Passive Ranging with Flank and Towed Array Sensors

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Abstract

In the current sensor suites on board submarines the Passive Ranging Sonar (PRS) is a separate sensor, usually with three or more hydrophone groups on either side of the submarine. The aperture of this sensor is limited by the length of the boat, which makes ranging up to moderate distances possible. The combination of the towed and flank array sonar can be used to create a passive ranging sonar with a much larger acoustic aperture, resulting in a very long ranging capacity. Based on simulated data a calculation method was developed that combines adaptive beamformers, fine bearing estimation and a target localisation technique originating from an acoustic artillery ranging system. The method was evaluated on operational recordings of a towed and flank array sensor. If the target is detectable on both sensors, ranging can be performed instantaneous. The method is robust and can provide an increased passive ranging performance.

Figure 1 Walrus class submarine departing from Den Helder (Photo: Michel Overeijnder).

1 Introduction

Modern submarines are one of the most powerful weapons that a navy can count in its order of battle. Undetectable by radar and with acoustic discretion it confers considerable fighting potential and as such it forms a vital element of any homogeneous fleet. For detection submarines rely on passive sonar sensors. This has the advantage of being silent, but the disadvantage that ranging is cumbersome.

To determine the range of a target with a passive sonar is an intriguing problem. Most solutions rely on target's motion analysis, which often provides reliable results, but is time-consuming. For instantaneous ranging on many submarines distributed arrays are mounted. This so-called passive ranging sonar is able to determine ranges for targets in the near field of the sensor. The range that separates the far field from the near field is proportional to the array separation (L) squared divided by the wavelength (λ):

$$R_f = L^2 / \lambda \qquad (1)$$

This is usually called the *Fresnel Range* (R_f), it is used as an indication for the maximum measurable range. For practical applications the Fresnel range is in the order of a few kilometres.

An alternative is the combined use of the submarine's towed and flank array. This passive long-ranging sonar can be considered as two directional sensors spaced by a large distance (mainly determined by the length of the tow cable assembly). In this system the Fresnel range is considerably larger, in the order of 10 kilometres.

Unfortunately this is only theory. In practice this idea is not widely implemented. The main reason is the limited processing capacity for the necessary high-resolution beamforming. Another problem are physical limitations due the uncertainty in towed array position and heading. However, the latter can be overcome by a new passive ranging algorithm as worked out in this paper. Apart from bearings this new

algorithm uses the coherence in signals received on the flank and towed array to estimate a third parameter, such that more accurate and robust ranging is feasible.
To see whether an implementation on the Walrus class submarines is possible and to find the necessary conditions for such an implementation a simulator was built in Matlab programming language. The simulator is based on theory as given in section 2 and 3. Simulation results were promising (section 4 and 5) and therefore algorithms were also applied to real data in section 6 of this paper.

2 Theory

Consider two directional acoustic sensors (S1 and S2) each separated by a distance *d* from the acoustic centre and a target source at range *R* form this centre. The sensors represent the line arrays of the submarine; the flank array (FA) and towed array (TA) respectively. The target is in the far field of both arrays, but in the near field of the combination; see Figure 2.

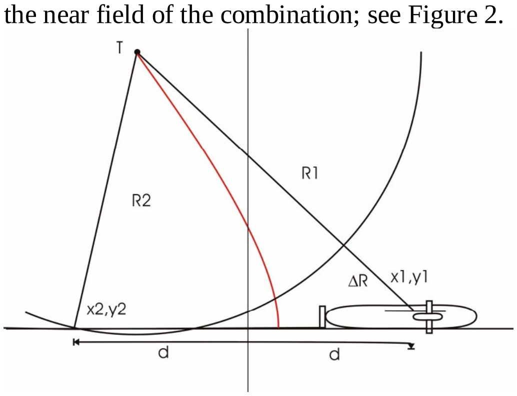


Figure 2 The concept of using Flank Array and Towed array as passive ranging sonar.

