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Determining Point of Burst of Artillery Shells using Acoustic Source Localisation

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ABSTRACT

Source localisation is a method to estimate position of a source. In case of acoustic source localisation (ASL), the location of sound source is estimated using acoustic sensors such as a microphone. In case of ASL, time difference of arrival (TDOA) from each pair of microphones is estimated. For any pair of microphones, the surface on which the TDOA is constant is a hyperboloid of two sheets. Then the source location is estimated at the point where all associated hyperboloids most nearly intersect. This concept has been used in our range in finding the point-of-burst of artillery shell using an array of sensors. In this paper, a simulation model has been developed to examine the applicability of acoustic source localisation for determining point-of-burst of artillery shells. The randomness in the model has been incorporated in terms of gustiness of downrange sea wind. The result of the simulation has been validated with trajectory data of projectiles tracked by radar. Finally, an acoustic sensor array-based setup has been developed and used for localising point-of-bursts.

Keywords: Acoustics, source localisation, point-of-burst of artillery shells, discrete event simulation, accuracy of measurement

1. INTRODUCTION

Source localisation is a method by which position of a source is estimated. In case of acoustic source localisation (ASL), the location of sound source is estimated using acoustic sensors such as microphones. In case of ASL, time difference of arrival (TDOA) from each pair of microphones is estimated. For any pair of microphones, the surface on which the TDOA is constant is a hyperboloid of two sheets. Then the source location is estimated at the point where all associated hyperboloids most nearly intersect. Comparison of different source localisation techniques are covered Brutti[1], *et al*. Application of TDOA based source localisation in speaker identification is covered Doclo & Moonen[2]. Application of passive source localisation in the area of underwater vehicle detection is covered Zhao[3], *et al*. Details on Sparse acoustic pressure sensor array architecture to estimate the direction of arrival (DOA) of multiple acoustic sources is covered Kumar[4], *et al*. In this paper, TDOA concept has been used in our Range in finding the point of burst of artillery shell by using array of sensors. The study aims to present a methodology to localize the point-of-burst (PoB) of an artillery shell from a distant location. Artillery shells are characterized by their long range of trajectory. In natural Test Ranges like the one at PXE, Chandipur, line-of-fire (LOF) of artillery shells are fixed for ensuring the safety of the nearby human habitats. Most of the artillery shells function and explode over the sea surface at a distance of 1 km ~ 2.5 km away from the mainland coastline. The POB of the shell provides the measure of range and accuracy (R&A) of the weapon system. The present technique available at PXE for determining POB relies solely on triangulation method of theodolite systems. Since a transient explosion at a distance of 1 km ~ 2.5 km cannot be spotted accurately by the operators of theodolites, scope of inclusion of substantial degree of human error is inevitable in theodolite surveying. An alternative technique for POB measurement may be developed through the application of a tracking radar system. However, deployment of tracking radar involves substantial cost in terms of man and machine usage.

In this paper, we propose a low-cost, portable, easily-deployable collaborative acoustic setup for locating POB of artillery shells from a far-off distance with a fairly high degree of accuracy. Similar DOA measurement are used in noise/interference source identification in communication industry where the environment effect on the measurement is less for high frequency signals. To improve the accuracies of DOA in air media required to model and incorporate with measurement, the similar work carried various underwater applications[8].

2. THE METHODOLOGY

Before describing the methodology of collaborative acoustic measurement of POB, the criteria for which measurement of acoustic propagation method has been chosen.

2.1 Acoustic Wave Propagation: A Feasible Criterion

High intensity acoustic signature of explosion can be recorded by an acoustic sensor even from a fairly large

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distance. This was confirmed in cluster bomb drop trial. The time required for the acoustic signature of explosion to traverse the distance between the POB and the sensor can be measured over an arbitrary time scale. Since acoustic signatures become circular in far-field, therefore, an array of acoustic sensors can be used to locate the point of explosion deterministically. Hence, acoustic wave propagation is a feasible criterion for developing the methodology.

