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AN ANALYTICAL INVESTIGATION OF THE EFFECTS OF MISMATCH ON MATCHED FIELD PROCESSING

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I. Introduction

The performance of Matched Field Processing (MFP) is dependent on mismatch. This report will investigate the dependence of MFP to environmental mismatch, source radial velocity mismatch, array tilt and random modal phases. In the analysis it is assumed that sound propagation is described by Normal Modes (NM).

Following the introduction there are in section II separate analysis of mismatch for vertical and horizontal arrays. Environmental and source velocity mismatches, for vertical arrays, result in modal phase errors that increasing degrade MFP with increasing source range. For horizontal arrays, environmental and source velocity mismatch result in hydrophone and modal phase errors. The hydrophone phase errors increasing degrade MFP with increasing array length and increasing source bearing as measured from broadside. Furthermore, analysis indicate that phase errors can seperate into a mean phase error that may be forgiven and a variation about the mean. The ratio of the mean phase error to the standard deviation of the variation about the mean is a measure of how forgiving the MFP is to the mismatch.

Array tilt mismatch for vertical and horizontal arrays are analyzed seperately. For vertical arrays the mismatch is found to increase with increasing array tilt and array length. For horizontal arrays the mismatch increases with increasing tilt, array length and bearing as measured from broadside. Section II concludes with a brief analysis of random modal phases.

Section III is the simulation of environmental, source speed and array tilt mismatch. Simulation results are in good agreement with analysis. Section IV is the report summary and conclusions.

II. Mismatch Analysis

To analysis mismatch effects in MFP, first a NM description of sound propagation is used (eqn. 1).

$\hat{p}_\ell(r,z)$ = pressure at ℓ^{th} hydrophone of a vertical array due to stationary source at range 'r' and depth 'z'

$$= \text{constant} \sum_{m=1}^{M} U_m(z_0)U_m(z)e^{iK_m r}/\sqrt{K_m r} \qquad (1)$$

where

M = number of normal modes

z_ℓ = depth of ℓ^{th} hydrophone

$U_m(z)$ = the m^{th} NM eigenfunction

K_m = m^{th} NM eigenvalue (will be complex when there is modal attenuation).

Second, to analysis mismatch, a linear, data normalized MFP beamformer b(r,z) is used (eqn. 2).

$$b(r,z) = \frac{\left|\sum_{\ell=1}^{L} p_\ell^{*}, \hat{p}_\ell(r,z)\right|^2}{\sum_{\ell=1}^{L} |p_\ell|^2 \sum_{\ell=1}^{L} |\hat{p}_\ell(r,z)|^2} \qquad (2)$$

where

L = number of hydrophones

p_ℓ = measured pressure at ℓ^{th} hydrophone.

For beamforming the constant of eqn. 1 can be set equal to unity and $\sqrt{r}$ factor in the denominator ignored. $\hat{p}_\ell(r,z)$ is referred to as the replical vector and p_ℓ as the data vector.

The NM eigenvalues and eigenfunctions are dependent on the ocean environment. Since the environment is not perfectly known there is an environmental mismatch effect in MFP.

First environmental mismatch for vertical arrays is investigated. Let K_{mc} , $U_{mc}(z)$ denote the mismatched NM eigenvalue and eigenfunction of the m^{th} mode. Then

$$K_{mc} = K_m + \mu + \mu_m \tag{3}$$

$$U_{mc}(z) \approx U_m(z) \tag{4}$$

where

μ = mean eigenvalue error

$$= \frac{1}{M} \sum_{m=1}^{M} (K_{mc} - K_m) \tag{5}$$

μ_m = variation of eigenvalue error about the mean = $K_{mc} - K_m - \mu$ (6)

σ_μ^2 = variance of eigenvalue error

$$= \frac{1}{M} \sum_{m=1}^{m} \mu_m^2 \ . \tag{7}$$

We assume in eqn. 4 the mismatch of the eigenfunctions are less important than the mismatch of the eigenvalue as amplitude mismatch is less important than phase mismatch. This will be commented upon later.

Rewriting a mismatched eqn. 1 for a vertical line array has

$$\hat{p}_\ell(r,z) = \sum_{m=1}^{M} U_{mc}(z_\ell) U_{mc}(z) \frac{e^{iK_{mc}r}}{\sqrt{K_{mc}}} \quad . \tag{8}$$

Substituting eqns. 3 and 4 yields

$$\hat{p}_\ell(r,z) \approx e^{i\mu r} \sum_{m=1}^{M} U_m(z_\ell) U_m(z) \frac{e^{iK_m r}}{\sqrt{K_m}} \cdot e^{i\mu_m r} \tag{9}$$

where

$e^{i\mu r}$ is a hydrophone phase error which is forgiven as it is absorbed in the modulus of eqn. 2.