As both sensors are directional the easiest way to find the source is by means of ”cross-bearings”, also called “*triangulation*”. The target’s bearing relative to the two arrays is known (though not extremely accurate) and by application of the sine-rule to the triangle S1-S2-T the target range can be estimated as:

$$R_1 = 2d \sin(\pi/180\ \theta_1) / \sin(\pi/180\ \theta_2\text{-}\theta_1) \qquad (2)$$

where θ_1 and θ_2 are the measured target’s bearings of the FA and TA respectively, in degrees relative to the sailing direction.
This method is very simple and straightforward, but not very accurate and robust. The reason is that the method is highly sensitive to accurate bearing estimations. The sensitivity shows up in the θ_2-θ_1 term in the denominator, which is always very small (typically a few degrees, 2^o-6^o) for ranges of interest, i.e. targets further away than the PRS maximum range. As a consequence a bearing error of only 1^o can already induce a range error varying from 20-50%.
Unfortunately bearings are poorly known due to limited aperture of the line arrays, whose beamwidth is some 4^o or more. Some higher accuracy can be gained by ”fine-bearing estimation”, a beam interpolation method. Depending on the SNR the minimum required accuracy of 1^o can be reached. But still, unknown offsets in bearing occur due to uncertainties in the towed array heading (even if it has a highly accurate compass, the errors are at least 0.5^o).

The above problem is well known and probably the reason for the lack of success of the method. A good attempt to solve the problem is given in [Mills 1], where ranging is combined with tracking via a Kalman filter. In this way successive range estimates reduce the errors, at the expense of losing the instantaneous character [Melkevik 2, Ganesh 3 and Dzielski 4].

3 Advanced method

3.1 Basic idea

To improve accuracy and robustness of the triangulation method an additional method is proposed in this paper. The addition is based on delay-time measurements (by means of correlation methods) between the two sensors. Such methods are commonly applied in acoustic artillery localisation systems, such as the used by the 101th artillery support battery of the Dutch Army. If a delay-time of source signal arrival on the two sensors is measured it can be shown that the target is located on a hyperbola with the sensors in the focal points; see Figure 2.
The exact location of the source is now estimated by crossing the lines-of-sight of the arrays with the hyperbola. This provides two other, fully independent range measurements. These range measurements are often more accurate than the triangulation range. Due to the high bandwidth of the sonar delay-time between the signal arrivals on the two arrays can be measured very accurately by cross-correlation of the beam outputs.

3.2 Expected accuracies

The performance of the ranging methods is limited by the accuracies of the measurements of the inputs. In this section the theoretical accuracies of the three inputs for the ranging algorithms are determined. These three measured inputs are:

1. FA bearing
2. TA bearing
3. Delay-time

The measurements of the bearings of the FA and TA are limited by the beamwidths, and the delay-time estimation by the bandwidth. Furthermore the accuracy depends on the (square root of the) SNR on the hydrophones.

3.2.1 Accuracy of flank array bearing estimation:

In general the accuracy of an array measurement depends on the 3dB beamwidth (= resolving power) and on the SNR in the beam. According the Cramer-Rao lower bound the minimal measurement error is given by:

$$\Delta\theta_1 = \theta_1^{3\,\mathrm{dB}} / \sqrt{\mathrm{SNR}_1} \qquad (3)$$

For a towed array the beamwidth is determined by the number of hydrophones, at the design frequency it can be approximated by [Nielsen 5]:

$$\theta^{3\,\mathrm{dB}} = 100^{\circ} / N. \qquad (4)$$

The SNR in the beam is (again for the design frequency) the array gain times the single hydrophone SNR: $\mathrm{SNR}_1 = N\ \mathrm{SNR}_0$

Note that the formula above provides the accuracy for each frequency bin. If the total beampattern is built up from broadband computations using a large number of (statistically independent) bins, the total accuracy can be divided by the square root of the number of bins. The number of frequency bins used in broadband computations is the product of the integration bandwidth and integration time (*BT- product*).

After all these considerations we find that the accuracy in the flank array bearing measurement is:

$$\Delta\theta_1 = 100^{\circ} / (N^{1.5}\ \sqrt{BT}\ \sqrt{\mathrm{SNR}_0}\,) \qquad (5)$$

Typically for flank arrays we take: $N = 16$ and $BT = 400$, assuming a high $\mathrm{SNR}_0 = 1$ we get:

$$\Delta\theta_1 = 0.08^{\circ}\ (\cong 0.04\ \%\ ) \qquad (6)$$

This value is well reproduced in the simulations; see e.g. the example in the next section. It can be seen as the upper limit of the accuracy for two reasons:

- In broadband we are below the design frequency (so the effective N is smaller)
- The single hydrophone SNR is in practical cases (much) lower than 0 dB.