2.2 Other Infeasible Criteria

- *Shock Wave Propagation*: To use this criterion, the sensors should be deployed close to the point of explosion since shock intensity attenuates at a very fast rate. As the exact position of explosion is not known prior to explosion, this criterion is not feasible. Fig 1.

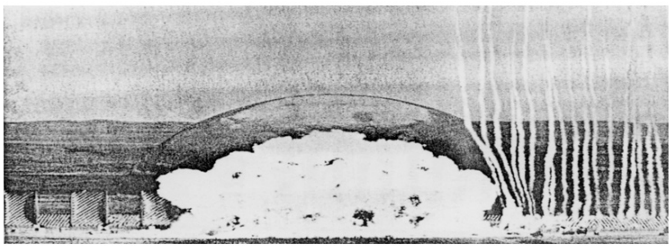


Figure 1. Photograph of shock wave characteristics.

- *Photography*: A series of photographs can be taken of the actual blast, and then the time difference between each photo and the shock state from the photo can be taken into account to measure at desired result. This criterion is also not feasible due to the same limitation associated.
- *Global Positioning System (GPS)*: POB can be determined using GPS. But this method cannot be used to locate the position instantaneously. Also, there might be an error due to the fact that the position would be determined with a vagueness of a few metres.
- *Human Sighting*: Position of explosion can be determined by triangulation calculation using theodolites. This measurement technique is subject to high level of human error, as discussed earlier. Hence, it should be replaced with a less error-prone measurement technique.

2.3 Collaborative Acoustic Framework for POB Measurement

Figure 2. illustrates a setup for collaborative acoustic sensing conceptualised for measurement of POB in downrange. The front-end of the setup consists of three acoustic sensors S_i, i = 1,2,3 placed at intervals of S m along a straight line. A data acquisition system (DAS) at the back-end registers the temporal information of the acoustic signature of shell bursting sensed by each sensor.

The time difference of arrival (TDOA) of acoustic signatures between any two sensors may be used to get the locus of sound source on a horizontal plane. In the present setup, we get two such loci were got using the middle and left sensor pair and middle and right sensor pair. The point of intersection of these loci is the POB. The Fig. 3. flow chart shows the steps of POB measurement.

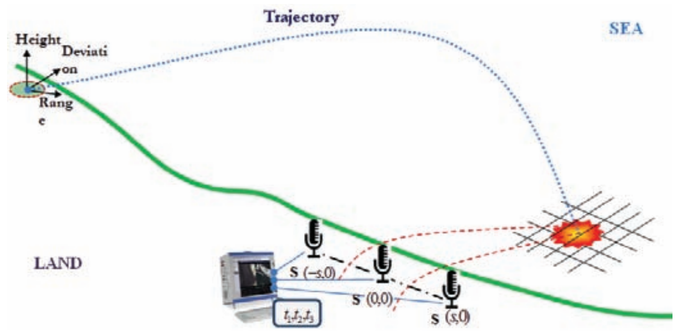


Figure 2. Collaborative acoustic setup for POB measurement.

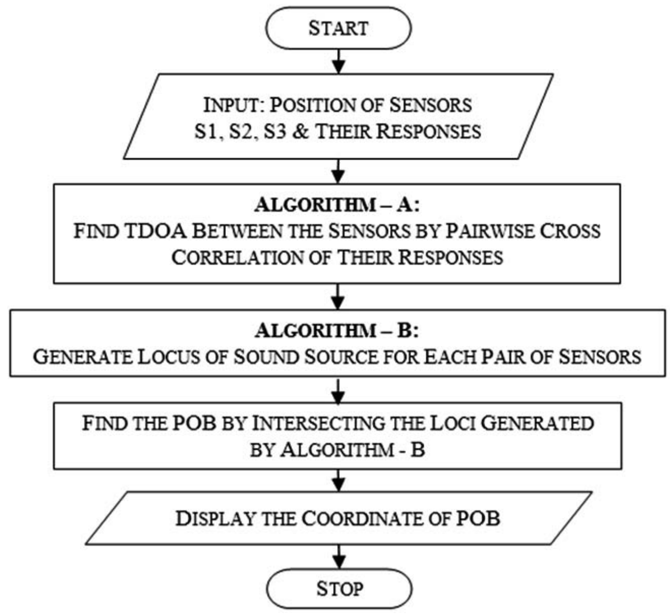


Figure 3. Flow chart of the methodology for locating POB.

