LIMITATIONS OF JOINT SPACE AND TIME PROCESSING FOR MOVING SOURCE LOCALIZATION WITH A FEW SENSORS

Y. CHOCHEYRAS and L. KOPP

Thomson-Sintra ASM, BP.57, 06903 Sophia-Antipolis Cedex, France

ABSTRACT

The problem of instantaneous source location estimation with passive differential delay measurements is considered. A maneuvering source is assumed to move close to a few sensors and radiates both broadband and narrowband noise. Differential doppler compensation is required to estimate differential delays between sensors. As near field source motion induces high dynamics in range and signal level, threshold variation linked with inherent signal ambiguity is the prevailing effect in delay estimation. These effects are studied through the calculation of multiple passband Modified Ziv Zakai Lower Bound. Taking these effects into account, an instantaneous estimator of location, speed and course is presented. The new and conventional estimators performance are then compared on simulation and with an at sea experiment.

1. INTRODUCTION

In underwater acoustics, extensive work has been performed both on Time Delay Estimation and Target Motion Analysis. In modern devices, there has been an increasing requirement for Delay Differences TMA since numerous heterogeneous sensors can be used to localize targets. A new perspective is provided by the use of test ranges constituted by a field of several seabed localized sensors to passively localize high speed targets. In this context, differential doppler compensation is required to estimate differential delay between pairs of sensors [3], [2], [13], [14], [9].

Besides this decorrelation effect, the most important phenomenum that must be considered is signal level and spectrum variations. As the radiated spectrum is both composed by broadband and high energy narrowband components, Time Delay estimation is largely dependant on signal ambiguity considerations. These effects are pointed out with a calculation of the Modified Ziv-Zakai Lower Bound (MZZLB) [7] in Section 3; Then the related location accuracy is derived through Cramer-Rao Lower Bound showing that the delay ambiguity has direct location ambiguity consequences.

2. PROBLEM STATEMENT

2.1. Target location estimation

Let's consider a set of N sensors distributed in the 3D space and denote X_i the 3-component sensor location vector of the ith sensor. Let's assume that $\widehat{\tau}_{ij}(t)$ are the estimated differential delays between sensors i and j at time t. These measures can be gathered into a single measurement vector denoted $\widehat{M}(t)$. Then assuming that the measurement errors are gaussian, conventional Maximum Likelihood estimator of location is given by the least squares estimator:

$$\widehat{X}(t) \quad = \quad \arg\min_{X} || \, M(X) - \widehat{M}(t)||^{2}_{\Sigma} \qquad (1)$$

where $M(X)$ is the model vector linking the state vector $X = (x, y)$ and the measurements. The practical estimation procedure is then the following :

- estimation of $\widehat{X}^0$, an initial guess of the state vector [15], [4].
- estimation of $\widehat{X}$ with a Newton-like algorithm [17].

The remaining problem consists in choosing the best independant pairs of sensors among all possible pairs. This will be provided through differential delay estimation accuracy analysis.

2.2. Multiple Passband Modified Ziv-Zakai Lower Bound

The effect of ambiguities in Time Delay Estimation has been adressed for a long time by various authors in two ways:

- statistical analysis of cross-correlator output [16]
- suboptimal decision process qualification (Modified Ziv-Zakai Lower Bound) [7].

The first approach is particularly effective in the case of low pass signals, but band pass extension proves to be difficult. The second approach is more general and allows calculation of a lower bound of Time Delay Estimation for any signal and noise spectrum. Nevertheless practical results are only available for bandpass case ie. constant SNR on the frequency band $[f_0 - B/2, f_0 + B/2]$. We recall and introduce hereafter the equations allowing us to apply general MZZLB results to the 2-passband case. The objective of this calcultaion is to show the high variability of the first ambiguity threshold with respect to signal spectrum.