3.2.2 Accuracy of towed array bearing estimation

For the towed array measurement the accuracy is very much the same:

$$\Delta\theta_2 = 100^{\circ} / (N^{1.5}\ \sqrt{BT}\ \sqrt{\mathrm{SNR}_0}\,) \qquad (7)$$

With only difference a larger number of hydrophones (and ignoring the lower self noise levels) we take now $N = 64$, $BT = 400$ and again $\mathrm{SNR}_0 = 1$ to get:

$$\Delta\theta_2 = 0.01^{\circ}\ (\cong 0.005\ \%\ ) \qquad (8)$$

So the TA is at least two times more accurate than the FA and in case of high self-noise even more than that.

3.3.3 Accuracy of delay-time estimation

Also here a comparable consideration:

$$\Delta\tau = \tau_{3\,\mathrm{dB}} / \sqrt{\mathrm{SNR}} \qquad (9)$$

The 3 dB width of a correlation measurement depends only on the bandwidth: $\tau_{3\,\mathrm{dB}} = 1/B$, where B is now the total bandwidth of the sonar. This is larger than the beamforming bandwidth, which is only the upper octave or even less. The output SNR is the input SNR (minimum of the beam SNRs and thus $\mathrm{SNR}_2 = 16\ \mathrm{SNR}_0$) multiplied by the correlation gain, which is BT. So we get:

$$\Delta\tau = 1/\,(B\ \sqrt{BT}\ \sqrt{N}\ \mathrm{SNR}_0\,) \qquad (10)$$

Substitution of realistic (optimistic) values gives

$$\Delta\tau = 0.011\ \mathrm{ms} \qquad (11)$$
$$(\cong 0.01\ \%\ \text{depending on bearing})$$

Note that it depends on bearing, near broadside delay times are smaller and the relative error becomes larger. Still the delay-time estimation is generally more accurate than the FA measurement and in the same order of magnitude as the TA measurement.

3.3 Possible implementations

The advanced method introduces a luxury problem, three solutions for the range instead of one. This redundancy originates from the fact that three independent measurements (θ_1, θ_2 and τ) are used to estimate only two unknowns (the two coordinates (R and θ) of the target's position). It is not clear how to use this redundancy in an optimal way. A small theoretical consideration is given. There are several possibilities:

1. Use the most reliable solution;
    - If the TA is not equipped with an accurate compass the offset in θ_2 is probably the largest error. The range can be computed from θ_1 and τ only.
    - In case an accurate compass is available in the TA, the FA bearing θ_1 is the least accurate. The range can be computed from θ_2 and τ only.

2. Optimise the solution by mathematical methods for over-defined sets of equations;

- Simply average the solutions,
- Outlier removal by averaging the two most intimate solutions,
- Perform a least square optimisation.

3. Estimate a third unknown;
    - A systematic error (e.g. the offset in the TA heading) could be estimated.

The simulator can help to sort out the best way to go. It is described in the next section.

4 Simulator

4.1 Set-up

To develop and implement passive ranging algorithms for LRS sensors a simulator is constructed. In this simulator the following steps are made:

1. LRS sensor parameters are set.
2. Array and source positions are defined relative to the acoustic centre (origin)
3. Travel times from the source to each individual hydrophone are determined
4. Source signal is generated as sum of broadband noise and tonals; data are transferred to the frequency domain (by means of an FFT) for further processing
5. Receive hydrophone array signal generation by delaying emitted signal corresponding to travel times (by means of phase-shifting in the frequency domain); further omni-directional (uncorrelated) noise is added for given SNR.
6. Beamforming (conventional) of both line arrays and integration over upper octave
7. Target bearing estimation and fine bearing tuning by clever interpolation [Parker 6].
8. TA-FA target beam output (full bandwidth) cross correlation to find delay-time between arrival on TA and FA, resp.
9. Refine delay-time by interpolation. (oversampling) of cross correlation output.
10. Calculate ranges by sine rule (triangulation) and intersection of array lines of sight with hyperbola.
11. Display results.

