TRACKING IN RANGE VERSUS TIME WITH APPLICATION TO MATCHED FIELD PROCESSING OF VERTICAL LINE ARRAY DATA

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ABSTRACT

Efficient linear three dimensional tracking techniques have been used to improve source localization over that from a single matched-field processing (MFP) ambiguity surface. This paper describes an efficient MFP tracker for data collected by a Vertical Line Array (VLA). The tracker assumes that the source moves at constant speed. Our two dimensional algorithm differs from tracking in three dimensions in that only source range and depth information are required, as would be available for a VLA in an essentially azimuthally independent environment. The source's initial and final range as well as its speed are estimated by the algorithm described in this paper. The method was applied to data which were collected from a VLA as part of PACIFIC SHELF 93. This trial was carried out in the shallow water of the continental shelf and slope off the western coast of Vancouver Island in the north-eastern Pacific Ocean during September 1993. Source track parameters recovered by applying the linear tracker at both 45 and 72 Hz were found to be within the uncertainty associated with the GPS records for the track when the 100 m range uncertainty introduced by the array tether was taken into account. The source level at 45 Hz was typical of a strong line on a merchant vessel while the 72 Hz line was 20 dB lower.

SOMMAIRE

Des techniques de poursuite linéaires à trois dimensions ont servi à améliorer la localisation de sources par rapport à l'emploi d'une selle surface de doute au traitement de champs appariés (TCA). Dans cet article nous décrivons un suiveur au TCA efficace pour des données saisies au moyen d'un réseau à ligne verticale (RLV). Le suiveur présume que la source se déplace à une vitesse constante. Notre algorithme à deux dimensions diffère de la poursuite à trois dimensions puisque seulement les renseignements à propos de la portée et de la profondur des sources sont nécessaires, tels que seraient disponibles pour un RLV dans un environnement essentiellement indépendent de l'azimut. Nous avons employé l'algorithme décrit dans cet article pour calculer par approximation les portées initiale et finale ainsi que la vitesse de la source. Nous avons appliqué la méthode aux données saisies d'un RLV en tante que parti du projet PACIFIC SHELF 93. Cet essai a éta exécuté dans les eaux peu profondes du plateau continental et du talus continental sur la côte ouest de l'île de Vancouver au nord-est de l'Ocean Pacifique durant septembre 1993. Nous avons constaté que les paramètres de poursuite des sources recouvrés en appliquant le suiveur linéaire à 45, aussi bien qu'à 72 Hz, étaient dans le cadre de l'incertitude associée avec les données du systeme mondial de positionnement pour la voie lorsque l'on a tenu compte de l'incertitude de la portée de 100 m introduite par l'amarre du réseau. Le niveau de la source à 45 Hz était typique d'une ligne forte sur un navire de commerce tandis que la ligne à 72 Hz était 20 dB plus faible.

1. INTRODUCTION

This paper describes a tracker that may be employed to track a source when its range alone is known as a function of time. Our application is to ranges determined from Matched Field Processing (MFP) in underwater acoustics. However, the algorithm may be applied to other acoustics problems or tracking with radar.

MFP is an advanced signal processing method for the localization and detection of acoustic sources.[1] In MFP the measured acoustic field is matched against a prediction of the acoustic field for all possible source positions in the search region. The (unnormalized) correlation between measured and predicted fields is called an ambiguity surface. In many cases, however, especially for low SNR sources, it is impossible to infer a source's position unambiguously based on these matches from an individual ambiguity surface. For a set of MFP ambiguity surfaces contiguous in time, an efficient three dimensional (i.e., range, depth and bearing) technique to track acoustic sources moving linearly at constant speed and heading has been proposed.[2,3] The method has been successfully applied to both simulated[2,3] and measured data.[4] For this tracker the strongest peaks on the set of ambiguity surfaces are used to define possible source tracks. Linear tracks passing through pairwise combinations of the positions of these strongest peaks, taken from ambiguity surfaces corresponding to different times, are candidate source tracks. In the next stage of the algorithm tracks corresponding to target speeds that are not physically possible are rejected. To find the most likely tracks the averages of the processor output are found for each position predicted by the remaining candidate source tracks. The track with the largest average, provided that it is also greater than a preassigned threshold, is considered a source track. The number of tracks examined is orders of magnitude less than the exhaustive case of all linear constant speed tracks through the possible source positions that comprise the ambiguity surface.

