

# Sensitivity study of Matched Field Processor and Geoacoustic Inversion with combined BMV processor

Sanjeev Naithani<sup>1</sup>, P.V. Hareesh Kumar<sup>1</sup>, Rao Tatavarti<sup>2</sup> and Y. Satyanaryana<sup>1</sup>

<sup>1</sup>Naval Physical and Oceanographic Laboratory, Thrikkakara, Kochi, India

<sup>2</sup>Now in Gayatri Vidya Parishad College of Engineering, Visakhapatnam, India

\*Corresponding Author: sannaitani@gmail.com

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## ABSTRACT

Estimation of geoacoustic parameters via Matched Field Inversion is controlled by many factors. This study presents the performance of Bartlett and Minimum Variance processors with respect to sensitivity of geoacoustic parameters, acoustic frequencies and signal to noise ratio. The cost function of processors is studied by assuming a geoacoustic model. Subsequently, it is proposed to use both the processors in tandem as they complement each other. The performance of Bartlett and Minimum Variance processors individually is compared with the tandem use of both the processors through geoacoustic inversion with Genetic Algorithm. The inversion results show that the joint usage of both the processors gives better estimates and can be used for matched field geoacoustic inversion.

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## INTRODUCTION

The propagation of sound in the ocean depends on hosts of environmental parameters; one among them is the geoacoustic parameters of the sediments namely, sound speed and its attenuation, bulk density and bottom and sub bottom profiles of the sediment layer thicknesses. The influence of sea bottom and sub bottom parameters depends on the geoacoustic model of the region acquired from geophysical exploration and laboratory measurements. In actual scenario the sea bottom geoacoustic model could be complicated than what is assumed under the propagation studies (Hamilton, 1971; 1980). In situ measurements are always not feasible due to enormity in the spatial variation of these parameters on the ocean floor and sub bottom sediment layers. This has prompted the development of various remote inversion techniques utilizing acoustic data. Matched Field Inversion (MFI) is one such technique (Tolstoy, 1993; Jesus, 1995; Dosso and Wilmut, 2002). The MFI searches for optimum parameters between the predefined search bound that gives the maximum processor power between the observed and replica field along an array of sensors for a given experimental setup.

The most widely used processor is the Bartlett, due to its robustness and lesser sensitivity to error in experimental setup, modeling and parameter mismatch. Disadvantage of this processor is presence of local maxima along with global maxima. This, evidently, introduces ambiguity in properly segregating the two and analysing (Tolstoy, 1993). Its cost value is given as (Tolstoy, 1993),

$$C_{BRT} = e^+ R e \quad (1)$$

Here,  $e$  is the vector of the replica pressure along the array of sensors,  $+$  denotes the conjugate transpose.  $R$  is

the Cross-spectral matrix of the measured pressure across the array.

Another matched field processor is the Minimum Variance (MV). The cost function has very sharp main lobe for perfect match between observed and replica field (higher resolution) in addition to suppressed side lobes. The processor is highly sensitive to mismatch and experimental errors. It also requires finer sampling of parameter search bounds for MFI (Tolstoy, 1993). Cost value of this processor is given as (Tolstoy, 1993),

$$C_M = \frac{1}{e^+ R^{-1} e} \quad (2)$$

In order to utilize the MV processor, its sensitivity is reduced by adding a small value to diagonal of the cross-spectral matrix and also to ensure the matrix inversion (Jesus, 1995; Rajan, 1998; Abwai, 2000). For a frequency band the processor output is  $C_f = \frac{1}{L} \sum_{i=1}^L C_i$ , where  $L$  is number of frequencies.

The geoacoustic inversion is not as simple as it looks (Tolstoy; 1993). The Bartlett cost function surface may have multiple side lobes along with main lobe or it may have a broader main lobe. The accuracy with which the parameters to be inverted depends upon their sensitivity to forward model. The inversion also depends on the frequency of the source as the depth of penetration as well as the resolution of the sediment layer thickness is a function of acoustic wavelength. The estimated sound speed of the sediment through MFI is an average value over the layer thickness. Finally, the presence of noise in the data results in erroneous estimates of parameters. Therefore, as the first step, we have studied the sensitivity of geoacoustic model parameters, the influence of frequency