4.2 Example

The simulator is explained by a series of figures demonstrating a typical example. In Figure 3 the geometry is shown. The TA (blue) and FA (green) are on the *x*-axis and the target (red) is situated at 1000 m from the submarine, which is sailing to the right. Array lines-of-sight and the hyperbola of equal delay-times are shown.

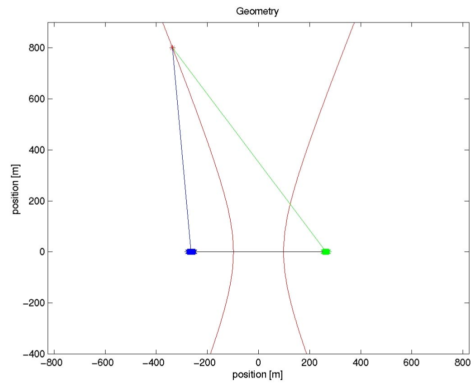


Figure 3 Simulated geometry.

The emitted signal of the target is a sum of broadband noise and tonals. Simulated received hydrophone data are delayed corresponding to the delay-time for each hydrophone and are "corrupted" with omni-directional noise. The SNR can be chosen (here SNR_0 = 10 dB).

The hydrophone data are beamformed using a common delay and sum beamformer in the frequency domain. For bearing estimation the beamformer outputs are integrated over the upper octave of the arrays. The resulting beampatterns are shown in Figure 4. The target is detected in the bearing as expected from Figure 3.

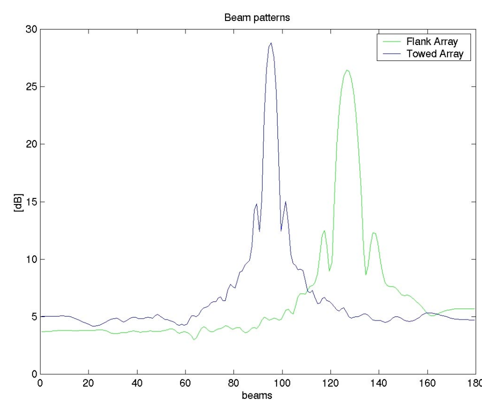


Figure 4 Beampatterns for FA (green) and TA (blue)

After the beam with maximum output is determined, an interpolation procedure finds the true maximum [Parker 6]. The target beams (all frequencies) of the two arrays now go to a cross-correlation process. The beam output of the TA is multiplied by the complex conjugate of the FA output. This product is brought back to the time domain by an IFFT. This IFFT is heavily oversampled to guarantee high accuracy. The correlator has a maximum at the true delay-time; see Figure 5.

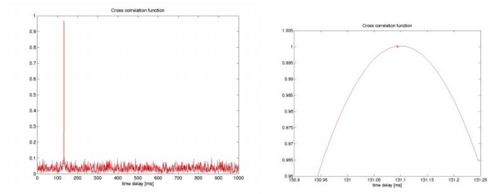


Figure 5 Correlator output (left) with zoom on the maximum (right). The location of the maximum is estimated with high resolution using an interpolation method described by Parker [6].

Displayed simulation results (and exact theoretical results)

Target bearing by FA = 126.85^o (126.87^o)
Target bearing by TA = 95.20^o (95.21^o)
Delay-time = 131.094 (131.093) ms

Target range method 1 = 1000 (1000) m Target range method 2 = 1000 (1000) m Target range method 3 = 1000 (1000) m

The simulator reproduces the theoretical expectations in high SNR cases, which is reassuring.

5 Results of the simulator

5.1 Assumptions and error sources

In the simulations we made the following assumptions on possible error sources:

1. Good quality arrays
2. Sensor positions well known
3. No coherence loss
4. No multi-path propagation

Ad 1: We assume that all hydrophones function well so that bearings are well estimated by the beamformer [Beerens 7].

Ad 2: Sensor positions should be known. Uncertainties occur by unknown cable scope and TA Heading. Although the first might seem trivial, the results depend critically on the exact value. In practice the cable scope can quite accurately be derived from acoustic optimisation using a target of opportunity. The second is a real problem. TA Bearing offsets result in large range errors at long ranges. Also here a simulation study is performed.

Ad 3: It is known that even in shallow waters sufficient coherence is guaranteed over more than an array length (128 wavelengths as a rule of thumb). However, the cable is much longer. The amount of required coherence is subject to a simulation study. The real data used in this study are coherent enough for accurate delay-time estimation.