As noted above an efficient three dimensional tracker, for sources with constant speed and heading, has been successfully applied to both simulated [2,3] and measured data.[4] Reference 4 tracks the source in three dimensions in the PACIFIC SHELF data, assuming it is moving at constant speed and heading, by approximating the two legs of the track as radial tracks. Reference [7] also tracks the source in three dimensions but removes the radial track restriction. Reference [8] exhaustively searches in two dimensions for constant speed radial tracks in a similar experiment, called SWellEX-3, by determining the track with the largest average value for the normalized Bartlett processor i.e. *correlation* along the track.[9]

When acoustic data comes from a Vertical Line Array (VLA) in an essentially azimuthally symmetric environment only source range and depth can be determined. The azimuth of a source can not be determined because of the environmental and array symmetry. Under such conditions a two dimensional tracker, in many respects similar to the three dimensional tracker just described, is required for combining the positions on the range-depth ambiguity surfaces. The difference from the three dimensional tracker is that the source's bearing is not obtained; only its depth, start and stop ranges and speed, or their equivalent, can be estimated. To estimate these quantities with the VLA tracker source ranges at three distinct times are required. This differs from the three dimensional tracker [7] for which (range,depth,bearing) coordinates at two distinct times are required. The input to these trackers is chosen to be the Bartlett processor[1] output as a function of time and range *for a constant depth*, although other processors could be used. The tracker can be generalized to track sources that have constant diving or surfacing rates. This paper describes and applies a tracker to a signal at a single frequency, however the algorithm would work equally well for broadband radiated energy from a sound source.The algorithm described efficiently searches in two dimensions for the constant speed and heading track, radial or non-radial, with the largest Bartlett average along the track. Localization is restricted to range and depth in this study on account of the symmetry of the array and environment.

The paper is organized as follows. Following this introduction a brief description is given of the environment and VLA data collected during the PACIFIC SHELF experiment and of the generation of ambiguity surfaces. Next the tracking algorithm for VLA data is outlined and the algorithm applied to track the source at two of the source frequencies.

2. PACIFIC SHELF EXPERIMENT AND MFP PROCESSING

2.1 Scenario

A series of ocean acoustic experiments referred to as the PACIFIC SHELF trials were completed in September, 1993 by the Defence Research Establishment Pacific, Victoria, B.C., and the Applied Research Laboratory, University of Texas at Austin. The experiment is summarized below and described more fully in Ozard et al.[4] The experiments were conducted at the site shown

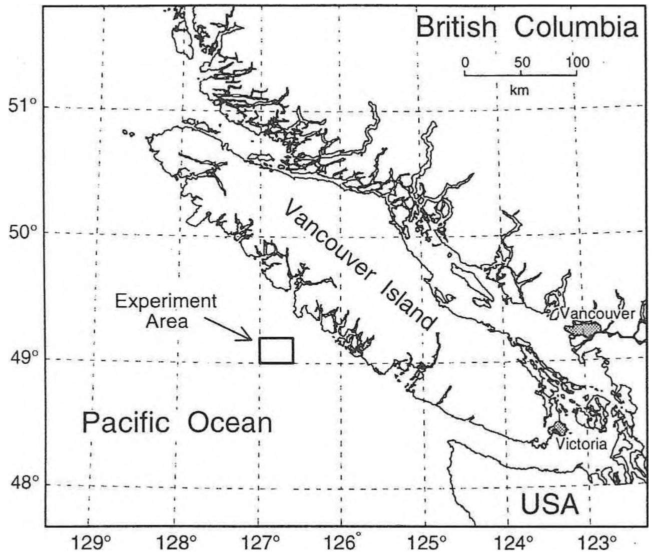

Figure 1: The location of the experiment is shown with respect to the south-western coastline of British Columbia, Canada.