Let's denote $P_e(x)$ the probability of error related with the Delay estimation. The expression of the Modified Ziv-Zakai Lower Bound is the following [7] :

$$\sigma^2_{MZZLB} \geq \frac{1}{T} \int_0^T x F\left(P_e(x)\right) dx \qquad (2)$$

0-7803-2431-5/95 $4.00

where F is the non linear operator transforming the globally decreasing function $P_e(x)$ in a strictly decreasing function; $P_e(x)$ is provided by the Chernoff bound formula [7], [8] :

$$P_e(x) = \exp\left(a(x) + b(x)\right)\operatorname{erfc}(\sqrt{2b(x)}) \quad (3)$$

and

$$a(x) = -T\int_0^\infty \ln\left(1 + \sin^2(\pi f x)\mathrm{SNR}(f)\right) df \quad (4)$$

$$b(x) = T\int_0^\infty \frac{\sin^2(\pi f x)\mathrm{SNR}(f)}{1+\sin^2(\pi f x)\mathrm{SNR}(f)} df \quad (5)$$

$$\mathrm{SNR}(f) = \frac{\mathrm{SNR}_1(f)\mathrm{SNR}_2(f)}{1+\mathrm{SNR}_1(f)\mathrm{SNR}_2(f)} \quad (6)$$

with as usual (7)

$$\operatorname{erfc}(u) = \frac{1}{\sqrt{2\pi}}\int_u^\infty \exp(-\frac{v^2}{2})dv \quad (8)$$

3. AMBIGUITY FLUCTUATION CHARACTERISTICS : MULTIPLE PASS-BAND CASE

As seen before the calculation of MZZLB relies on the 2 functions $a(x)$ and $b(x)$; let's consider a the prototype problem linked with a 2 pass band signal. This example must be considered as an illustration of the ambiguity threshold variation with small signal spectrum variation. Let's consider that f_1 and f_2 are the central frequencies of the two bands of width B. Then the spectral integration support is limited to the intervals $[f_1 - B/2, f_1 + B/2]$ and $[f_2 - B/2, f_2 + B/2]$ Thus :

$$a(x) = \int_{f_1-B/2}^{f_1+B/2} f(x)dx + \int_{f_2-B/2}^{f_2+B/2} f(x)dx \quad (9)$$

$$b(x) = \int_{f_1-B/2}^{f_1+B/2} g(x)dx + \int_{f_2-B/2}^{f_2+B/2} g(x)dx \quad (10)$$

with $f(x)$ and $g(x)$ defined by eq. (4) and eq. (5).
Then the two pass band MZZLB has been computed by means of numerical integration. The variation of this threshold has been plotted on figure 1 in the case of the following prototype problem :
- two pass band processing
- elementary bandwidth : 10Hz
- $f_1 = 200$Hz
- f_2 varying from 100Hz to 130Hz
(the two bands have the same spectral level)
A threshold variation of 10 dB is then observed for a frequency shift of 13 Hz ($f_2 = 100$Hz and $f_1 = 113$Hz). In addition the corresponding MZZLB vs. SNR plots are given on figures 2 and 3. This threshold must be compared with single band pass first ambiguity threshold [7] :

$$\eta(f_0, B) = [\frac{6}{\pi^2}][\frac{f_0}{B}]^2[\operatorname{erfc}^{-1}(\frac{B^2}{24(f_0)^2})]^2 \quad (11)$$

$\eta(f_0 = f_1, 2B) = 25$dB which is an evident upper bound of 2-passband threshold. In addition the corresponding MZZLB vs. SNR plots are given on figures 2 and 3 : the Time Delay estimation accuracy is decreased within a range of 100 in standard deviation for the same 13 Hz frequency shift.

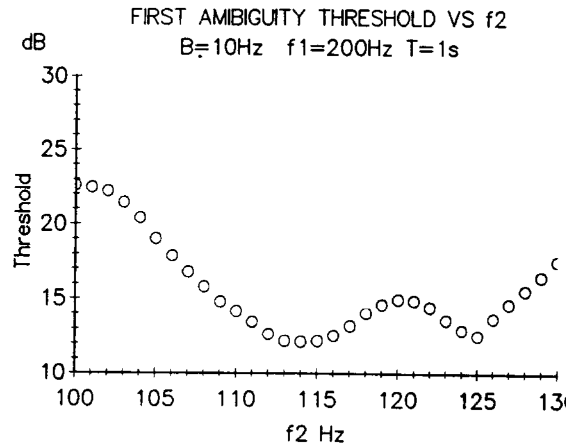

Figure 1. First ambiguity threshold

4. LOCATION ESTIMATION

Following the results of previous section, the accuracy of Time Delay estimation can be described as follows:
- Large sensitivity to SNR variations (eq. 6) induced by space variations (distances in a range 1 to 10)
- Ambiguity threshold sensitivity to little spectrum variation even with constant radiated energy.