Ad 4: In a severe multi-path environment the subsequent arrivals of the signal on the arrays may lead to highly unstable delay-time estimations. The direct path (often the shortest) is not always the strongest. If on one sensor the direct path and on the other sensor a reflected path is strongest, the delay-time gets biased.

In the simulations we looked at the accuracy of the different methods to obtain target ranges and at their sensitivity to the above error sources (2, 3 and 4).

5.2 Studied methods and expected accuracies

In this section we will study three methods to determine the range from simulated data using two independent measurements:

1. FA-TA cross bearings (classic triangulation)
2. TA bearing and delay-time are used
3. FA bearing and delay-time are used

The methods are evaluated for 5 scenarios to investigate the consequence of the errors.

5.2.1 *Ideal case (no error sources)*

In the ideal case (without any of the errors as classified in section 5.1) the three methods are applied. A target is simulated 35^o off broadside. In the simulations the input (single hydrophone) SNR was fixed at 10 dB, which is unrealistically high. However, this study is merely meant to judge the methods. A more realistic scenario with moderate and low SNR is studied in the next section.

R	Error 1 θ_1 and θ_2		Error 2 τ and θ_2		Error 3 τ and θ_1	
[km]	[m]	%	[m]	%	[m]	%
0.5	1	0.2	0	0.0	0	0.0
1	2	0.2	1	0.1	1	0.1
2	8	0.4	3	0.2	6	0.3
4	69	1.7	15	0.4	38	1.0
8	159	2.0	152	1.9	154	1.9
16	622	3.9	530	3.3	594	3.7

The table shows that Method 2 is most accurate, than Method 3 and least is the classic Method 1. This corresponds well to the expectations from accuracy of the input measurements in this scenario. The delay-time (τ) is most accurately measured, followed by the TA bearing *(θ_2)* and the FA bearing *(θ_1)*. The errors (also the relative errors) grow with range. The relative errors grow almost linearly and thus the absolute errors quadratically with range. This is according to theoretical predictions for quantities depending on two measurements. Even after the Fresnel range (= 10 km) the methods still seem to work, although there sensitivities to measurement errors become significant. So, ranging is possible far out, provided that the SNR is still sufficient and the measurements are accurate.

5.2.2 Influence of SNR

In the following simulations a more realistic scenario is studied. The SNR was not fixed, but decreased with range following a spherical "propagation loss" law (PL = 20 log R). Single hydrophone SNR was 0 dB for a target at 1 km. The values in the table are averages over a small number of simulations. Therefore they are only indicative and not statistically reliable.

R	SNR	Error 1		Error 2		Error 3	
km	[dB]	[m]	%	[m]	%	[m]	%
1	0	2	0.2	1	0.1	1	0.1
2	-6	20	1.0	11	0.6	15	0.8
4	-12	201	2.0	69	1.7	70	1.8
8	-18	###	>10	634	8.0	###	>10
16	-24	###		###		###	

(Note: ### means no solution due to lost track)

Here we see that detection is limiting the ranging performance. Once a target is detected ranging seems possible with the system. On the edge of detection ranging errors are well within operational demands. Note that the DI-s of the FA and TA are 13 and 18 dB, respectively, so that maximum detection ranges are R_1= 5 km and R_2 =8 km in this simulation. Within these ranges the methods seems to work, but if SNR is too low the methods fail. Method 2 performs best for low SNR.

5.2.3 TA has biased heading (Unstable TA)

In the following simulations the influence of an error in the TA heading is studied. TA headings are uncertain as the TA is freely moving through the water and is influenced by (tidal) currents and motions of the tow ship. In the simulations the SNR is fixed at 0 dB for a target at 1 km. Results get rapidly (quadratically) worse at longer range.

θ_2-error	Error 1		Error 2		Error 3	
[deg]	[m]	%	[m]	%	[m]	%
0	2	0.2	1	0.1	1	0.1
0.5	14	1.4	28	2.8	3	0.3
1	24	2.4	48	4.8	6	0.6
2	49	4.9	90	9.0	7	0.7
4	95	9.5	162	16	15	1.5

For a TA with a (good) compass the error will be about 0.5^o [Volwerk 8], however apart from these random errors also biases can be present. These biases can be in the order of 1^o-2^o and may vary in time (after course or depth change).