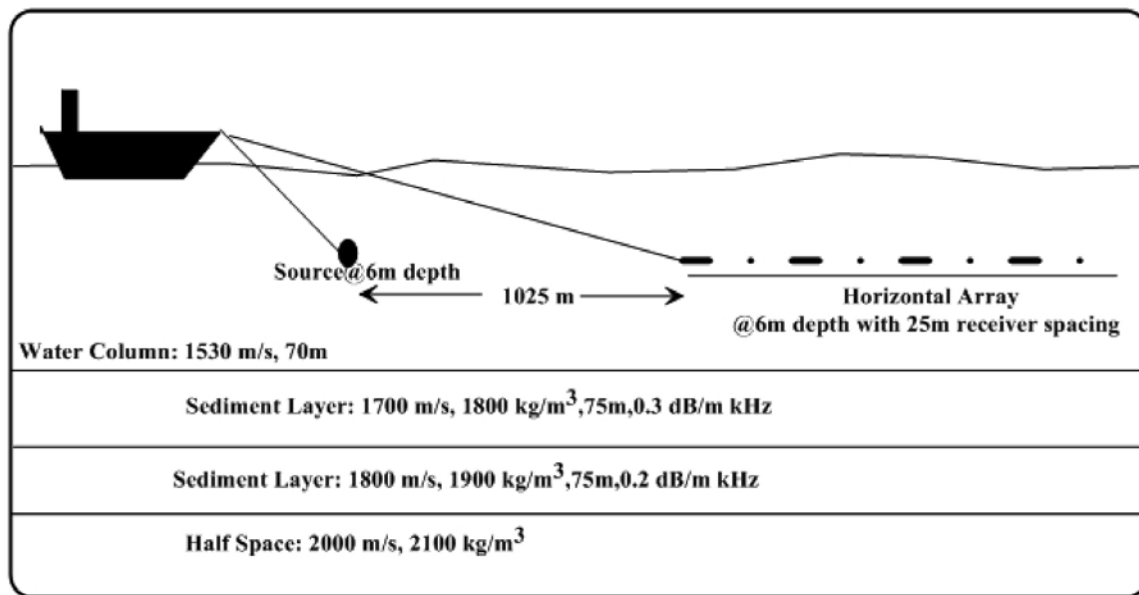


Figure 1. Experimental setup and geoacoustic model considered for simulations

changes and the given Signal to Noise Ratio (SNR), to assess the performance of Bartlett and MV processor for a given geoacoustic model and experimental setup. The performance of the processors is then compared via geoacoustic inversion using Genetic Algorithm. The study is also further extended by combining the Bartlett and Minimum Variance processor to understand improvement in the inversion.

## METHODOLOGY

The experimental setup and the geoacoustic model considered for simulation pertains to the data acquired during seismic surveys. The setup consists of a seismic source and a streamer hydrophone array towed behind the ship at a depth of 6 m. The receiver array consists of 40 hydrophones with spacing of 25 m and the distance from source to first receiver being 1025 m. The geoacoustic model comprises two layers, viz, sediment layer and a sediment half space underlying a water column of 70 m thick with constant sound speed of 1530 m/s. As the source is seismic, which has a low frequency band (10-120 Hz), it is reasonable to assume water column as iso-speed. The geoacoustic model along with parameter values is presented in Fig. 1.