Then an improved Location estimator would consist in estimating all the possible Time Delays between sensors (with Differential Doppler compensation). In a four sensor case this leads to increase the whole system computation load by approximately a factor 2 (6 Doppler compensated Time Delay computations vs. 3 computations in the conventional processor case). In order to cope with Time Delay estimation accuracy variations an alternative way is to define a new location estimator processor ; it is based on on-line Delay Track variance estimation and reference sensor switching with the following rules :
- initialization : selection of a reference sensor
- reference sensor update :
- computation of each delay track variance (estimated on few last recurrences) (N-1 tracks)
- comparison of minimum and maximum track variance
- exchange of reference sensor if the maximum variance to the minimum variance ratio exceeds a given threshold : the new reference sensor corresponds to the minimum variance track.

5. RESULTS

Let us describe the real experiment : the recorded signals are given by 4 sensors located close to the sea bed with an approximate immersion of 250 m; 3 sensors are equispaced on a 1000 m radius circle. The 4th sensor is located at the center of this circle. A moving surface ship has had a maneuver constituted by 5 rectilinear segments separated by circle trajectories. Its speed was constant (15 Knots). The useful bandwidth was 500 Hz and the coherent integration time 2s. Differential Delay and Doppler estimates are provided by a SCOT Differential Doppler compensated Cross Correlation [3], [5]. Processed tracks examples are showed on figures 4 and 5 . The two processors have been compared with this available data.

Then two X,Y plots show the processing results:
Figure 6 : Conventional processing ; 3 pairs of independant sensors are used, sensor 1 taken as reference. Figure 7 : New processing scheme : a set of 3 independant sensors are used taken among 4 possible sets, the best set beeing choosen with on line variance control. Processor parameters :
- track variance estimation computed with 8 time recurrences.
- track variance threshold = 4.

The estimations are similar when the moving source is close to sensor 1, whereas important improvement is observed when it is near one of the peripheral sensors (especially sensor 2).

6. CONCLUSION

The first contribution of this paper has been to show examples of Modified Ziv-Zakai Lower Bound in the case of multiple pass band signals. Then variation with respect to relative frequency centers of first ambiguity threshold effect has been showed leading to important estimation accuracy variation. Then the induced location effects have been presented, leading to an estimator taking into account these effects. At last the estimation improvements are showed on an at sea experiment.

ACKNOWLEDGMENT

This work was partly supported by DRET (French MOD, Paris, France).

REFERENCES

[1] E. Weinstein, "Measurement of Differential Doppler Shift", *IEEE trans. on Acoustics Speech and Signal Processing*, Vol ASSP 30 no 1 Feb. 1982.

[2] P.M. Schultheiss, E. Weinstein, "Estimation of Differential Doppler Shifts", *JASA* , Vol 66, Nov 1979.

[3] G.C. Carter and C.H. Knapp, "Estimation of Time Delay in the presence of source or receiver motion", In *JASA* vol 61 no 6 June 1977.

[4] Y. Chocheyras, "Time-delay and differential doppler tracking on real data", In *Proc. of the Underwater and Defence Technology Conf.* (London, UK, Feb. 1990).

[5] C.H. Knapp and G.C. Carter, "The Generalized Correlation method for estimation of Time Delay", *IEEE trans. on Acoustics Speech and Signal Processing*, vol ASSP 24 no 4 Aug. 1976.

[6] Y. Chocheyras, "Near Field Three Dimensional Time Delay and Doppler Target Motion Analysis", *Proc. ICASSP* , Glasgow, UK, May 1989 pp. 2649-2652 .