$e^{i\mu_m r}$ is a range dependent modal phase error and is related to the mean eigenvalue error μ (eqn. 6), the standard deviation σ_μ (eqn. 7) and consequently to the ratio $|\mu|/\sigma_\mu$.

The mean error μ is forgiven but the μ_m which is related to σ_μ, is not. The higher the $|\mu|/\sigma_\mu$ ratio, the more forgiving MFP is to the mismatch. This is demonstrated in the simulations.

Second, mismatch for horizontal arrays will be analyzed. A farfield source is assumed, that is, the array is not focused.

$$r_\ell \equiv \text{source to } \ell^{th} \text{ hydrophone distance}$$

$$\simeq r + x_\ell \sin\beta \tag{10}$$

where

$r \equiv$ source to array mid-point distance

$x_\ell \equiv$ coordinate of ℓ^{th} hydrophone on the x-axis

β = source bearing measured from broadside.

Rewriting mismatched eqn. 1 for horizontal arrays yields

$$\hat{p}_\ell(r,z,\beta) = \sum_{m=1}^{M} U_{me}(z_a)U_{me}(z)\,\frac{e^{iK_{me}r_\ell}}{\sqrt{K_m}} \tag{11}$$

where

z_a = array depth .

Substituting eqns. 3, 4 and 10 into eqn. 11 yields

$$\hat{p}_\ell(r,z,\beta) = \sum_{m=1}^{M} U_m(z_a)U_m(z)\,\frac{e^{i(K_m+\mu+\mu_m)(r+x_\ell\sin\beta)}}{\sqrt{K_m+\mu+\mu_m}}$$

$$\simeq e^{i\mu r}\cdot e^{i\mu x_\ell \sin\beta}\sum_{m=1}^{M} U_m(z_a)U_m(z)\,\frac{e^{iK_m(r+x_\ell\sin\beta)}\cdot e^{i\mu_m(r+x_\ell\sin\beta)}}{\sqrt{K_m}} \quad . \tag{12}$$

In eqn. 12

$e^{i\mu r}$ is again a forgiven hydrophone phase error factor

$e^{i\mu x_\ell \sin\beta}$ is a hydrophone phase error factor which increases with increasing array length and increasing bearing as measured from broadside

$e^{i\mu_m (r + x_\ell \sin\beta)}$ is a modal phase error factor which increases with source range.

Hawker [1] derived NM theory for a moving source. To first order, conversion of eqn. 1 to the moving source scenario requires:

$$K_m \Rightarrow K_m/(1+\dot{r}/V_{gm}) \tag{13}$$

where

$\dot{r}$ = radial velocity

V_{gm} = group velocity of the m^{th} normal mode .

Matching to a moving source with normal modes of a non-moving source results, to first order, a source speed mismatch with (from eqns. 5, 6 and 7).

μ = mean eigenvalue error

$$= \frac{1}{M}\sum_{m=1}^{M} (K_{mc} - K_m)$$

$$\simeq -\frac{\dot{r}}{M}\sum_{m=1}^{M} K_m / V_{gm} \tag{14}$$

μ_m = mismatch minus mean mismatch

$$= K_m/(1+\dot{r}/V_{gm}) - K_m - \mu$$

$$\simeq -\dot{r}\, K_m/V_{gm} - \mu \tag{15}$$

σ_μ^2 = variance of eigenvalue error

$$= \frac{1}{M}\sum_{m=1}^{m} \mu_m^2$$

$$\simeq \frac{\dot{r}^2}{M}\sum_m \left(\frac{K_m}{V_{gm}}\right)^2 + 3\,\frac{\dot{r}^2}{M^2}\left(\sum_m \frac{K_m}{V_{gm}}\right)^2 \quad . \tag{16}$$

The source speed mismatch analysis is identical to the environmental mismatch analysis.

Array tilt α, measured from the vertical for vertical arrays requires the substitutions

$r \Rightarrow r + (z_\ell - z_1) \sin \alpha$

$z_\ell \Rightarrow z_1 + (z_\ell - z_1) \cos \alpha$

in eqn. 1 yielding

$$\hat{p}_\ell(r,z) = \sum_{m=1}^{M} U_m(z_1 + (z_\ell - z_1)\cos\alpha) U_m(z) \frac{e^{iK_m(r+(z_\ell - z_1)\sin\alpha)}}{\sqrt{K_m}} \quad . \tag{17}$$

The array tilt mismatch, for vertical arrays, is a function of $z_\ell - z_1$ and therefore is array length dependent.