Algorithm – A: Finding TDOA by Pair-wise Cross Correlation

The value of TDOA (of acoustic pressure front)for a pair of sensors depends on inter-sensor distance. Let the continuous signal of sensor S_i be $C_i(t)$ for $i = 1,2,3$ .The TDOA for any pair of sensors $\{S_i, S_j\}$ can be found from the cross-correlation between $C_i(t)$ and $C_j(t)$, that gives a measure of similarity of the two signals as a function of time lag τ applied to one of the signals. The measure of correlation between $C_i(t)$ and $C_j(t)$ is given by the following relation:

$$\left(C_i * C_j\right)(t) = \int_{-\infty}^{+\infty} \phi_i(\tau)\phi_i(t+\tau)\,d\tau \tag{1}$$

Hence, the TDOA for $\{S_i, S_j\}$ can easily be found from the following equation:

$$\Delta t_{ij} = \arg\max_t \left(C_i * C_j\right)(t) \tag{2}$$

In case of three sensors, it is suggested to use normalised cross correlation technique. Normalised cross-correlation details are covered Stearns & Hush[5].

Algorithm – B: Generate Locus of Sound Source for Each Sensor Post

This algorithm localises coordinates of acoustic source. The algorithm is very different from the popular direction-of-arrival (DOA) algorithms described in[6]. Our algorithm is superior to the other DOA algorithms in respect of its scope of easy incorporation of meteorological random parameters like gustiness of wind, temperature variation, and humidity of downrange sea condition that directly influence sound velocity. However, at this stage, any meteorological correction mechanism has not been incorporated. To visualize the working of algorithm–B refer to Fig. 4.

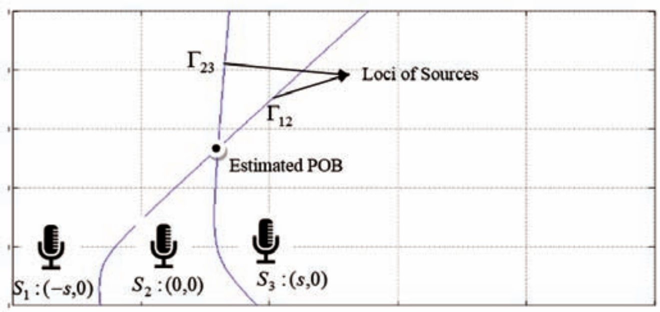


Figure 4. POB on the intersection of two sound source loci.

The position coordinates of the three sensors S_1, S_2, and S_3 be $(-s,0),(0,0)$, and $(s,0)$, respectively. For each pair of sensors $\{S_i, S_j\}$, a locus of sound source $\Gamma_{ij}(x,y)$ can be defined in a way such that all points on $\Gamma_{ij}(x,y)$ ensure generation of identical TODA (Δt_{ij}) for $\{S_i, S_j\}$. The algorithm applied for calculation of $\Gamma_{23}(x,y)$ is given below:

$\Gamma_{23}(x,y)=[x_0 \quad y_0]$; per cent Initialisation

for $d = 0:3000$ per cent distance of sound source $\leq 3km$

$$x = \underset{x^2+y^2=d^2}{solve}\left\langle (x+s)^2 + y^2 = (d + V_s * \Delta t_{23})^2 \right\rangle;$$

per cent V_s = Velocity of sound

$$y = \underset{x^2+y^2=d^2}{solve}\left\langle x^2 + y^2 = d^2 \right\rangle;$$

update $\Gamma_{23}(x,y)$; end

The algorithm is so powerful that the initial value (x_0, y_0) does not impact on the overall solution. POB can be easily measured by finding the intersection of two such loci determined by any two pair of sensors. In case of n sensors, it is possible to get ${}^nC_2$ numbers of loci were got. In the present configuration 3 loci were got. However, it is claim that two loci are sufficient to get a fair estimate of POB.

