

# SNIPER LOCALIZATION FOR ASYNCHRONOUS SENSORS

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## ABSTRACT

This paper describes a novel sniper localization method for a network of sensors. This approach relies only on the time difference of arrival (TDOA) between the muzzle blast and shock wave from multiple single-sensor nodes, relaxing the need for precise time synchronization across the network. This method is best suited where an array of sensors, on a per-node basis, is not feasible. We provide results from data collected in a field.

## 1. Introduction

There are several commercial sniper localization systems by various vendors [1, 2]. Vanderbilt University developed a soldier wearable shooter localization system [3]. All these systems are based on real-time operating systems such as UNIX, LINUX, etc., and have elaborate time synchronization mechanism. Time synchronization allows all deployed sensors to share a common time reference so that they can determine the exact time of arrival (TOA) for both shock wave and the muzzle blast for supersonic gun fire. The commercial systems employ array of microphones at each location to determine the angle of arrival (AOA) of the muzzle blast and the shockwave. With the knowledge of the difference between the muzzle blast and shockwave arrival times it is easy to determine the sniper location and the trajectory of the bullet [1, 3]. However, the array based sensors are less suitable for man-wearable systems.

The goal of this research is to develop a sniper localization system using distributed single microphone sensors or PDAs using only time differences between the shockwave and muzzle blast at each sensor. When the sensors are distributed, time synchronization among the sensors is critical. If one uses a non real time operating system such as Window CE, the synchronization among the sensors is not guaranteed. As a result, the TOA estimates of different events could be off by 1-2 seconds making the localization impossible. Figure 1a shows the shockwave and muzzle blast and figure 1b shows the recordings of the same gun shot data on four different PDAs showing bigger time delays due to lack of time synchronization. However, if the internal clocks of the sensors are stable, one can estimate the difference in TOA of shockwave and muzzle blast. In this paper, we provide sniper localization based on the

time difference of arrival (TDOA) of muzzle blast and shockwave.

In section 2 we present the problem and derive the necessary equations required to determine the sniper location using the TDOA of muzzle blast and shock acoustic wave at individual microphone sensors. In section 3, we present the algorithm and the sensor localization results for real data corresponding to a rifle fired from a location. In section 4, we present the conclusions.

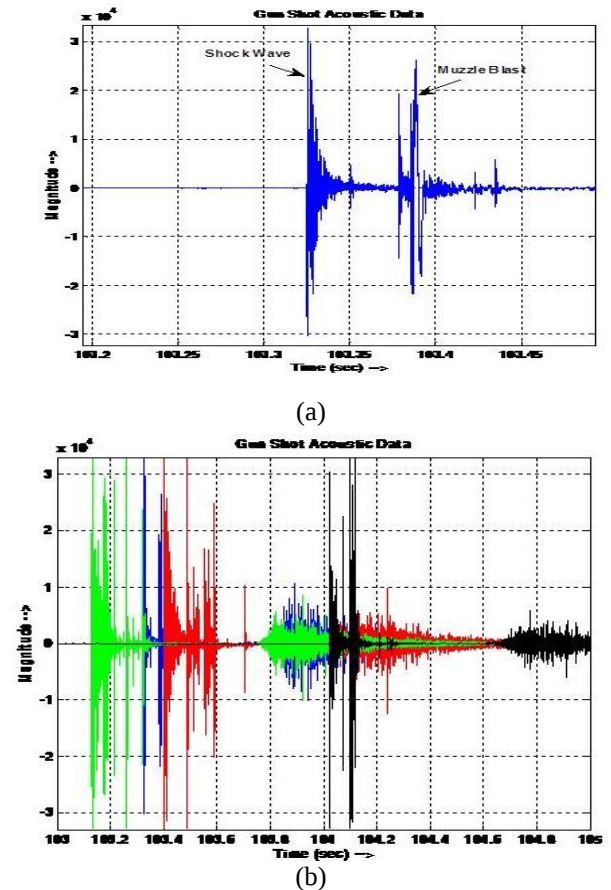


Figure 1: (a) Shock wave and muzzle blast of a gun shot, (b) data recorded by four PDAs

## 2. Sniper Localization Using TDOA between the Muzzle blast and Shockwave

We assume that the sensors are single microphone sensors capable of recording the acoustic signals due to

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rifle firing. Individual microphones can detect the acoustic signals and are capable of detecting the time of arrival of muzzle blast and the shockwave and hence the TDOA between the two. Even though the sensors are not synchronized to a single time frame, we assume that the TDOA of muzzle blast and shockwave at each sensor can be estimated accurately. It is well known from the ballistic data that the bullet loses its speed due to friction as it moves away from the gun. In order to develop the theory, we first present the sniper localization using a constant velocity model for the bullet and then change the model for the more realistic case where the velocity is not constant. In both the cases we assume that the trajectory of the bullet is a straight line – which is a valid assumption for the distances up to 300 m [4].