Array tilt α, measured from the horizontal, for horizontal arrays requires the substitutions

$r_\ell \Rightarrow r + x_\ell \sin \beta \cos \alpha$

$z_a \Rightarrow z_a + x_\ell \sin \alpha$

in eqn. 11 yielding

$$\hat{p}_\ell(r,z,\beta) = \sum_{m=1}^{M} U_m(z_a + x_\ell \sin\alpha) U_m(z) \frac{e^{iK_m(r + x_\ell \sin\beta \cos\alpha)}}{\sqrt{K_m}} \quad . \tag{18}$$

The array tilt mismatch effects for horizontal arrays are a function of x_ℓ and $x_\ell \sin \beta$ resulting in array length and source bearing dependence.

Including random modal phase errors ϕ_m in eqn. 1 results in

$$\hat{p}_\ell(r,z) = \sum_{m=1}^{M} U_m(z_\ell) U_m(z) \frac{e^{i(K_m r + \phi_m)}}{\sqrt{K_m}} \quad . \tag{19}$$

The mean modal phase error μ defined by

$$\mu = \frac{1}{M} \sum_{m=1}^{M} \phi_m \tag{20}$$

will be forgiven but the variation μ_m about the mean defined by

$$\mu_m = K_m - \mu \tag{21}$$

will result in modal phase error mismatch. The analysis for horizontal arrays is identical. For further analysis of random modal phase see Klemm [2].

III. Simulations

For the simulations to follow NM code for a simple isovelocity waveguide with a hard bottom is used. The normal modes for this waveguide are:

K_m = m^{th} normal mode eigenvalue (horizontal wave number)

$$= \sqrt{w^2/c^2 - \gamma_n^2} \tag{22}$$

$U_m(z)$ = m^{th} normal mode eigenfunction

$$= \sqrt{\tfrac{2}{h}} \sin \gamma_n z \tag{23}$$

where

$w = 2\pi \cdot$ source frequency (f)

c = speed of sound in the waveguide

h = waveguide depth

γ_n = vertical wavenumber

$$= \tfrac{\pi}{h} (n - \tfrac{1}{2}) \quad . \tag{24}$$

Also

N = number of normal modes

$$= \text{integer}\,(\tfrac{1}{2} + \tfrac{wh}{\pi c}) \quad . \tag{25}$$

In the simulations, unless stated otherwise, the data is generated with

$f = 20H_z$

c = 1500 m/sec

h = 400 m

also

rs = source range

= 20 km

zs = source depth

= 150 m

vs = source radial velocity

= 0 m/sec.

The group velocity $V_{gm} \equiv \partial w/\partial K_m$ is for our simple waveguide

$V_{gm} \equiv c^2 K_m/w$

Examples of vertical array environmental mismatch:

For the previously defined environmental parameters, the number of normal modes via eqn. 25 is $N = 11$. The vertical array consist of 15 hydrophones. The uppermost hydrophone is at 20 m and the hydrophone spacing is 20 m. The horizontal array consist of 30 hydrophones with hydrophone spacings of 20 m or 40 m. The array depth is 100 m. The source range = 20 km and the source depth is 150 m unless specified otherwise. For vertical array tables a course grid search (grid spacings $\Delta r = 25$, $\Delta z = 5m$) is followed by a fine grid search (grid spacings $\Delta r = 5m$, $\Delta z = 1m$). For horizontal array tables a course grid search (grid spacings $\Delta r = 50m$, $\Delta z = 5m$, $\Delta\beta = 1$ deg.) is followed by a fine grid search (grid spacings $\Delta r = 5m$, $\Delta z = 1m$, $\Delta\beta = 1$ deg.). In all tables the beamformer output max.b is given by eqn. 2. In generating the replica field $\hat{p}(r,z)$ for the linear beamformer defined by eqn. 2 a sound speed mismatch of $c = 1505$ m/sec is used. This sound speed mismatch effects only the eigenvalues and not the eigenfunctions (see eqns. 22 and 24).