3. TEST OF FEASIBILITY AT DOWNRANGE CONDITION

No correction mechanism has been incorporated any for the meteorological randomness of downrange environment in the proposed methodology. This puts a question on its suitability in actual application. Therefore, a discrete event simulation model has been designed to replicate the downrange condition with meteorological randomness due to wind, temperature, and humidity. Discrete event simulation details are covered in[7].

3.1 Simulation of Randomness of Meteorological Parameters

Effects of the random variable values of the following meteorological parameters have been considered in the simulation model.

3.1.1 *Wind Flow*

Wind velocity has an additive effect on the velocity of sound. Gustiness of downrange wind changes sound velocity randomly. Figure 5 shows the wind flow profile in North-South direction recorded by an anemometer at MET Department.

The wind flow profile clearly shows existence of gustiness. Effect of gustiness of wind is taken care by introducing the random variable $V_w(w(t),\theta(t))$ that represents wind velocity magnitude of $w(t)$ and direction of $\theta(t)$ at time 't'. According to the MET Department, the magnitude of wind velocity varies between 0 m/s ~ 7 m/s. Hence, the distribution of $w(t)$ was considered to be a uniform β-distribution ranging between 0 m/s ~ 7 m/s. $\theta(t)$ is considered to take random values from a uniform distribution between 0.1° ~ 360.0°.

3.1.2 *Temperature*

Temperature (T) has been considered to be uniformly distributed over a range 20 °C ~ 40 °C. Temperature variation is almost negligible in the spatial domain of 1 km ~ 2.5 km in the downrange. Therefore, T is kept constant over each simulation run. Velocity of sound in air at temperature T K is $V_s = 331.15 * \sqrt{T/T_0}$ m/s, where, T_0 = 273.15 K. Details of above are covered in Deo[8], *et al.*

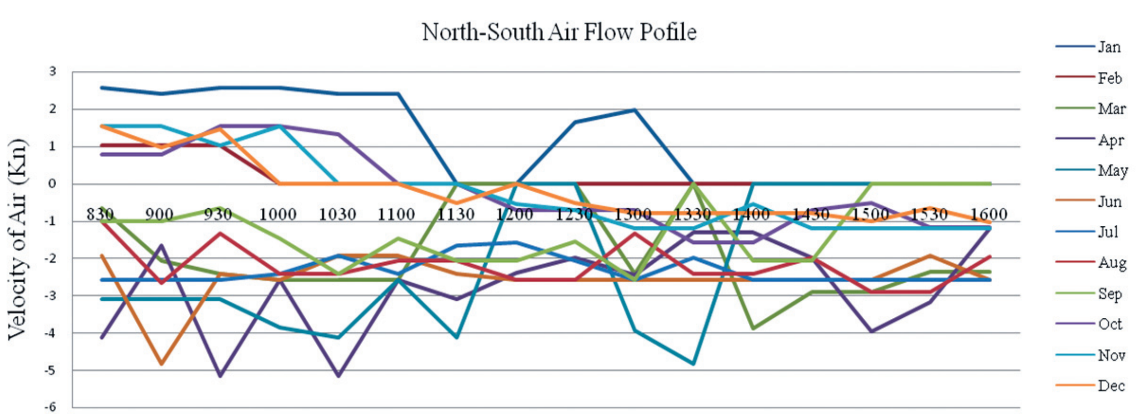


Figure 5. North-south wind flow at PXE, Chandipur.

3.1.3 Humidity

Variation of sound velocity due to humidity is much less. Within the normal range of air temperature, sound travels approximately 1 m/s faster in humid air than in dry air. Details on above are covered in[9].