Methods 1 and 2, which directly rely on the TA heading are already sensitive to the smallest errors. Without a compass errors can be larger (1^o - 4^o) and here only Method 3 is reliable. In Method 3 the TA heading is only indirectly used when the TA beam is selected for cross-correlation. This method is robust against TA errors less than (twice) the beamwidth (< 6^o), which is well within practical limits.

An alternative for using Method 1 (which relies on the poor measurement of the FA bearing) is to estimate the bearing offset (bias) of the TA from the three measurements. This technique (Method 4) in theory could compensate for the bias error completely.

5.2.4 Received signals on FA and TA lack coherence

In the correlation methods we rely on the fact that the received signals on the TA and FA are similar. Only a phase difference due to the different travel time is assumed. In practice this need not be the case. The different acoustic paths do not only differ in length, but also in nature. In case inhomogenities (e.g. eddies, fronts, fresh water masses) are present, the correlation may drop. Random phase errors depending on frequency (related to eddy sizes) will occur and delay-time estimation will become inaccurate. This is simulated by adding random phase noise to the beam outputs that enter the correlator.

CL	Error 1		Error 2		Error 3	
[dB]	[m]	%	[m]	%	[m]	%
0	2	0.2	1	0.1	1	0.1
-6	2	0.2	1	0.1	1	0.1
–20	2	0.2	3	0.3	7	0.7
–26	2	0.2	191	19	466	47
–40	2	0.2	446	45	760	76

Both Method 2 and 3 use the correlator output. They seem rather insensitive to coherence loss until the loss is larger than the correlator gain (= 10 log $BT \cong$ 26 dB). From that point the correlator does not find the correct maximum anymore and delay-times become random. Method 1 (cross-bearings) does not rely on the correlator and can always be used in case of bad coherence.

5.2.5 Multi-path arrivals (destroying unambiguous solutions for delay-time)

In multi-path environments an offset in the delay-time can occur. In some conditions (more often than one expects) the direct path is not the strongest. As reflected paths have a longer travel time a bias in the delay-time can be observed when a direct path is measured on one array and a reflected path is measured on the other. Typically multi-path travel times are 3-20 ms longer.

Error in τ	Error 1		Error 2		Error 3	
[ms]	[m]	%	[m]	%	[m]	%
0	39	3.9	12	1	31	3
1	40	4.0	106	11	120	12
3	40	4.0	225	22	395	40
10	41	4.1	526	53	###	

The effect of multi-path is quite dramatic. Realistic values of delay-times errors induce unacceptable ranging errors. Therefore it is expected that Methods 2 and 3 fail in heavy multi-path environments.

6 Application to Real Data

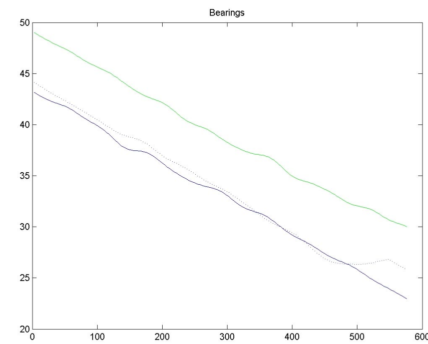
6.1 Processing

On a set of data recorded on a Walrus class submarine the super PRS algorithms were tested. The processing chain used was:

- Hydrophone preprocessing
- Adaptive beamforming of the FA and TA, see [Beerens 7]. Adaptive beamforming results in (much) better bearing resolution than conventional beamforming and accurate bearing estimation is exactly what is needed.
- Post-processing and Tracking: local maxima are determined in time bearing waterfalls and isolated points are removed. On the result a tracker is applied. The tracking algorithm is quite powerful, even if the SNR on the target is reduced by increased self noise. However, with reduced SNR the bearing estimate becomes less accurate (in accordance to Cramer-Rao theory).
- Fine-bearing estimation: on the detected bearing a fine-bearing estimation following a slightly modified Parker's algorithm. Modifications were necessary as Parker's algorithm was dedicated to frequency estimations after an FFT. This problem is equivalent to bearing estimations after conventional beamforming. For adaptive beamforming the response function is no longer a "sinc", but something sharper. Therefore the interpolation algorithm performs better with a slightly different tuning. If the track is temporarily lost bearings are re-estimated by low pass filtering.
- Delay-time estimation from target spectra: now the bearings are determined and ranging by means of triangulation can be done. However, for the new algorithm also the delay-time is required. This is derived from the spectra of the target in the proper beam. The target is followed through the beams (a spotlight method) to guarantee high SNR in the spectra. The spectra are input for a correlator. The spectrum of the FA is multiplied to the complex conjugate spectrum of the TA and after an IFFT we obtain the delay-times between the target signal's arrival on FA and TA as function of time.
- Range fixing (4 Methods)