**Constant Velocity Model:** Figure 2 shows the geometry of the bullet trajectory and the shockwave cone. In figure 2,  $Z$  denotes the location of the sniper and  $U$  is the unit vector in the direction of the bullet. As the bullet travels at super sonic speed the shockwave generates a

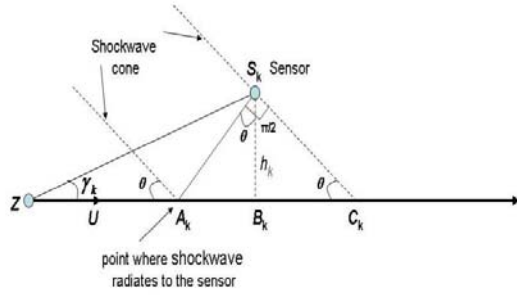


Figure 2: Geometry of the bullets trajectory and the shockwave cone

cone with angle  $\theta$ , where  $\sin \theta = 1/m$ ,  $m$  is the mach number. The shockwave propagates perpendicular to the cone surface and reaches the sensor  $S_k$ . The point where the shockwave radiates towards the sensor is denoted by  $A_k$ . By the time the shockwave reaches the sensor  $S_k$ , the bullet has traveled from  $A_k$  to  $C_k$  and the miss distance is given by  $h_k = \|S_k - B_k\|$ , where  $\|B\|$  denotes the norm of the vector  $B$ . Let  $\gamma_k$  is the angle between the trajectory of the bullet and the line joining the sniper location and the sensor location  $S_k$ .

Let us denote the time of arrival of muzzle blast and the shockwave as  $T_k$  and  $t_k$  respectively,

$$T_k = \frac{\|S_k - Z\|}{v}; \quad t_k = \frac{\|A_k - Z\|}{mv} + \frac{\|S_k - A_k\|}{v} \quad (1)$$

where  $v$  denotes the propagation velocity of the sound. Note that in the time the shockwave propagates from  $A_k$  to  $S_k$ , the bullet travels from  $A_k$  to  $C_k$ ; thus the bullet travels from  $Z$  to  $C_k$  during the time period  $t_k$ . Then  $t_k$  can be re-written as

$$\begin{aligned} t_k &= \frac{\|A_k - Z\|}{mv} + \frac{\|S_k - A_k\|}{v} = \frac{\|C_k - Z\|}{mv} \\ t_k &= \frac{\|B_k - Z\|}{mv} + \frac{\|C_k - B_k\|}{mv} \\ t_k &= \frac{1}{mv} \left( (S_k - Z)^T U + h_k \cot \theta \right) \end{aligned} \quad (2)$$

where 'T' is the transpose and we used the relationship that  $\|B_k - Z\|$  is nothing but the projection of the vector  $S_k - Z$  onto the trajectory of the bullet with unit vector  $U$ . Using the trigonometric relations that  $\|B_k - Z\| = \|S_k - Z\| \cos \gamma_k$  and  $h_k = \|S_k - Z\| \sin \gamma_k$  and  $\sin \theta = 1/m$  we get

$$t_k = \frac{\|S_k - Z\|}{v} (\sin \theta \cos \gamma_k + \cos \theta \sin \gamma_k) \quad (3)$$

$$\begin{aligned} t_k &= \frac{\|S_k - Z\|}{v} \sin(\theta + \gamma_k) \\ \frac{(S_k - Z)^T U}{\|S_k - Z\|} &= \cos \gamma_k \end{aligned} \quad (4)$$

From equations (1) and (3) we find the TDOA

$$\begin{aligned} T_k - t_k &= \frac{\|S_k - Z\|}{v} [1 - \sin(\theta + \gamma_k)] \\ \|S_k - Z\| &= \frac{d_k}{q_k} \end{aligned} \quad (5)$$

where  $d_k = v(T_k - t_k)$  and  $q_k = [1 - \sin(\theta + \gamma_k)]$

We use equations (5) and (4) to solve for the sniper location and the trajectory of the bullet. We now consider the case where the bullet's velocity changes during the course of its travel.