3.1.4 Scope of the Simulation Model

The simulation model considers 3 acoustic sensors positioned in equal intervals of s metres. 's' takes values between 10 m to 100 m. The coordinates of the sensors are the inputs to the model. The purpose of the simulation is to find the accuracy of the proposed methodology in terms POB measurement. Therefore, coordinate of the actual POB is another input to the model. The time interval between simulation steps, Δt is equal to the sampling time of the DAS which will be used for validation experiment, i.e., $\Delta t =$ sampling time of DAS. A sampling rate of 32 kS/s of DAS has been considered and accordingly, $\Delta t = 31.25$us. Number of runs of the simulation can be determined based on the required precision level of the methodology. We have conducted 460 runs.

3.2 Simulation Mechanism

The resultant velocity of the acoustic front passing through a point at time t is the vector sum of sound velocity $V_s(t)$ and local wind velocity $V_w(t)$. Therefore, the resultant approaching velocity of the acoustic front in respect of sensor S_i is expressed as follows:

$$V_{Acco}^{i}(t) = V_s(t) + w_t \cos\theta_t \tag{4}$$

The spatial advancement of acoustic front of explosion between time interval Δt is given by the following expression:

$$d_{\Delta t} = V_{Acco}^{i}(t) * \Delta t \tag{5}$$

The Fig 6. illustrates the straightforward mechanism of simulation.

With input of POB coordinate and sensor coordinate, the simulation model calculates the times at which the acoustic front of the explosion reaches the sensors. Then it uses the methodology described in the earlier section to find out the POB. The flow chart of the simulation scheme is given in Fig. 7.

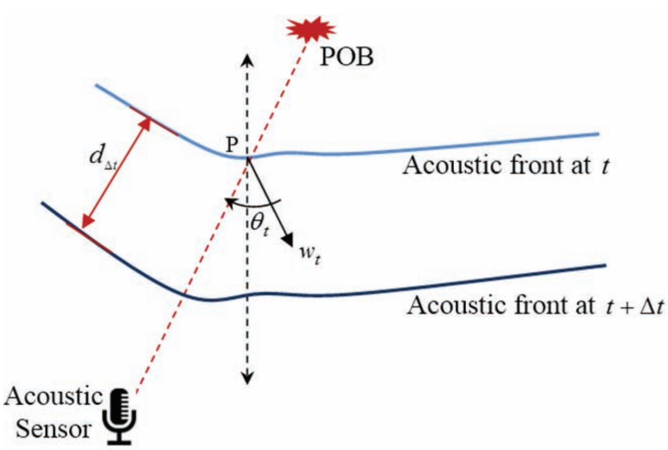


Figure 6. The Mechanism of Wind-flow Simulation.

The movement of the acoustic front of an explosion in a simulation run is displayed in Fig. 8.

The histogram of measurement error for 460 simulation runs is shown in Fig. 9.

The error associated with the proposed methodology for POB measurement is found to be 43.355 m/km with ± 3 per cent deviation in 19 out of 20 occasions.

4. VALIDATION OF ASL SIMULATION WITH TRACKING RADAR DATA

The simulation model has been validated using the acoustic signals obtained by sensors and comparing it with the