Table 1 demonstrates the predicited range dependence (eqn. 9) of the sound speed profile mismatch (exact $c = 1500$ m/sec vs. estimated $c = 1505$ m/sec). The maximum beamformer output 'max.b' decreases with source range except for one anomaly. Again table 2 is a repeat of the table 1 scenario except with a greater sound speed profile mismatch (exact c = 1500 m/sec vs. estimated c = 1510 m/sec). As in table 1 the maximum beamformer output decreases, as predicited, with range with again the exception of one anomaly.

r(m)	est. r(m)	est. z(m)	max. b
2500	2485	154	.9736
5000	4950	153	.9295
10000	9925	154	.9389
15000	14885	150	.8845
20000	19850	152	.8226

Table 1: Sound Speed Profile Mismatch (c = 1505 m/sec) for Vertical Array

r(m)	est. r(m)	est. z(m)	max. b
2500	2465	152	.9694
5000	4925	154	.8956
10000	9855	153	.7891
15000	14910	149	.6145
20000	19845	150	.6989

Table 2: Sound Speed Profile Mismatch (c = 1510 m/sec) for Vertical Array

r(m)	est. r(m)	est. z(m)	max. b
2500	2600	151	.9485
5000	5200	154	.9122
10000	10260	151	.7796
15000	15465	149	.8652
20000	20675	155	.7540

Table 3: Ocean Depth Mismatch (h = 405m) for Vertical Array

r(m)	est. r(m)	est. z(m)	max. b
2500	2600	149	.9513
5000	5200	152	.9021
10000	10260	149	.7799
15000	15465	148	.8556
20000	20675	153	.7547

Table 4: Ocean Depth Mismatch (h = 405m) with Non-mismatched Eigenfunctions for Vertical Array

Ocean depth 'h' mismatches are illustrated in tables 3 and 4. In table 3 the ocean depth mismatch (exact h = 400m vs. estimated h = 405m) results in a decreasing beamformer output as range increases except for one anomaly. In table 3 the replica pressures were calculated for eigenfunctions $U_m(z)$ and eigenvalues K_m for ocean depth h = 400m . In table 4 the replica pressures were calculated for eigenfunctions $U_m(z)$ for the exact ocean depth h = 400m and for eigenvalues K_m for the mismatched ocean depth h = 405m . Comparing tables 3 and 4 indicate the mismatch effects are dominated by the error in the eigenvalue K_m and not the error in the eigenfunction $U_m(z)$.

β(deg)	est. r(m)	est. z(M)	est. β(deg)	max. b
20	20695	150	20	.8968
45	20695	150	46	.8825
70	20700	150	74	.8454
90	19155	149	90	.7651

Table 5: Sound Speed Mismatch (c = 1505 m/sec) for Horizontal Array, Hydrophone Spacing = 40m .

β(deg)	est. r(m)	est. z(M)	est. β(deg)	max. b
20	19160	150	20	.9854
45	19160	151	45	.9574
70	20695	151	71	.8793
90	20695	150	90	.8631

Table 6: Sound Speed Mismatch (c = 1505 m/sec) for Horizontal Array, Hydrophone Spacing = 20m .

Mismatch in horizontal array results in both hydrophone and modal phase errors. the hydrophone phase error $\mu x_\ell \sin\beta$ increases with increasing bearing as demonstrated in tables 5 and 6. The hydrophone phase error also increases with array length. The horizontal arrays have 30 hydrophones. In table 5 the hydrophone spacing is 40m ; in table 6 the hydrophone spacing is 20m . A comparison of corresponding 'max b' values in tables 5 and 6 demonstrate the predicted hydrophone phase error dependence on array length.

Environmental mismatch results in hydrophone phase errors and modal phase errors for horizontal arrays. For vertical arrays environmental mismatch results in only modal phase errors and it has been demonstrated these result in a loss of mainlobe height with increasing range. With horizontal arrays it may appear that there should be again a loss of mainlobe height with increasing range as the modal error is multiplied by range. However, simulations indicate that hydrophone and modal phase errors together do not result in environmental mismatch range dependent effects. Although the hydrophone phase errors result in predictable array length and bearing dependent effects, the modal phase errors effects are not independent of the hydrophone phase errors, that is, the hydrophone and modal phase error effects are coupled. In table 7, the array spacing is 40m, the source bearing is 45 deg. and output 'max b' is tabulated as a function of range and demonstrates no range dependent effect of modal phase errors on 'max b' when hydrophone phase errors are present.

Source speed mismatch (v = 10 m/sec, est. v = 0 m/sec) is illustrated in tables 8 and 9 for vertical and horizontal arrays respectively. The source speed mismatch loss is range dependent as predicted. Furthermore the loss as a function of range compared to the sample environmental mismatches, is small. This is very important for real world scenarios as MFP search space can be restricted to source position thereby reducing processing requirements.