[7] E. Weinstein and A.J. Weiss, "Fundamental limitation in passive Time Delay Estimation Part 2 : Wide-Band systems", *IEEE trans. on Acoustics Speech and Signal Processing*, vol. ASSP 32 no 5 Oct 1984 pp 1064-1077.

[8] H.L. Van Trees, "Detection, Estimation, and Modulation Theory" *Wiley 1968*, Part 1 pp 116-133.

[9] D. Jaarsma, R.A. Davis, "Joint Estimation of Time Delay and Doppler Ratio from broadband Data Using Discrete Estimation Techniques", *Proc. ICASSP* , Toronto, Canada, May 1991, 428-432.

[10] L.C. Ng, Y. Bar-Shalom, "Multisensor Multitarget Time Delay Vector Estimation", *IEEE trans. on Acoustics Speech and Signal Processing*, vol. ASSP 34 no 4 Aug. 1986.

[11] B .Friedlander, "On The Cramer-Rao Bound for Time Delay and Doppler Estimation", *IEEE trans. on Information Theory* vol IT 30, no 3, May 1984.

[12] P.M. Schultheiss, E. Weinstein, "Lower bounds of the localization errors of a moving source observed by a passive array", *IEEE trans. on ASSP*, vol. 29, No 3, June 1981, 600-607.

[13] W.B. Adams, J.P. Kuhn and W.P. Whyland, "Correlator Compensation Requirements for Passive Time-Delay Estimation with Moving Source or Receivers", *IEEE trans. on ASSP*, vol. 28, no. 2, pp 158-168, April 1980

[14] J.T. Rickard , "Signal Decorrelation due to Differential Doppler ", *Proc. Asilomar Conf.*, Nineteenth Asilomar Conference on Circuits, Systems and Computer.

[15] J.O. Smith, J.S. Abel, "The spherical interpolation Method of Source Localization" *IEEE J. of Oceanic Engineering*, vol OE no.12, no 1 January 1987.

[16] J.P. Ianniello, "Time Delay Estimation via Cross-Correlation in the Presence of Large Estimation Errors" *IEEE Trans. on ASSP* vol 30 no. 6, pp 998-1003 Dec. 1982.

[17] S.C. Nardone, A.G. Lindgren, K.F. Gong, "Conventional Bearings-only Target Motion Analysis", *IEEE trans. on AC* vol 29, no. 9, sept 1984.