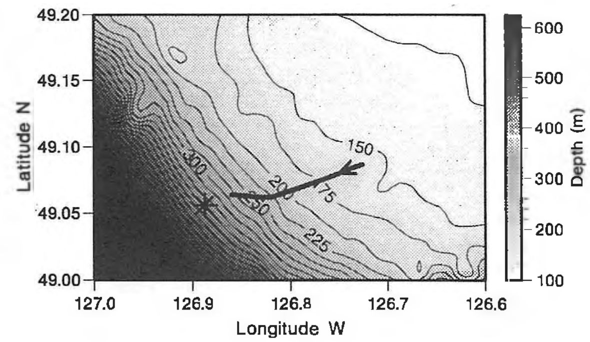

Figure 2: The towed source's track, which closed on the array, is shown superimposed on the bathymetry. The star represents the VLA location at the beginning of the experiment.

in Figure 1 on the continental slope and shelf regions off Vancouver Island, which is situated in the North-East Pacific Ocean.

The CSS WE RICKER was the source ship for the impulsive sources and the multi-frequency Continuous Wave (CW) towed sound source, while the CFAV ENDEAVOUR collected acoustical data from either a Vertical Line Array or Horizontal Line Array (HLA). In the portion of the trial analyzed here a CW multi-frequency source was towed at constant speed and heading along two segments that formed a dog leg pattern shown in Figure 2.

As can be seen the towed source's track began on the continental shelf, where the water depth was about 150 m, and proceeded towards the VLA located in deeper water on the continental slope at an approximate water depth of 375 m. The source tow took a total of about 65 minutes. At the start time, the initial source to receiver range was about 12 km. As can be seen in Figure 2, there was an abrupt source ship course change 41 minutes after the start time. Since the algorithm tracks a source of constant speed and heading the data analysed in this paper was partitioned into two data sets. These two data sets will be referred to as far-range (before the course change) and near-range (after the course change). The array float position and tow ship position were measured with Global Positioning System (GPS) receivers. The GPS measurement errors (100 m), combined with the error associated with the tether length between array and buoy containing the GPS and telemetry electronics (100 m), resulted in an overall uncertainty of the source to receiver range of approximately 200 m.

In Figure 3 the depths of the VLA are plotted over environmental information used to model the field. There were sixteen hydrophones equispaced at 15 m with the depth for the uppermost hydrophone being 90 m $\pm$ 2 m. The data were collected at a sample rate of 1500 Hz.

The environmental model was based on the measured sound speed profile, taken at the time of the experiment, and other parameters were obtained from the analysis of the impulsive source data collected in the vicinity of the array in an associated seismic experiment.[5]

2.2 MFP Processing

The Bartlett processor [1] $B(p)$, at position p, defined as

$$B(p) = \frac{1}{NA} \sum_{i=1}^{NA} \mid r(p)^* d_i \mid^2, \qquad (1)$$

was used for this study. Here d_i, NA and r, represent respectively the transformed data vectors, the number of data averages and the unit norm replica vector. The transformed data is obtained from a 4096 point Fast Fourier Transform of the time series data at the signal frequencies of 45 or 72 Hz or the nearby noise frequencies of 43 or 75 Hz. The number of inner products averaged was NA=11; thus each Bartlett output represents about 30 seconds of data. The replica or modelled fields

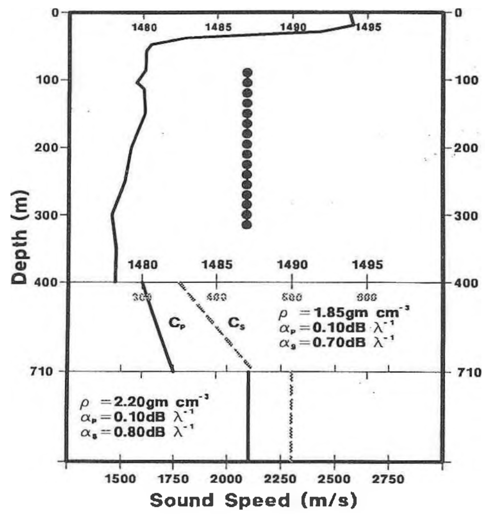

Figure 3: The sound-speed profile used in the environment model is shown as well as the shear speed (dashed) and compressional speed (solid) for which the two lower abscissa scales apply respectively. The hydrophone depths are also noted.