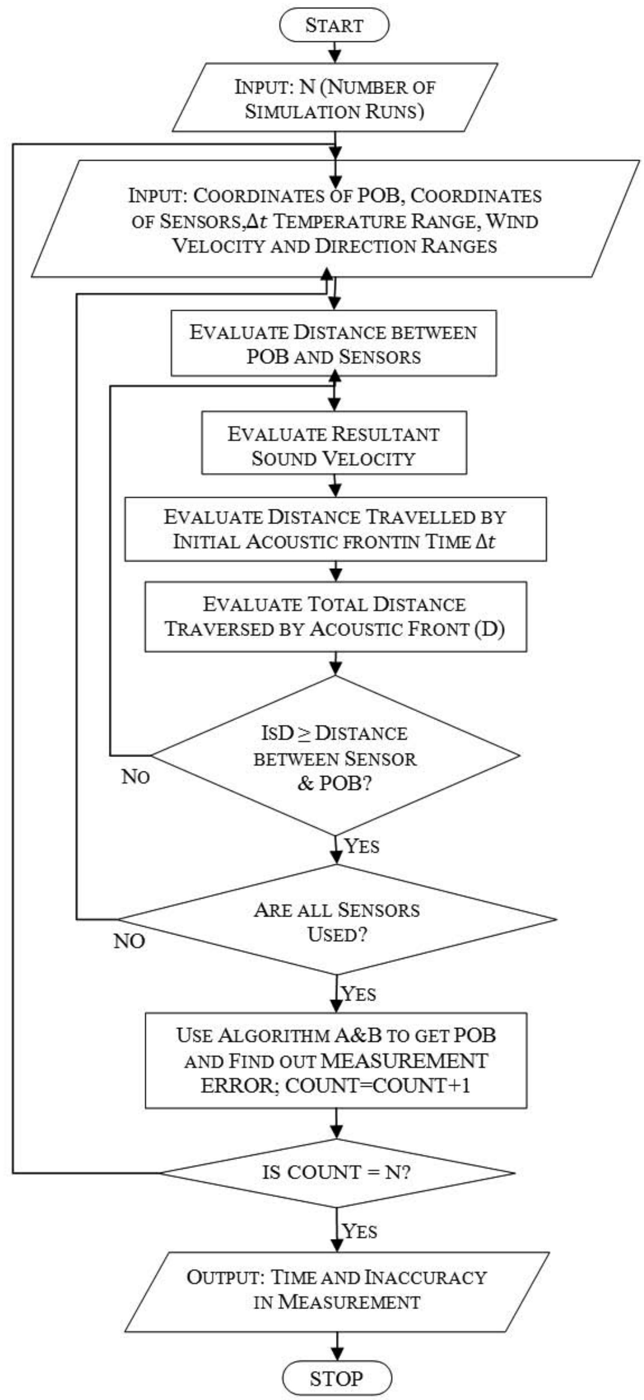


Figure 7. The flowchart of the simulation scheme.

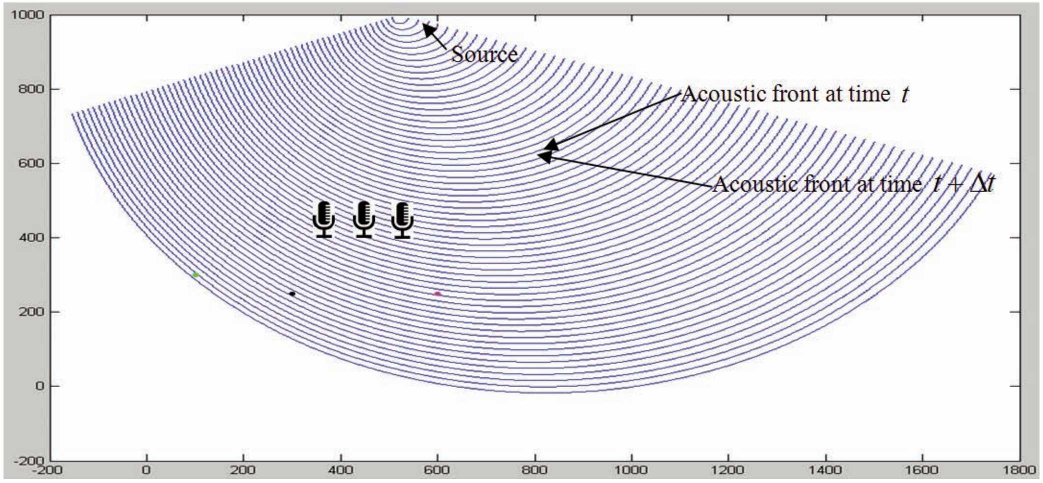


Figure 8. Simulated acoustic front of explosion approaching the sensors.