In general the ratio of the mean e.v. mismatch to the std. dev. of the e.v. mismatch $|\mu|/\sigma_\mu$ is a measure of forgiveness. For example when the sound speed mismatch (exact c = 1500 m/sec, est. c = 1505 m/sec) was increased to (exact c = 1500 m/sec, est. c = 1510 m/sec) the ratio $|\mu|/\sigma_\mu$ decreased from 1.228 to 1.158 and the mean increased from .00048 to .00098. The mean $|\mu|$ is forgiven but the std. dev. σ is not. This decrease in forgiveness is illustrated in tables 1 and 2. An example of a large $|\mu|/\sigma_\mu$ ratio is for the source speed mismtch demonstrated in tables 8 and 9. The $|\mu|/\sigma_\mu$ ratio of both tables is 118.5 with $|\mu| = .00055$. With large $|\mu|/\sigma_\mu$ ratios MFP is very forgiving of source speed mismatches.

r(m)	est. r(m)	est. z(m)	est. β(deg)	max. b
10000	10345	150	45	.8058
20000	20695	150	46	.8825
30000	29500	149	45	.7936
40000	40960	154	46	.9138

Table 7: Ocean Depth Mismatch (h = 405m)
for Horizontal Array

r(m)	est. r(m)	est. z(m)	max. b
10000	10000	150	.9991
20000	20000	150	.9964
30000	30000	150	.9914
40000	40000	150	.9852

Table 8: Source Speed Mismatch (v = 10 m/sec) for Vertical Array

r(m)	est. r(m)	est. z(m)	est. β(deg)	max. b
10000	9995	150	44	.9930
20000	19995	150	44	.9920
30000	29995	150	44	.9883
40000	39995	150	44	.9853

Table 9: Source Speed Mismatch (v = 10 m/sec) for Horizontal Array

Table 10 illustrates array tilt mismatch for a vertical array of 15 hydrophones and array tilts of 2 deg. and 4 deg. The array tilt mismatch increases with array tilt and array length.

Array tilt mismatch for horizontal arrays is illustrated in tables 11 ($\beta = 45$ deg.) and 12 ($\beta = 90$ deg). As predicted the array tilt mismatch for horizontal arrays increases with tilt, array length and bearing.

Δz(m)	α (deg.)	est. r(m)	est. z(deg)	max. b
10	2	20000	149	.9944
20	2	20005	149	.9632
10	4	20005	149	.9804
20	4	20010	148	.8657

Table 10: Array Tilt Mismatch for Vertical Array

$\Delta x(m)$	α (deg.)	est. r(m)	est. z(m)	est. β (deg.)	max. b
20	1	20000	150	45	.9914
40	1	20000	151	45	.9467
20	2	20000	151	45	.9625
40	2	20005	152	46	.7355

Table 11: Array Tilt Mismatch for Horizontal Array, $\beta = 45$ deg.

$\Delta x(m)$	α (deg.)	est. r(m)	est. z(m)	est. β (deg.)	max. b
20	1	20000	150	90	.9893
40	1	20000	150	90	.9342
20	2	20000	150	90	.9563
40	2	2000	151	90	.6819

Table 12: Array Tilt Mismatch for Horizontal Array, $\beta = 90$ deg.

IV. Summary and Conclusions

For environmental or source velocity mismatch the resulting replica N.M. eigenvalue is separated into its exact value K_m, a mean mismatch μ and a residual mismatch μ_m, that is

$$\text{mismatched } K_m = \text{exact } K_m + \mu + \mu_m .$$

Analysis and simulations for vertical arrays indicate the mean mismatch μ is forgiven and the μ_m mismatch effects are modal phase errors that increase with increasing source range. For horizontal arrays the mean mismatch μ results in hydrophone phase errors that increase with array length and source bearing. The residual modal phase errors μ_m do not produce mismatch that is independent of the hydrophone phase errors, that is, the modal phase errors do not result in a range dependent mismatch.

Array tilt for vertical arrays produced a mismatch that increased with increasing tilt and array length. Horizontal array tilt resulted in a mismatch that increased with increasing tilt, array length and source bearing measured from broadside.

Random modal phases have the mean forgiven otherwise they result in a range independent mismatch.

In conclusion MFP has a built-in forgiveness to environmental and source speed mismatch. Frequent objections of MFP sensitivity to environmental or source speed mismatch do not refer to the forgiveness mechanism or the mismatch dependence on array length and if the array is horizontal, dependence on source bearing. Shallow water applications of MFP with shorter vertical arrays will be less sensitive to array tilt than deeper water with longer vertical arrays. Array tilts in long vertical array or long horizontal arrays may require dividing the array into subarrays with incoherent MFP averaging if array tilt is excessive and unknown.

References

[1] Kenneth E. Hawker, A Normal Mode Theory of Acoustic Doppler Effects in the Oceanic Waveguide, J. Acoust. Soc. Am., 65(3), Mar. 1979.

[2] R. Klemm, Range and Depth Estimation by Line Arrays in Shallow Water, Signal Processing 3 (1981).

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