**Changing Velocity Model:** Figure 3 shows the geometry of the bullet trajectory. Notice that the cone angles are different at the point  $A_k$  when the shockwave propagates to the sensor and at the point  $C_k$  at the time the shockwave reaches the sensor. This is due to the decreasing speed of the bullet. For the sake of analysis we assume that the bullet travels at average of speed of mach  $m_1$  from  $Z$  to  $B_k$  and  $\sin \theta_1 = 1/m_1$ ; then the

bullet travels from  $B_k$  to  $C_k$  at an average speed of mach  $m_2$  and  $\sin \theta_2 = 1/m_2$ .

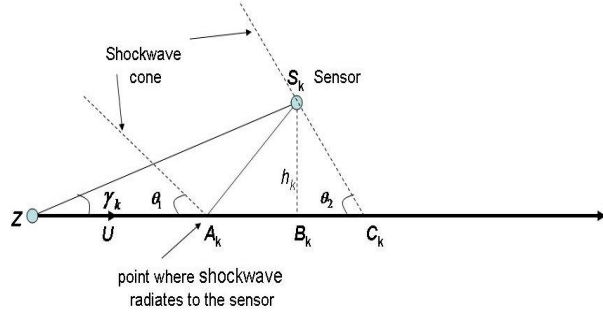


Figure 3: Trajectory of the bullet with different cone angles

From figure 3, we find the TOA of shockwave is given by

$$\begin{aligned}
 t_k &= \frac{\|B_k - Z\|}{m_1 v} + \frac{\|C_k - B_k\|}{m_2 v} \\
 t_k &= \frac{\|S_k - Z\|}{v} \left( \frac{\cos \gamma_k}{m_1} + \frac{\sin \gamma_k}{m_2} \cot \theta \right) \\
 t_k &= \frac{\|B_k - Z\|}{m_1 v} + \frac{\|C_k - B_k\|}{m_2 v} = \frac{\|S_k - Z\|}{v} \left[ \frac{\cos \gamma_k}{m_1} + \frac{\sin \gamma_k}{m_2} \cot \theta_2 \right] \\
 t_k &= \frac{\|S_k - Z\|}{v} [\sin \theta_1 \cos \gamma_k + \cos \theta_2 \sin \gamma_k] \\
 t_k &= \frac{\beta \|S_k - Z\|}{v} \sin(\alpha + \gamma_k)
 \end{aligned} \tag{6}$$

where  $\beta = \sqrt{\sin^2 \theta_1 + \cos^2 \theta_2}$  and  $\alpha = \sin^{-1} \left( \frac{\sin \theta_1}{\beta} \right)$ .

Then the TDOA is

$$\begin{aligned}
 T_k - t_k &= \frac{\|S_k - Z\|}{v} [1 - \beta \sin(\alpha + \gamma_k)] \\
 \|S_k - Z\| &= \frac{d_k}{w_k}
 \end{aligned} \tag{7}$$

where  $w_k = 1 - \beta \sin(\alpha + \gamma_k)$  and  $d_k = v(T_k - t_k)$ . Just as in the case of constant velocity model, the unit vector in the direction of bullet trajectory is related to  $\gamma_k$  by

$$\frac{(S_k - Z)^T U}{\|S_k - Z\|} = \cos \gamma_k.$$

## 2.1 Implementation of Sniper Localization Algorithm & Results

**Data Collection:** In order to test the algorithm, we collected supersonic rifle firing data with eight

microphone sensors distributed closely in a field as shown in figure 4. The rifle is fired in several directions from two locations and the data is collected for process-