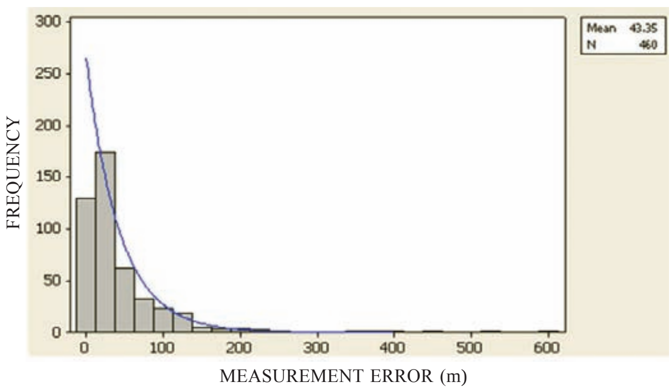


Figure 9. Histogram of POB measurement error (N=460 runs).

Tracking radar data. The deployment scenario is given in Fig. 10 (a). In this case, the trial was the functioning proof of 130 mm High Explosive Shell. The sensor array was positioned at a distance of 2.5 km from the explosion area. Distance between gun point and explosion area is of the order of 12 km. The sensor array location details are given in Table 1.

It may be noticed that the sensors were neither placed in a straightline nor these were equidistant. However, this configuration does not affect our model anyway. The present configuration of sensor positions was made to impart a kind of stress to our proposed model.

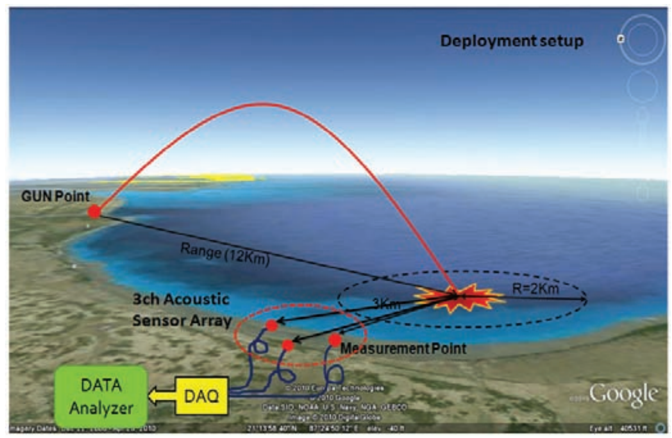
The data acquisition unit and analysis application are given in Figs 10(b) and 10(c).

The microphone used is of Condenser type, ½" Diameter and of diffuse field type. This model has been selected as a trade-off between sensitivity and frequency response.

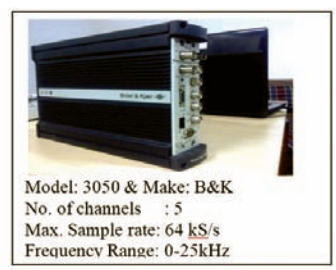
The acoustic signature and cross correlation signature

Table 1. Sensor positions

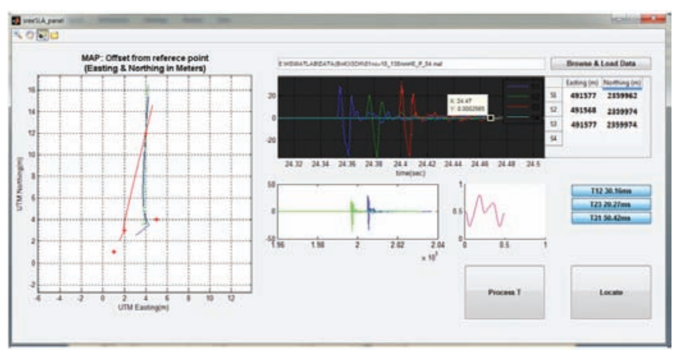
Parameter	Sensor 1	Sensor 2	Sensor 3
Latitude	21°20’29.954"	21°20’ 30.340"	21°20’ 30.354"
Longitude	86 °55’07.567"	86°55’ 07.275"	86°55’ 07.565"
Inter-sensor Dist.	14.5345 m	8.3561 m	12.3042 m
Datum D_WGS_1984			



(a)



(b) **(c)**



(d)

Figure 10. (a) Deployment Scenario (b) and (c) acoustic sensor and data acquisition unit used of validation (d) data analysis application.

details are given in Figs 11(a) and 11(b), respectively.