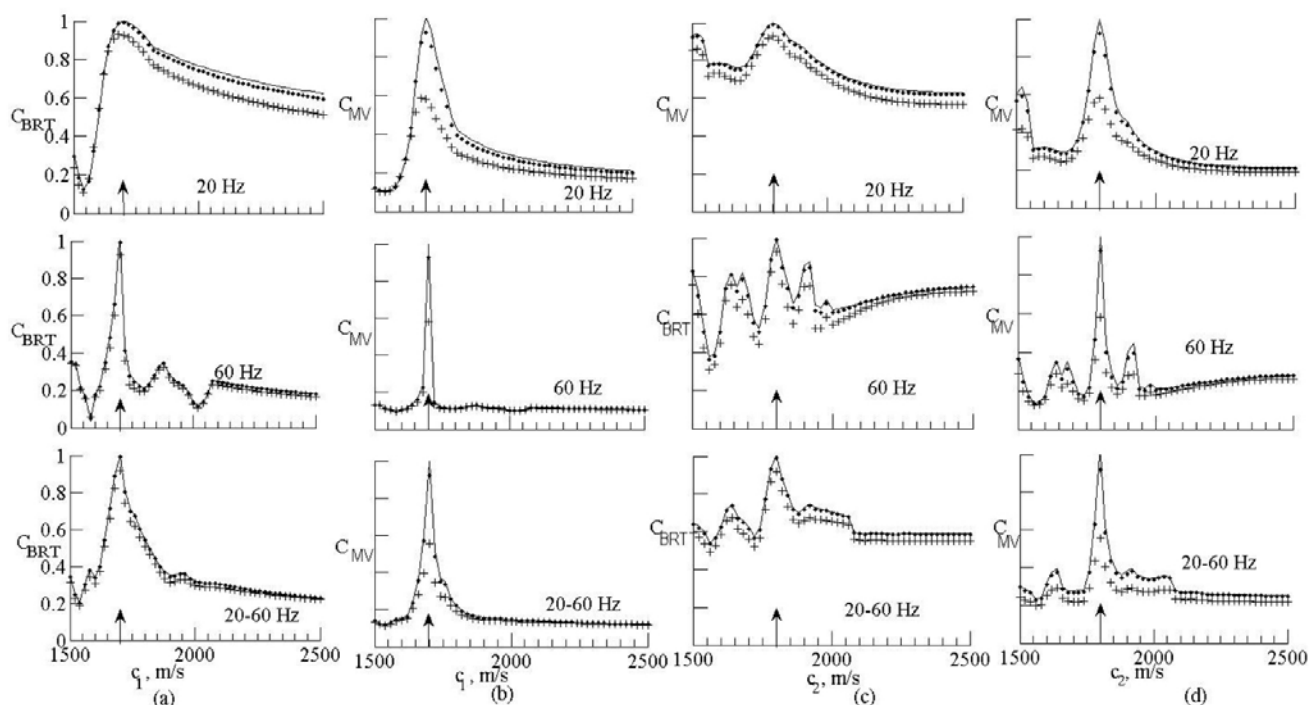
## RESULTS

The variation in processor output based on acoustic frequency is determined by altering one parameter at a time within pre-defined parameter bounds and keeping other parameter fixed at its true value. For every perturbation, Kraken normal mode model is used to compute replica

field (Porter and Reiss, 1984; 1985). The observed field is simulated using same forward model by keeping all parameters at their true value. In this study, two single frequencies viz., 20 Hz and 60 Hz and frequency band of 20 to 60 Hz is used.

The Bartlett cost function in the case of first layer compressional speed is broader around the main lobe (variation of 0.15) at 20 Hz. While the cost function becomes sharper at 60 Hz with presence of side lobes, in band of 20 to 60 Hz, the side lobes are reduced (Fig. 2a). For the second layer compressional speed, a side lobe exists at cost value of 0.95 in 20 Hz, and at 60 Hz the number of side lobes has increased. In 20 to 60 Hz band the side lobes are suppressed with significant difference in cost value from main lobe (Fig. 2c).

The Bartlett cost function for the sediment layer thickness exhibits a wide main lobe at 20 Hz, particularly for the second layer. The difference between minimum and maximum cost value is 0.07. At 60 Hz the side lobes appear with sharper main lobe. Whereas, side lobes are subdued for band of 20 to 60 Hz (Fig. 3a, c). For the first layer, the side lobes appear at 25 m, 50 m and 105 m (Fig. 3a, 60 Hz), which is about one, two and three times the wavelength (28 m). In the case of second layer thickness, the side lobes are at 40 m and 110 m (Fig. 3c, 60 Hz). These are slightly away from the multiple of wavelength (30 m). By adding both the layer thicknesses pertaining to side lobes with high cost value, the total sediment thickness is worked out to be 90 m, 150 m and 215 m, respectively. These pertain to three, five and seven times the wavelength corresponding to the average speed of both the sediment layers. The cost function for the sediment density remains almost constant



**Figure 2.** Cost function for sediment compressional speed at 20, 60 and 20-60 Hz (a) First sediment layer ( $c_1$ ) for Bartlett, (b) First sediment layer ( $c_1$ ) for Minimum Variance., (c) Second sediment layer ( $c_2$ ) for Bartlett and (d) Second sediment layer ( $c_2$ ) for Minimum Variance. \_\_\_ No noise, --- 20 dB SNR and +++ 10 dB SNR