6.2 Ranging results

The FA bearing, TA bearing and the delay-time form the ingredients for the PRS algorithms.



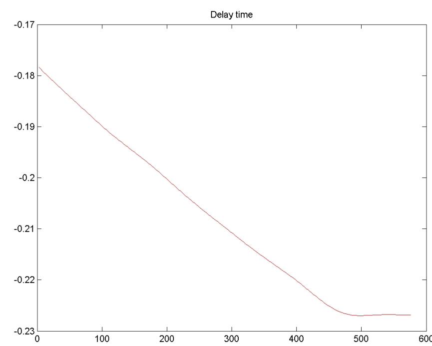


Figure 6 Upper part: the target's bearing relative to the FA (green) and TA (blue). The target's bearing is decreasing with time (passing across the front). Figure 7 Lower part: delay time between signal arrival on FA and TA as a function of time. The delay-time increases, the minus sign denotes that the emitted noise reaches the FA first.

In total 4 PRS algorithms to estimate the range are compared in performance on real data.

1. FA-TA cross bearing (classic triangulation) are used
2. TA bearing and delay-time are used
3. FA bearing and delay-time are used
4. All ingredients are used; TA bias estimated using FA bearing and delay-time, after which corrected TA bearing and delay-time are used.

The first three methods have also been tested in the simulator. The first algorithm is the classic triangulation method, which is the one to beat. The next two algorithms have no independent meaning. Their results can be used in combination with method 3 to find more reliable results, e.g. by some kind of averaging. The fourth method is an integrated combination of the first three methods and it is expected to outperform the others in real life.

The resulting ranges are depicted in Figure 7**.** In this run the results of the four algorithms are remarkably close. They all agree that the target is passing across the front, thereby closing in from 3000 to 2000 m at the end of the run (at t=500 s whenever the FA loses track). As ground truth is lacking it is hard to judge what method performs best in this situation. Considering the input data (unstable FA bearing) one would expect the lower range estimates (Method 2) to be more reliable than the higher estimates of Method 3. On the other hand the TA bearing could be biased. If the estimated bias is correct Method 2 may underestimate the range and Method 4 will be closer. Furthermore it is remarkable that in this case there is nothing wrong with the classic Method 1.

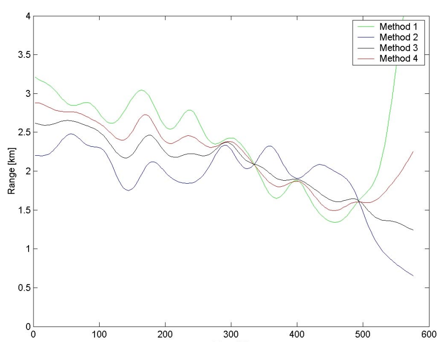


Figure 7 Target's range according the 4 different algorithms on real data.

Application to other data sets showed similar results. The methods differed little. In deep water Method 4 seems most reliable, but in shallow water Method 3 was most robust.

7 Discussion

Implementation of the long-range PRS concept is not so easy. The main problem is that highly accurate bearing estimates are a vital input. In this paper we have shown that this can be achieved by means of well-tuned adaptive beamforming of the Towed and Flank arrays followed by fine-bearing estimation. Doing so, quite accurate ranges were estimated from data of the Towed and Flank arrays of a Walrus class submarine for targets in the range from 500 – 8000 m. There seem no real limitations (other than SNR) to ranging even further out.

To increase robustness and reliability additional algorithms based on time-delay measurements have been tried to estimate the target's range. Little added value can be obtained from these techniques. They provide more accurate solutions in deep water, in shallow water environments they cannot be applied without a solid multi-path analysis.

Acknowledgement

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