used in this analysis were based on previously described, but limited, environmental knowledge using Westwood's normal mode model, ORCA.[6] ORCA was selected for its reliability in finding the normal mode parameters in a shallow water environment. In the two dimensional analysis described here, the bottom bathmetry used to generate the replicas was that for the radial from the array to the starting point of the far range track position. The Bartlett output from Equation 1 was normalized to have a maximum value of unity by dividing by d^*d to form the Bartlett correlations. The maximum Bartlett correlations at 45 and 72 Hz ranged from 0.75 to 0.95 and 0.60 to 0.85, respectively.[4] These correlations reflect a good fit between the data and the replicas from the model. However the positions corresponding to these correlations did not always coincide with the source range and depth.

3. TRACKING ALGORITHM

The VLA tracking algorithm consists of five sets of computations performed at each possible source depth. While the algorithm described here applies to a source whose depth remains constant it can be modified to track a source that dives or surfaces at a constant rate over the track. The input is a time-versus-range ambiguity surface of the Bartlett outputs at some constant depth and frequency. The computations are:

(1) for each of the NT times, for which an ambiguity surface is available, the positions of the largest NPK peaks are determined;

(2) all combinations of three peak positions, at different times, are determined and the linear tracks, if any, passing through these combinations of points are found (See explanation at the end of this section). These are the combinatoric tracks ;

(3) a constraint to realistic maximum speeds for the source is imposed to reduce the combinatoric tracks to physically possible tracks;

(4) for each physically possible track the track statistic T is determined

$$T = \sum_{k=1}^{NT} \frac{1}{NT} B(p_k), \tag{2}$$

which sums the Bartlett output over the NT times for the points on the track. Here p_k represents the position from the range grid point which is nearest to the track at time k;

(5) the significant tracks are those with the largest estimated track SNR,

$$SNR = \frac{T - \bar{x}}{s}\sqrt{NT} \tag{3}$$

where $\bar{x}$ and s are the respective mean and standard deviation of the noise for the time versus range ambiguity surface at a neighbouring non-signal frequency at the depth of analysis.

The following is a description of the calculations used to determine the track parameters for the combinatoric tracks obtained at step 2 of the tracking algorithm. Recall that only range-versus-time information for the source position is available, so that no source bearing information can be deduced from the data. Any linear constant speed track can be characterized by its range a from the VLA at the origin O at time 0, its speed v and angle β which is measured from AO as shown in Figure 4. A is the source position at time 0. Note that the orientation of AO is unknown and cannot be determined in the azimuthally independent environment. At time t_i the range R_i obeys the Cosine Law

$$R_i^2 = a^2 + (vt_i)^2 - 2avt_i cos(\beta). \tag{4}$$

The data set $(t_i, R_i), i = 1,2,3; t_1 < t_2 < t_3$, obtained at step 1 of the algorithm, when substituted in Equation 4 results in a set of three equations with three unknowns. These equations define a linear constant speed track if they can be solved for a, v and $cos(\beta)$. When there is a solution the equations reduce to a set of two linear equations in a^2 and v^2, and then $cos(\beta)$ is easily found. The nature of the cosine means β is ambiguous; it could correspond to an angle measured clockwise or counterclockwise from AO. The dashed line in Figure 4 represents the alternate source track because of the ambiguity in β. Once a, v, and $cos(\beta)$ are estimated one can easily determine the range at the start time R_{st}, and range at the stop time, R_{sp}. The tracks found form families corresponding to the possible orientation of OA between 0 and 360 degrees and are ambiguous in the sign of β. These ambiguities are, of course, not apparent on a range versus time plot.