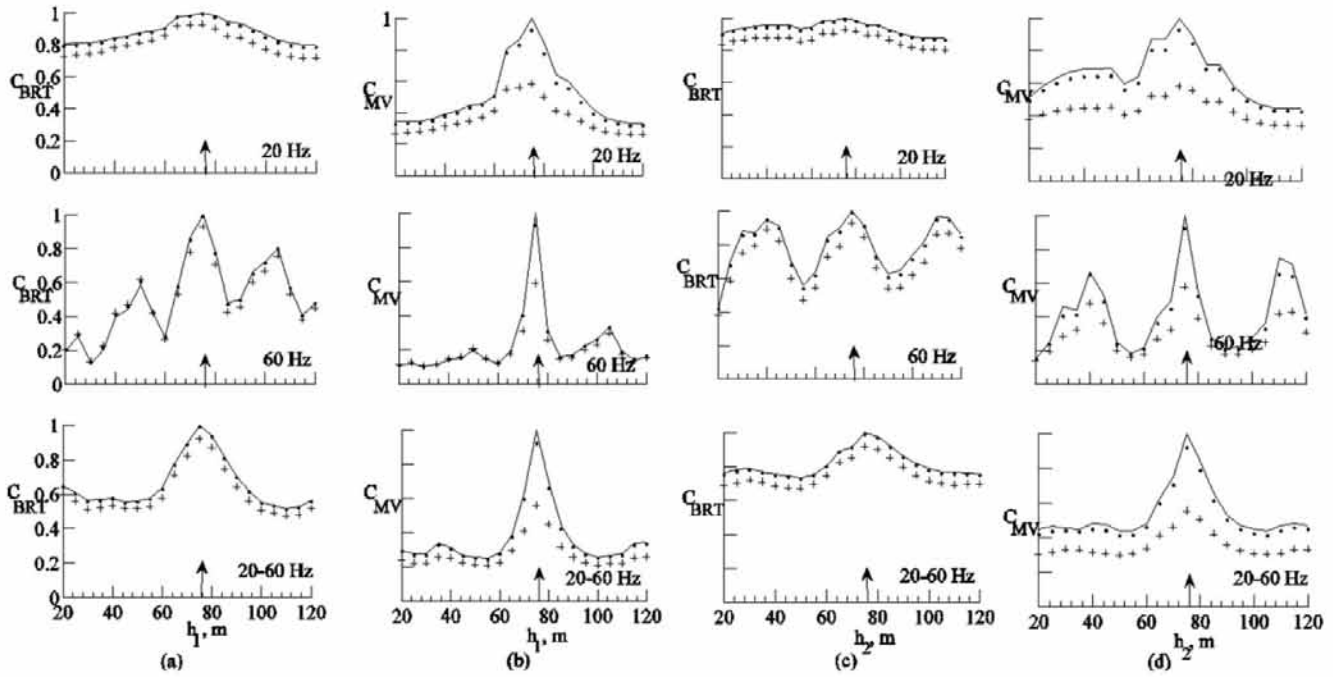
**Table- I.** Assumed geoacoustic model and parameter search range

	Parameter	True value	Search Range
Water Column	Thickness, m	70	10-120
	Speed, m/s	1530	1450-1550
First Sediment Layer	Compressional speed, m/s	1700	1500-3000
	Density, gm/cm <sup>3</sup>	1.80	1.5-2.4
	Thickness, m	75	10-120
	Attenuation, dB/m kHz	0.30	0.01-0.7
Second Sediment Layer	Compressional speed, m/s	1800	1500-3000
	Density, gm/cm <sup>3</sup>	1.90	1.5-2.3
	Thickness, m	75	10-110
	Attenuation, dB/m kHz	0.20	0.01-0.7
Half Space	Compressional speed, m/s	2000	1550-3000
	Density, gm/cm <sup>3</sup>	2.10	1.5-2.4

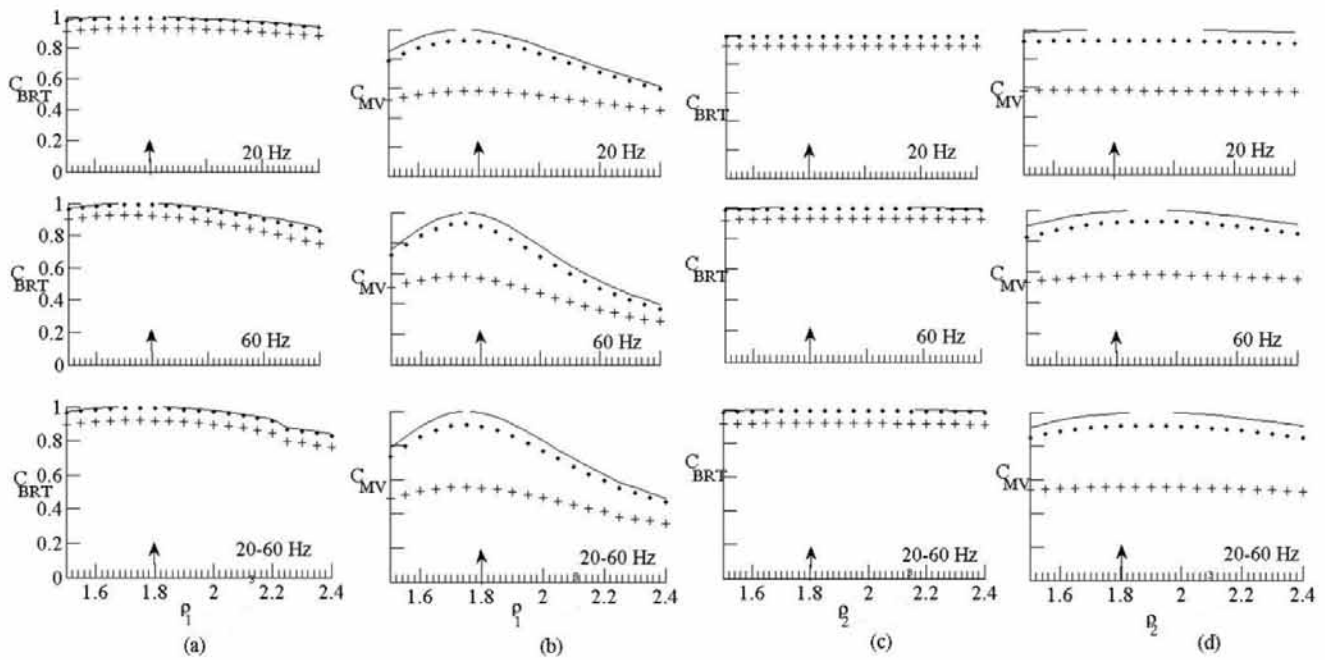
within the parameter search bounds (Fig. 4a, c), with cost value variation in the second and third decimal place at all the frequencies. For example, the Bartlett cost value in the case of first sediment layer density varies between 0.97 and 1 within the bounds and in the fourth decimal place between  $1.8 \pm 0.1$  gm/cm<sup>3</sup> for the second layer.