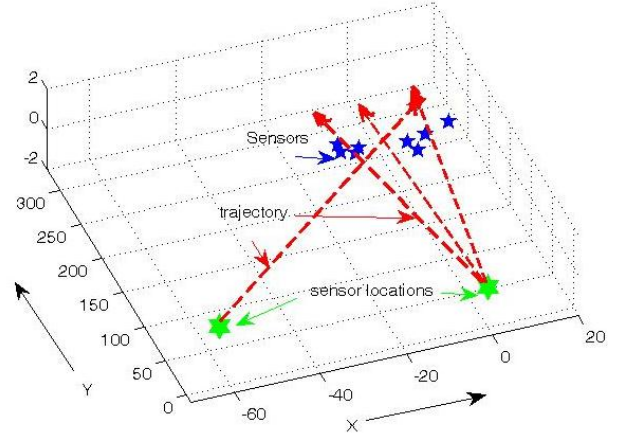


Figure 4: Data collection scenario with 8 microphones and two sniper locations

ing. We used two locations for the sniper which are roughly 60 m apart as shown in figure 4. The sensors were located about 250 m down range. A total of 8 sensors were used to collect the acoustic signatures. The data is collected at 100 KHz in order to capture the shockwave. The acoustic signatures collected were processed to detect the shockwave and muzzle blast. In the case of the constant velocity model, we solve equations (4) and (5) or in the case of changing velocity model we solve the equations (7) and (4). In order to solve equation (7), we need to compute the parameters  $\{v, w, \alpha, \gamma_k\}$ ,  $\forall k \in \{1, 2, \dots, 8\}$ . The propagation velocity of sound  $v$  is estimated using the meteorological data, i.e, the temperature using the formula

$$v = 331.3 \sqrt{1 + \frac{\tau}{273.15}} \text{ m/sec}$$

where the temperature  $\tau$  in Celsius. In order to estimate the parameters  $\alpha$  and  $\beta$  we first need to determine the mach numbers  $m_1$  and  $m_2$ . From the ballistics of the bullets used in the rifle, we used the average speed of the bullet from the time the bullet emerges from the muzzle and the bullets speed at a distance of 250 m for  $m_1$  and the speed of the bullet at the distance 250 m for  $m_2$ . Once  $m_1$  and  $m_2$  are known, we use (6) to determine  $\alpha$  and  $\beta$ . That leaves us with determining the parameters  $\gamma_k$  for all  $k$ . However, this is a difficult one to estimate without the knowledge of the sniper location. This is done iteratively with initially setting the values of

$\gamma_k = 0.01$  for all  $k$  and then estimating the sniper location  $Z$ . In order to estimate  $Z$  using equation (7) we first linearize it resulting in

$$(S_k - Z)^T (S_k - Z) = \frac{d_k^2}{w_k^2}$$

$$\|S_k\|^2 - 2S_k Z + \|Z\|^2 = \frac{d_k^2}{w_k^2} \quad (8)$$

Subtracting (8) for different sensors we get

$$2 \begin{bmatrix} (S_1 - S_2)^T \\ (S_1 - S_3)^T \\ \vdots \\ (S_{n-1} - S_n)^T \end{bmatrix} \tilde{Z} = \begin{bmatrix} \frac{d_2^2}{w_2^2} - \frac{d_1^2}{w_1^2} - S_2^2 + S_1^2 \\ \frac{d_3^2}{w_3^2} - \frac{d_1^2}{w_1^2} - S_3^2 + S_1^2 \\ \vdots \\ \frac{d_{n-1}^2}{w_{n-1}^2} - \frac{d_n^2}{w_n^2} - S_n^2 + S_{n-1}^2 \end{bmatrix} \quad (9)$$

where  $n$  is the number of sensors. From equation (9) we estimate the initial value of  $Z$  which is then used in estimating the values of  $\gamma_k$  denoted by  $\hat{\gamma}_k$  using equation (7), that is,

$$\hat{\gamma}_k = \sin^{-1} \left( \frac{1}{\beta} \left( 1 - \frac{d_k}{\|S_k - \tilde{Z}\|} \right) \right) - \alpha \quad (10)$$

