated using an acoustic model. Both the monostatic and the bistatic cases are considered. MSTPA [2] models the sonar performance of the buoy network. It employs a mode theoretic approach and takes into account the glint angles and Doppler effect to provide a realistic estimate of the total sonar performance of the network. All though MSTPA delivers sonar performance for all stages of sonar processing, we here use the modelled monostatic and bistatic signal excess only.

Receiver operating characteristic curves [3] are then used to estimate the probability of detection (PD). The PD is used to estimate the tracking performance, which is here defined as the probability that any buoy in the network initiates a track on the target [4] exceeds 50%. Finally, the localization error is estimated, as detailed in the previous chapter.

Tracking and localization performance are shown in Figure 11. Note that the parts of the target path with monostatic coverage are also covered in the multistatic case. The multistatic case therefore clearly outperforms the monostatic case in terms of tracking performance. Most of the portions of the target path covered by the sonobuoy network correspond to positions where a source/receiver combination achieves the glint effect (as indicated by the cyan and magenta lines connecting the buoys to the target path in Figure 11). The main reason why the multistatic case outperforms the monostatic case is the increased number of glint opportunities.

The localization accuracy is slightly better for the monostatic case than the multistatic case (Figure 11), but they are still comparable. The multistatic localization performance is generally considered sufficient for successful fusion of multi-sensor detection-level data in this case.

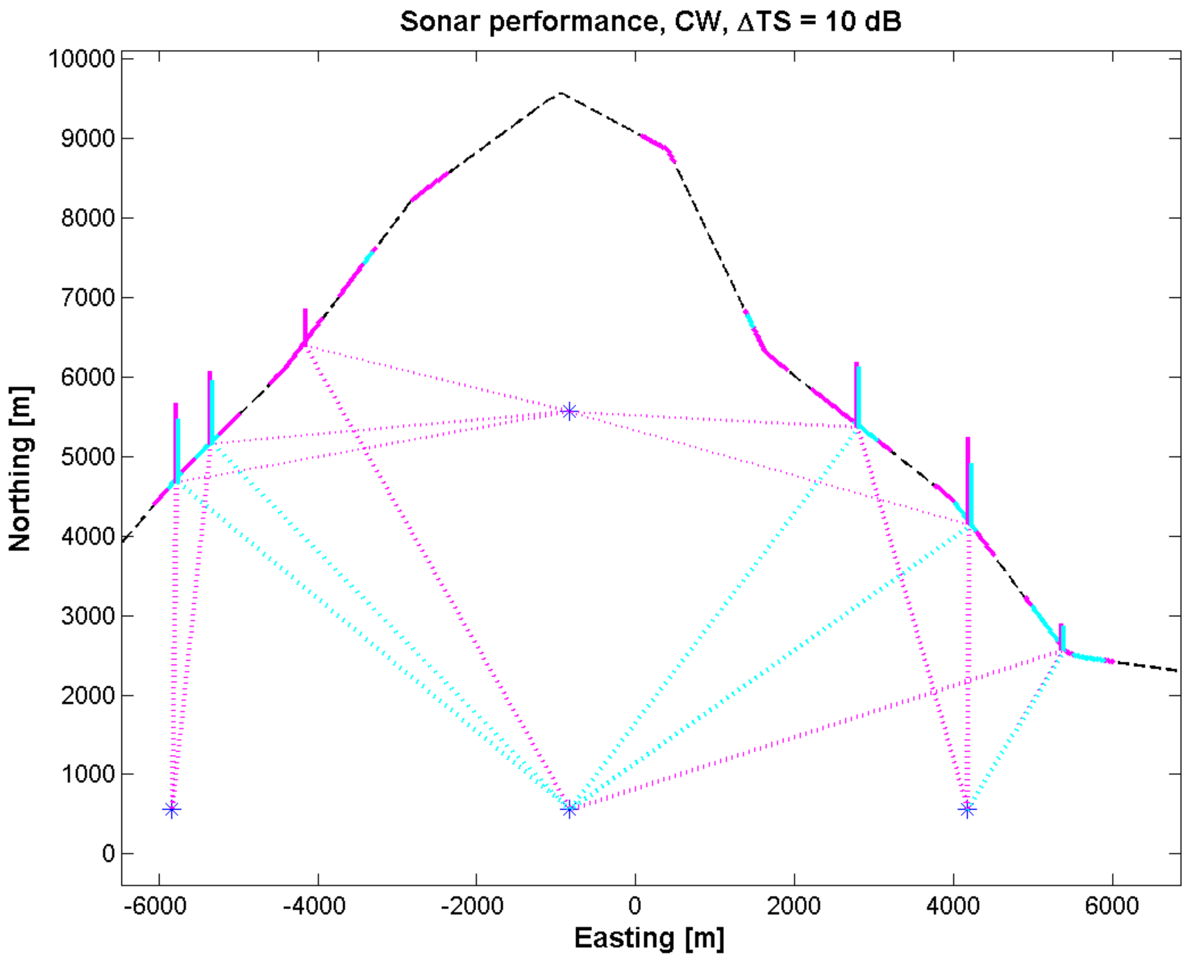

Figure 9 Positions of sonobuoys (blue stars), target path (dashed, black line), tracking performance (cyan-colored lines for monostatic and magenta lines for multistatic), and localization error (cyan bars for monostatic and magenta bars for bistatic). At selected positions along the target path, the source/receiver combination that has highest PD is shown for both the multistatic (magenta lines) and the monostatic (cyan lines) case.

CONCLUSIONS

In a sonobuoy operation where all the buoys are both sending and receiving, inclusion of bistatic reception increases the probability of tracking the target. In some cases the localization accuracy may also be improved by combining information from both monostatic and bistatic detections. However, the localization error is strongly dependent on the source/target/receiver geometry and on the bearing and time errors. To aid the tracker, every multistatic detection should be accompanied by a localization error estimate. Detections with high localization error estimates should be disregarded.

ACKNOWLEDGEMENTS

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