The cost function of MV processor shows sharper main lobe for the compressional speed of first sediment layer at all frequencies with no side lobes. However, the

difference between the least and the highest cost value is slightly higher (0.7) in comparison to Bartlett (Fig. 2b). The sharpness of the main lobe persists even for second sediment layer but a side lobe with processor power of 0.6 at 20 Hz exists (Fig. 2d). In addition, the response of the processor is flat over the bounds except around the true value of  $1800 \pm 40$  m/s. This type of response requires finer sampling of parameter search space for geoacoustic inversion.



**Figure 3.** Cost function for sediment layer thickness at 20, 60, 20-60 Hz, (a) First sediment layer ( $h_1$ ) for Bartlett, (b) First sediment layer ( $h_1$ ) for Minimum Variance, (c) Second sediment layer ( $h_2$ ) for Bartlett, (d) Second sediment layer ( $h_2$ ) for Minimum Variance. \_\_\_ No noise, --- 20 dB SNR and +++ 10 dB SNR.



**Figure 4.** Cost function for sediment layer density of first ( $\rho_1$ ) at 20, 60, 20-60 Hz, (a) First sediment layer ( $\rho_1$ ) for Bartlett, (b) First sediment layer ( $\rho_1$ ) for Minimum Variance, (c) Second sediment layer ( $\rho_2$ ) for Bartlett, (d) Second sediment layer ( $\rho_2$ ) for Minimum Variance. \_\_\_ No noise, --- 20 dB SNR and +++ 10 dB SNR

**Table II-** Sensitivity of the geoacoustic parameters.

Parameter	Difference in processor power	
	Bartlett	MV
First Layer Compressional speed, m/s	0.3	0.75
Water speed, m/s	0.2	0.6
Water column thickness, m	0.2	0.6
Second Layer Compressional speed, m/s	0.2	0.6
First Layer Thickness, m	0.15	0.6
Second Layer Thickness, m	0.2	0.6
Half Space Compressional speed, m/s	0.05	0.35
First Layer Density, gm/cm <sup>3</sup>	0.02	0.2
Second Layer Attenuation, dB/m kHz	0.03	0.2
First Layer Attenuation, dB/m kHz	0.02	0.1
Second Layer Density, gm/cm <sup>3</sup>	0.001	0.07
Third Layer Density, gm/cm <sup>3</sup>	0.001	0.05

The MV cost function has sharp main lobe for the first layer thickness compared to Bartlett (Fig. 3b). For second layer, the cost value varies from 0.4 to 0.6 within the search bounds (Fig. 3d). The side lobes are present at 60 Hz and are suppressed at 20 to 60 Hz band. In the case of first layer density, the MV processor power varies in the first decimal place at all frequencies compared to second and third decimal for Bartlett (Fig. 4b). The variation for second layer density is relatively better than the Bartlett (Fig. 4d), with variation in second decimal place.

Overall, MV cost function at 20 to 60 Hz is good for all the parameters except for second and third layer density (which may be due to the low sensitivity of the parameter and is addressed separately). The response of the frequency may change if there is change in assumed geoacoustic model or/and experimental setup. It is also observed that the variation in MV cost function is higher compared to Bartlett within the parameter search bounds.

The sensitivity of the geoacoustic parameter is very important prior to estimation of parameters through any inversion scheme. To determine the sensitivity of a parameter, the difference between minimum and maximum cost value within the parameter search bounds is computed for both Bartlett and MV processor at 20 to 60 Hz band (Fig. 2 to 4, Table II). It is observed that density and attenuation are the least sensitive parameters as indicated by the maximum difference in Bartlett cost value of 0.03 for attenuation and 0.001 for density. The corresponding values for the MV processor are 0.2 and 0.05, respectively. Additionally, the parameter sensitivity depends on the assumed geoacoustic model, experimental setup and the frequency. It is observed (Table II) that the resolution or the contrast in processor cost value is higher for MV processor than Bartlett.