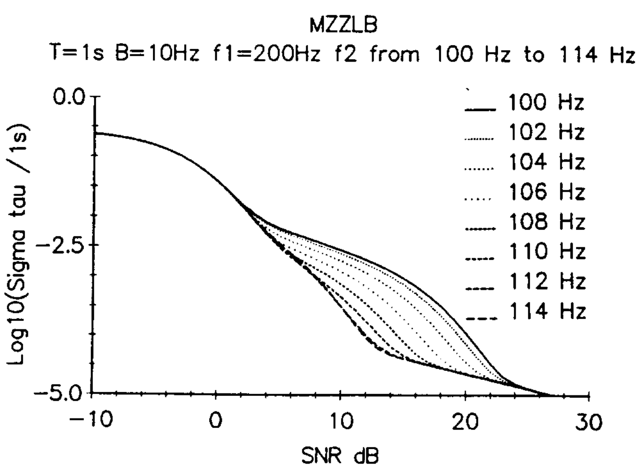

Figure 2. MZZLB f_2 from 100 Hz to 114 Hz

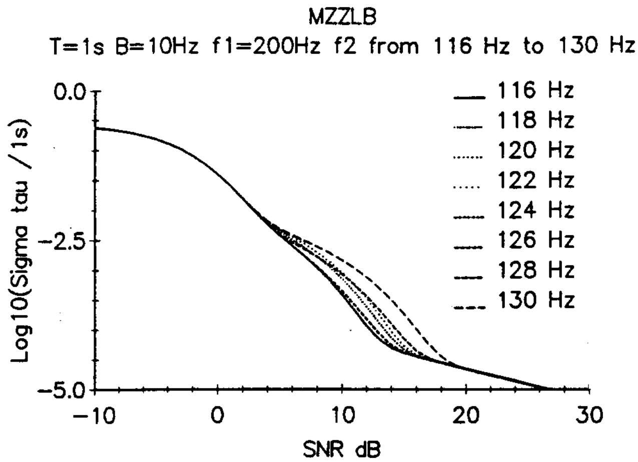

Figure 3. MZZLB f_2 from 116 Hz to 130 Hz

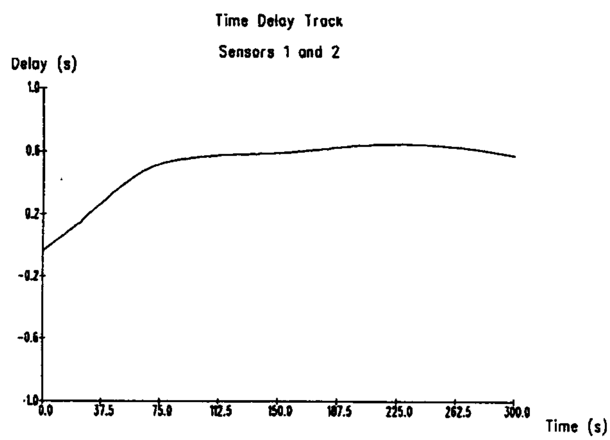

Figure 4. Time Delay track (sensors 1 and 2)

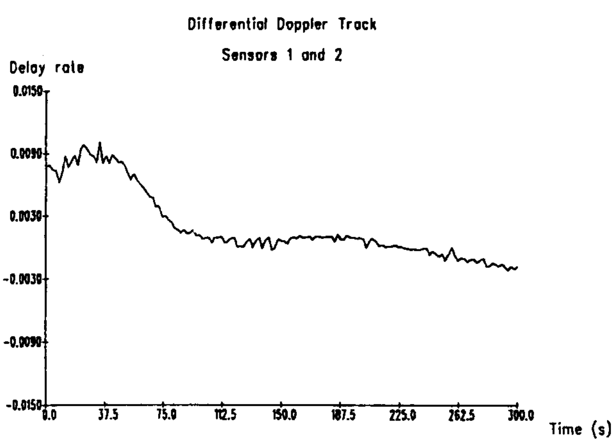

Figure 5. Differential Doppler track (sensors 1 and 2)

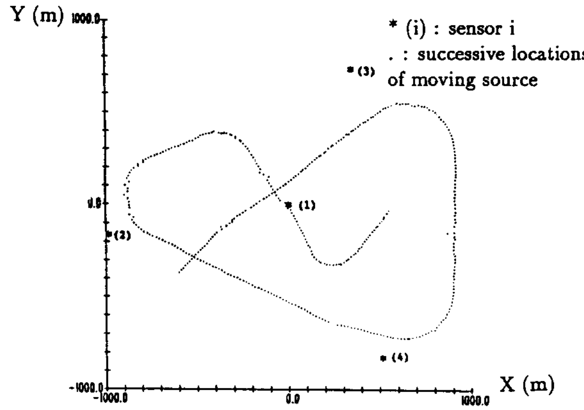

Figure 6. Estimated location (conventional processor)

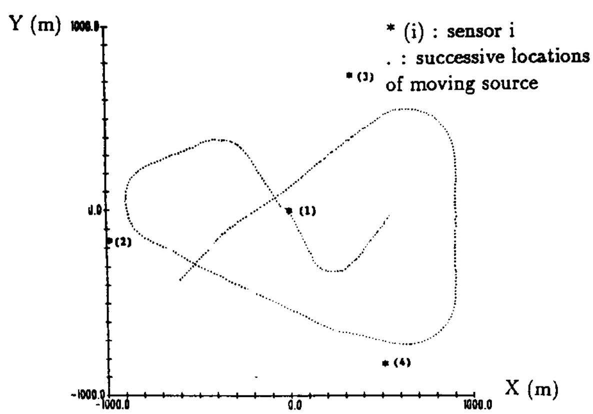

Figure 7. Estimated location (new processor)