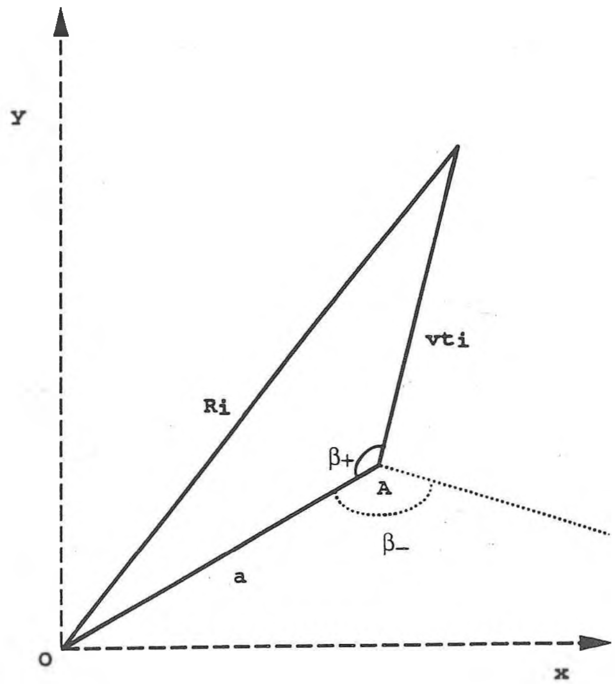

Figure 4: Parameters defining a linear track with constant speed v, distance a from the VLA at the origin O at time 0, and angle β in a cartesian coordinate system. A is the source position at time 0. The orientation of OA is unknown. The solid line corresponds to the track for the angle β measured clockwise from AO. The dotted line corresponds to the alternate track for the angle β measured counterclockwise from AO.

An exhaustive search for tracks passing through three points results in $[NT(NT-1)(NT-2)(NR)^3]/3!$ combinatoric tracks where NR is the number of ranges. In the efficient algorithm described here NR is replaced by the number of peaks NPK consequently the algorithm examines $[NT(NT-1)(NT-2)(NPK)^3]/3!$ combinatoric tracks. This reduces the number of combinatoric tracks by $(NPK/NR)^3$ or 1.5×10^{-5} for the example described here. Clearly such an algorithm is much more efficient than an exhaustive search.

4. TRACKING RESULTS

The VLA tracking algorithm operates on a time-versus-range ambiguity surface, i.e., the environment is treated as essentially azmuthally independent. There is slight symmetry breaking in the PACIFIC SHELF environment, as can be seen in Figure 2, however since azimuthal independence of the environment is not a requirement for the VLA tracker this data set can be used to demonstrate the application of the VLA tracker.

The ambiguity surface for the 72 Hz tone at 30 m depth. the source depth, is given in Figure 5. The dotted curve is the track range estimates from the VLA tracker for the far (5-12 km) and near (< 5 km) ranges. At any one time the source is likely to be at any of the bright regions in range while the tracker has identified the track with highest likelihood. Thus the tracker has reduced the ambiguity of the sound source's range throughout the time interval analysed. It should be noted that in the range time plot a linear track is a straight line only if the track is radial. The ambiguity surface and tracks at 45 Hz are similar. The VLA algorithm yielded the highest estimated track SNR at the 30 m source depth, indicating that the source was at a depth of 30 m, in agreement with the source depth in the trial log. For this analysis the 10 largest peaks were found for each snapshot in step 1 of the algorithm and the speed was constrained to be a maximum of 5 m/s. The estimated noise mean and standard deviation for 45 and 72 Hz were calculated from the 43 and 75 Hz ambiguity surfaces respectively. These estimates were used in Equation 3 to calculate the estimated track SNR. The source track parameter estimates for the algorithm for the far and near ranges for both tones are given in Tables 1 and 2. We do not use the Closest Point of Approach (CPA) as a track parameter because the CPA uncertainty can be very large at long ranges and is not a representative measure of the track position uncertainty. As can be seen from the table the range differences from the GPS results are between 17 and 190 m. Recall the error in measuring range position using GPS including the uncertainty from the array tether, is approximately 200 m. The speed estimates also agree well with estimates from the GPS values.