The signal recorded over array of sensors contains embedded noise. Therefore, it is necessary to understand

the performance of processor to a given Signal to Noise Ratio (SNR). The SNR is computed by adding zero mean Gaussian noise with variance  $\sigma^2$  to the signal as in Rajan (1998). The signal to noise ratio is given by

$$SNR = 10 \log_{10} \left[ \frac{\frac{1}{N} \sum_{i=1}^N P_i^2}{\sigma^2} \right] \tag{3}$$

Here,  $P_i$  is the observed pressure at  $i^{\text{th}}$  receiver.

The processor power is computed for SNR of 20 dB and 10 dB. The Bartlett processor is found to be good till 10 dB SNR as the maximum cost value dropped only by 0.1 from noise free case with similar overall shape of the cost function (Fig. 2 to 4). For MV processor the cost value dropped almost to zero with change occurring only at the fourth decimal place. Therefore, a value 0.1 is added to the diagonal elements of cross spectral matrix to ensure its inversion and to reduce sensitivity to mismatch (Hsu and Baggeroer, 1986; Tolstoy, 1993; Abwai, 2000). Subsequently, cost value dropped by 0.4 at 10 dB SNR with respect to noise free case (Fig. 2 to 4). MV processor also shows reduction of its sensitivity as evident from reduction in the sharpness of the peak at certain frequency for compressional speed and second layer at 20 Hz with appearance of side lobes. However, the global maximum is found to be very predominant. The diagonal padding further reduces the sensitivity of density and attenuation, but the change in processor cost value is still better than Bartlett. Overall, the MV processor is less sensitive to frequency changes and more sensitive to parameter mismatch, compared to Bartlett. The MV cost value drops to zero for compressional speed variation of 20 m/s, when its sensitivity is not reduced and subsequent to reduction, its cost function is better than Bartlett. At 10 dB SNR,

**Table-III.** Geoacoustic inversion results of all three MFP processors

Parameter	True value	Search Range	Bartlett	MV	BMV
First Layer Compressional speed, m/s	1700	1500-2000	1700.5	1700.0	1699.4
First Layer Thickness, m	75	40-140	75.4	77.0	76.2
First Layer Density, gm/cm <sup>3</sup>	1.75	1.4-2.1	1.77	1.74	1.75
First Layer Attenuation, dB/m kHz	0.3	0.01-0.7	0.36	0.29	0.29
Second Layer Compressional speed, m	1800	1500-2000	1797.5	1798.4	1800.4
Second Layer Thickness, m	75	40-140	74.6	73.8	74.6
Second Layer Density, gm/cm <sup>3</sup>	1.9	1.4-2.1	2.0	1.93	1.88
Second Layer Attenuation, dB/m kHz	0.2	0.01-0.7	0.18	0.21	0.20
Half Space Compressional speed, m/s	2000	1750-2250	2006.3	2002.4	2001.5
Half Space Density, gm/cm <sup>3</sup>	2.1	1.8-2.2	2.13	2.07	2.15

the maximum MV cost value is 0.6 compared to 0.9 for Bartlett. It is observed that even though MV has higher resolution, it is sensitive to the parameter mismatch and on the other hand Bartlett has lesser resolution and more sensitive to frequency changes; but is tolerant to parameter mismatch as given in (Tolstoy, 1993).

#### Bartlett Minimum Variance Processor (BMV)

From the preceding paragraphs it is evident that the output of matched field processor depends not only on frequency and geoacoustic model but also on the resolution or the sampling of parameter search space. Therefore, it would be innovative to use both the processors in tandem and take the final cost function output by combining both the processor. This can be written as,