The above figure gives the screenshot of the DAS readout that shows the acoustic signatures recorded in case of one round. Here Algorithm – A calculates the cross-correlation coefficients and the corresponding TDOAs for 3 sensor pairs. Algorithm generates the loci.

Based on the ambient temperature, the velocity of sound was considered to be 345 m/s. From the radar data it was found that the POBs for all the 5 rounds were around 2.5 km away from the acoustic sensors. Using the sensor data and simulation model, location of point-of-burst was determined. Point-of-burst was also obtained using continuous wave monopulse tracking radar. Comparison of radar and ASL data is shown in Table 2.

From the above table, sample mean of $\text{DIFF}_{A\sim R} = \mu_0 =$ 102.806 m and sample standard deviation of $\text{DIFF}_{A\sim R} = s =$ 7.991 m. So, the 95 per cent confidence interval for $\text{DIFF}_{A\sim R}$ is $\mu_0 \pm t_{n-1,1-\alpha}\, s/\sqrt{n}$, i.e., (92.885 m, 112.727 m).

Average expected error of acoustic measurement from simulation = 43.355 m/km. Since the average distance of POB from sensors is 2.5 km, the expected error of acoustic measurement from simulation = 43.355 m/km x 2.5 km = 108.388 m

Expected error of acoustic measurement obtained from simulation, i.e., 108.388 m is within 95 per cent CI of $\text{DIFF}_{A\sim R,}$ i.e., (92.885 m, 112.727 m). Hence the simulation model is validated.

It was found that the error of acoustic measurement found by our simulation model falls within the 95 per cent confidence interval (CI) of the mean of differences of the measurements of radar and acoustic setup. Hence, the validity of the simulation model is established.

It was observed that in all the five cases, acoustic measurement showed negative bias in comparison to radar measurement. A wind flow from the sea towards land increased velocity of sound and resulted in this bias.

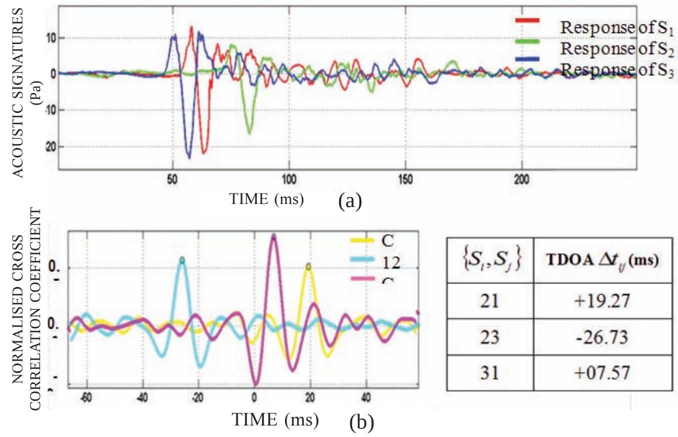


Figure 11. (a) Acoustic signatures (b) cross correlation of three acoustic sensors.

Table 2. Comparative analysis between Radar and ASL

Round No.	With respect to Launcher @ (0,0)				Difference between radar & acoustic measurement
	Radar		Acoustic		
(n)	$X(m)$	$Y(m)$	$X(m)$	$Y(m)$	$\text{DIFF}_{A\sim R} = \text{POB}_A - \text{POB}_R$
01	13985.611	70.423	13907.257	69.035	78.352 m
02	14262.416	143.522	14156.612	132.442	105.915 m
03	13993.126	188.098	13875.964	180.034	117.743 m
04	13922.460	94.876	13825.688	90.998	96.780 m
05	14001.277	225.440	13886.405	201.125	115.239 m

5. CONCLUSION

In this paper, TDOA-based acoustic source localisation simulation model has been developed. Microphone array-based setup and the simulation model has been implemented and point-of-burst of artillery shell has been determined. Point-of-burst has also been obtained using CW Monopulse tracking radar. The simulation model has been validated using the tracking radar data and it is found that the results are matching up to 95 per cent confidence interval.

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