The track SNR in Equation 3 is measured in standard de-

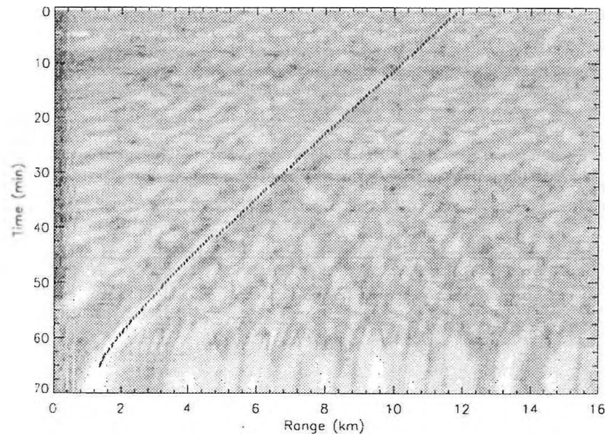

Figure 5: The logarithm of the Bartlett statistics for the PACIFIC SHELF 72 Hz tone, plotted for a time-versus-range ambiguity surface at a depth of 30 m. White represents a value of 30 dB and black 60 dB in this grey scale plot. The dotted curve is the track range estimates for the far and near ranges. The near range track extends to about 5 km while the far range set runs from 5 km to 12 km

viations of the noise ambiguity surface. If there is no mismatch, the noise is spatially uncorrelated and the SNR is constant along the track, the tracker increases the SNR by a factor of $NS * \sqrt{NT} * \sqrt{NA}$ (i.e., $16 * \sqrt{82} * \sqrt{11}$ or 26.6 dB) over the average sensor SNR. In practice we have mismatch in environmental parameters and array geometry and the sensor SNR is time dependent. Furthermore at 43 and 75 Hz the noise is spatially correlated. This is not surprising as the experiment was conducted in shallow water near a major shipping lane. The noisy tow ship and the recording ship near the array also contributed to the noise field. The over-estimation

Table 1: Comparison of GPS track and estimates from the VLA algorithm at 45 Hz and 72 Hz for the 41 minute far range data set. R_{st} is the start range in m, R_{sp} is the stop range in m and v is the speed in m/s while the track SNR is in dB. The range differences in m from GPS results are in parentheses.

Far range				
	R_{st}	R_{sp}	v	SNR
GPS	11778	4820	2.86	
45 Hz	11607 (-171)	4650 (-170)	2.87	21.0
72 Hz	11878 (100)	4850 (30)	2.89	17.8

Table 2: Comparison of GPS track and estimates from the VLA algorithm at 45 Hz and 72 Hz for the near range 24 minute data set. For details see the caption of Table 1.

Near range				
	R_{st}	R_{sp}	v	SNR
GPS	4820	1291	2.90	
45 Hz	4630 (-190)	1274 (17)	2.71	26.5
72 Hz	4663 (-157)	1353 (62)	2.72	22.7

of the noise level through spatial leakage and from correlated noise sources as well as the presence of mismatch imply that the measured track SNR is expected to be lower than the theoretical value for the idealized scenario. Nevertheless, the track SNR was a maximum at 30 m and the track identified agreed with the known source track.

With one VLA the bearing of a point on the track is ambiguous. This ambiguity would be reduced with information from hydrophones that are nearby but horizontally separated from the VLA.

5. CONCLUSIONS

An efficient VLA tracking algorithm for an azimuthally independent environment has been described and applied to data collected in shallow water. At both 45 Hz and 72 Hz, estimates from the acoustic data for the source's initial and final range and its speed agreed closely with the GPS measurements. The range difference between the GPS and tracking algorithm estimates at both frequencies is less than 200 m. A substantial part of this difference can be ascribed to the uncertainty introduced by the array to GPS buoy tether. The VLA tracker significantly reduced source range ambiguity compared to that obtained from individual ambiguity surfaces by determining the track of highest SNR, enabling tracking of the source range at distances up to 12 kilometres.

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