$$C_{BMV} = \frac{1}{2} [C_{BRT} + C_{MV}] \quad (4)$$

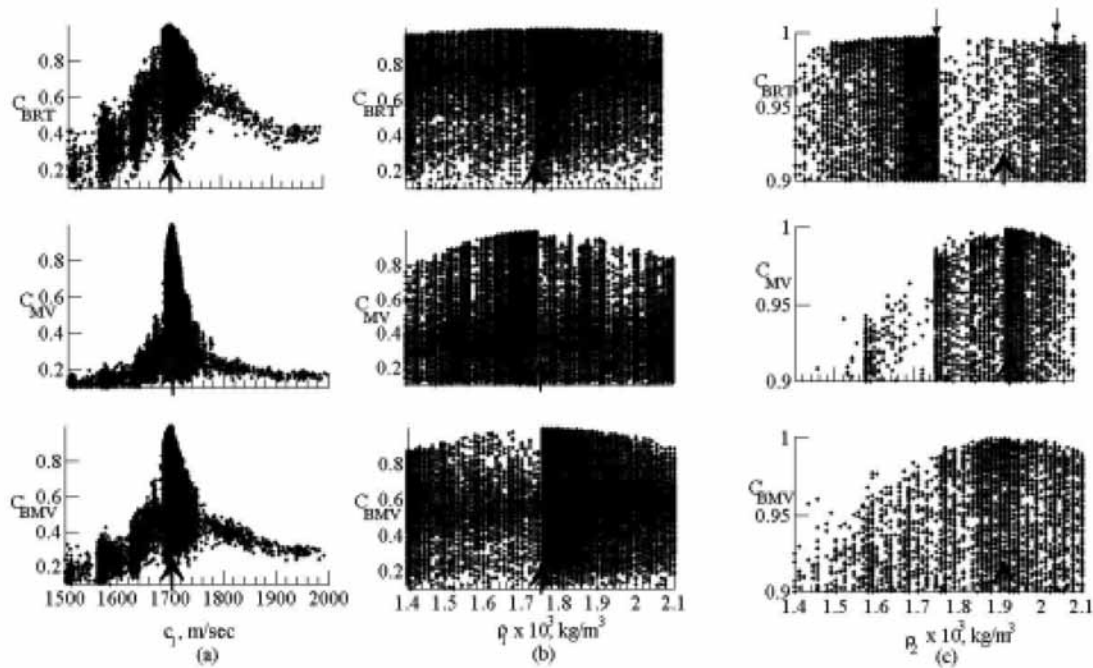
The advantage of averaging is that the cost function follows the trend of Bartlett processor and its value will get enhanced at global maxima due to MV processor with the advantage of reduction in side lobes. Thus, both processors behave like seesaw, when there is a parameter mismatch, Bartlett takes control and whenever there is reduction in sensitivity MV takes over.

#### Comparison Of Geoacoustic Inversion Results Of Processors

The performance of these processors is assessed via geoacoustic inversion using Genetic Algorithm (Gerstoft, 1995; Siderius, et al., 2002). The assumed geoacoustic model remains the same as discussed earlier. The geoacoustic parameter values, their search bounds and the inversion results are presented in Table III. The inversion shows that all the three (Bartlett, MV and BMV)

processors are comparable. However, better estimates for less sensitive parameters are obtained through MV and BMV processors. Inversion using BMV took 238 generations, while the corresponding values for Bartlett and MV are 198 and 347, respectively. Inversion via MV processor required more number of generations because of fine sampling of parameter bounds (sharper main lobe for sensitive parameter). It is essential to note that in the case of simulations it is easy to define finer sampling but for the field data this may not be feasible. BMV processor not only provides better estimates for less sensitive parameters but also reduces the number of forward model runs required to adequately sample parameter search bounds. On suppression of sensitivity, the MV processor probably can be used alone, but will still require more iterations to adequately sample the parameter search bounds. Moreover, there is a limit for diagonal padding of covariance matrix as it starts behaving like a linear processor (Abwai, 2000). For example, the global maximum of the sensitive parameter (compressional speed of first layer, Fig. 5a) is slightly wider for Bartlett processor, whereas, it is sharp and the cost function falls rapidly on either side of true maxima for MV processor. In such a case, performance of a processor will be affected if there is under sampling of parameter search bounds (Fig. 5a). In the case of BMV processor the global maxim is sharp and the cost function does not fall rapidly on adjacent sides.

For a less sensitive parameter like density, the processor power varies in the second decimal place for Bartlett and in first for MV and BMV processors. Close to global maximum (1.8 gm/cm<sup>3</sup>), variation of parameter value is in the third decimal place for all the three processors with parameter values between 1.69-1.95 gm/cm<sup>3</sup>, 1.69-1.75 gm/cm<sup>3</sup>, and 1.75-1.84 gm/cm<sup>3</sup>, respectively (Fig. 5b). The perturbation varies the cost value only in the third decimal place. Therefore, the resolution is not enhanced utilizing BMV processor. In the case of MV and BMV the variation around the global peak is between 0.995 and 0.9995, whereas it is between 0.997



**Figure 5.** Object function for (a) Compressional speed of first sediment layer ( $c_1$ ) for Bartlett, Minimum Variance and BMV processor, (b) Density of first sediment layer ( $\rho_1$ ), for Bartlett, Minimum Variance and BMV processors and (c) Density of second sediment layer ( $\rho_2$ ) for Bartlett, Minimum Variance and BMV processors

**Table- IV.** Geoacoustic inversion results at 20 and 10 dB SNR using BMV processor

Parameter	Search Range	True value	20 dB SNR	10 dB SNR
First Layer Compressional speed, m/s	1500-2000	1700	1700.6	1702.5
First Layer Thickness, m	40-140	75	77	77.7
First Layer Density, gm/cm <sup>3</sup>	1.4-2.1	1.75	1.75	1.77
First Layer Attenuation, dB/m kHz	0.01-0.7	0.3	0.29	0.29
Second Layer Compressional speed, m	1500-2000	1800	1798.4	1805.3
Second Layer Thickness, m	40-140	75	74.6	76.2
Second Layer Density, gm/cm <sup>3</sup>	1.4-2.1	1.9	1.94	1.83
Second Layer Attenuation, dB/m kHz	0.01-0.7	0.2	0.196	0.185
Half Space Compressional speed, m/s	1750-2250	2000	2001.5	2012.2
Half Space Density, gm/cm <sup>3</sup>	1.8-2.2	2.1	2.098	2.13

and 0.998 for Bartlett. It could be possible to enhance the sensitivity of BMV by reducing the value of diagonal padding, but this may lead to some other problem like enhancement of sensitivity to parameter mismatch, and as a result the performance of processor will degrade.

For the second layer attenuation, the cost function varies in the second decimal place around the main lobe, i.e., between 0.95 and 0.998, 0.7 and 0.999, 0.8 and 0.999 for Bartlett, MV and BMV respectively. This shows that even though the sensitivity of the parameter to the forward model remains same, it gets enhanced due to the processor. A notable observation with the BMV processor is the suppression of the side lobes and the enhancement of parameter sensitivity. This is seen in the case of second

layer density where BMV cost function has a main lobe at 1.93 gm/cm<sup>3</sup>, while the Bartlett has local maxima at 1.75 gm/cm<sup>3</sup> and maxima at 2.03 gm/cm<sup>3</sup> (Fig. 5c, indicated by arrow). The inversion result is encouraging for other geoacoustic parameters also utilizing BMV processor.

From the above results it is inferred that the variation in cost function is higher for MV processor than the Bartlett even for less sensitive parameter. The sensitive parameter has sharp main lobe for MV processor with cost function falling very rapidly on adjacent sides of main lobe compared to Bartlett, which has slightly broader main lobe. This suggests that in the inversion using MV processor, the perturbation of sensitive parameter causes significant change in cost value only around true value

(main lobe). Therefore, the rate of change of processor power will be very slow and it would require more number of parameter perturbations within the search bounds. This is the precise reason why a tandem use of both Bartlett and MV processors is suggested for geoacoustic inversion. The inversion results are encouraging at 10 dB and 20 dB SNR using BMV processor and results are presented in Table IV.

## CONCLUSIONS

It is well established in the past that the MV processor has higher resolution with high sensitivity to parameter mismatch and modeling errors. On the other hand Bartlett processor is less sensitive to mismatch errors but has lower resolution. Therefore, combining both the processors will complement each other as the advantage of one is the limitation of the other and vice versa. In order to put forward this study, the performance of the processors is studied for frequency changes, parameter sensitivity and signals to noise ratio. For the assumed geoacoustic model and the experimental setup, it is observed that the cost function of MV processor has sharper main lobe, found to be sensitive to given SNR and lesser sensitivity to frequency variations. On the other hand for Bartlett it is more sensitive to frequency changes with lesser sensitivity to parameter mismatch and given SNR. Therefore, it is understood that both processors can comprehend each other and hence we proposed to use both the processors (BMV) at tandem after reducing the sensitivity of MV processor by diagonally padding cross spectral matrix. The performance of Bartlett and MV processor is then compared with joint use of both the processors via geoacoustic inversion by genetic algorithm. The results showed that utilizing BMV processor could be innovative way for performing matched field inversion.

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**Sanjeev Naithani:** Working as a scientist at NPOL. His field of specialisation is Marine Geophysics. The field of interest includes geoacoustic inversion and remote sediment classification. Apart from this he also conducts marine geophysical surveys and data processing. He is life member of Ocean Society of India.



**Dr. P.V. Hareesh Kumar:** He is Group Head, Ocean Science, NPOL. His area of specialisation includes Physical Oceanography, Air-sea interaction, Mixed layer dynamics, Ocean Modeling, Currents and Circulation and Ocean Experiments. He is a member of Indian Meteorological Society, Indian Society of Remote Sensing, Ocean Society of India, Acoustic Society of India and Administrative Staff College of India.



**Dr. Rao Tatavarti:** He is senior professor and director (Engineering Research & Consultancy) of GVP-SIRC, GVP College of Engineering, Visakhapatnam. Has a significant contribution to the fields of ocean science, engineering and technology. Life Member of Scientific and Engineering professional bodies in India, Asia and North America; and the Founding Member of Ocean Society of India, OSI.



**Dr. Y. Satyanarayana:** Working as scientist in Naval Physical Oceanographic Laboratory, DRDO, Kochi. Prior to joining DRDO, he worked in GSI during 1987-1992 as geophysicist. His interests include mineral and oil exploration using seismic technique, marine geophysical studies, and geotechnical studies in offshore and onshore