The next step is to estimate the unit vector of the trajectory  $U$  denoted by  $\tilde{U}$  using linear equation (4) given by

$$\begin{bmatrix} (S_1 - \tilde{Z})^T \\ (S_2 - \tilde{Z})^T \\ \vdots \\ (S_n - \tilde{Z})^T \end{bmatrix} [\tilde{U}] = \begin{bmatrix} \|S_1 - \tilde{Z}\| \cos \hat{\gamma}_1 \\ \|S_2 - \tilde{Z}\| \cos \hat{\gamma}_2 \\ \vdots \\ \|S_n - \tilde{Z}\| \cos \hat{\gamma}_n \end{bmatrix} \quad (11)$$

which can be solved for  $\tilde{U}$  using regression. We have estimated the values of  $Z$ , and  $U$  which can be used to re-estimate the values of  $\gamma_k$  using the equation (4), that is,

$$\tilde{\gamma}_k = \cos^{-1} \left[ \frac{(S_k - \tilde{Z})^T \tilde{U}}{\|S_k - \tilde{Z}\|} \right] \quad (12)$$

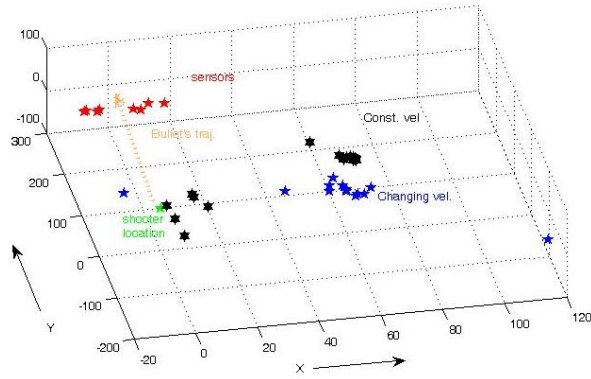
Ideally if the values of  $\tilde{Z} = Z$ , and  $\tilde{U} = U$  the values of  $\hat{\gamma}_k$  and  $\tilde{\gamma}_k$  calculated using the equations (10) and (12)

respectively, should be equal resulting in determining the sniper location and the bullet's trajectory.

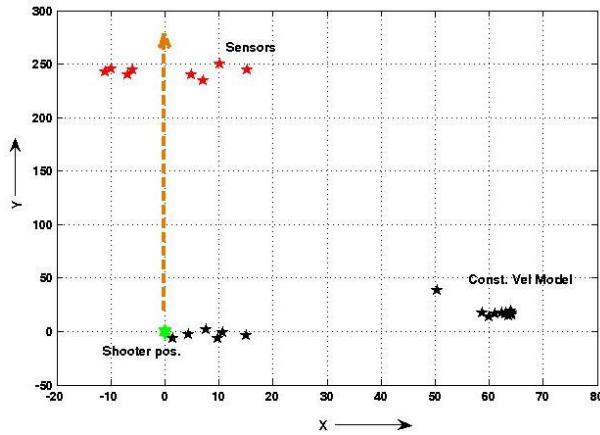
**Experimental Results:** From the processed data, we estimated the TOA of the shockwave and the muzzle blast which gave us the TDOA between the muzzle blast and shockwave. We then applied the algorithm given here to estimate the location of the sniper. In order to use the above algorithm, we need the information about the bullet speed and the propagation velocity of the sound. While the propagation velocity of the sound can be reasonably estimated using the meteorological data such as temperature, humidity and the wind velocity, the bullet speed varies from bullet to bullet due to the variations occurring in the manufacturing process. One can estimate the bullets velocity from the N-wave generated by the shockwave [1, 4]. This requires the knowledge of the diameter of the bullet, length of the bullet and the shape of the bullet. However, this does not provide the velocity of the bullet from the time it was fired from the gun to the point where the sensors are located. In order to overcome this, we allow the algorithm to estimate the Mach numbers  $m_1$  and  $m_2$ .

Better approach for estimation of  $m_1$  and  $m_2$  is to use optimization algorithm such as MATLAB's "fminsearch". We used *fminsearch* to determine the sniper location and optimize the values of  $m_1$  and  $m_2$  resulting in the minimization of the sum of the difference between  $\hat{\gamma}_k$  and  $\tilde{\gamma}_k$  for all  $k$ . These algorithms are basically search algorithms. Unfortunately there are several local minima and hence the sniper localization results are sensitive to the initial estimate of the sniper location used. In order to overcome this difficulty, the *fminsearch* is performed with starting points in the 3-dimensional grid with X & Y changing from -100 to 100 with an increment of 30 and Z changing from -10 to 100 with increments of 30. The resultant estimates of the algorithm are averaged to determine the overall estimation of the sniper location.

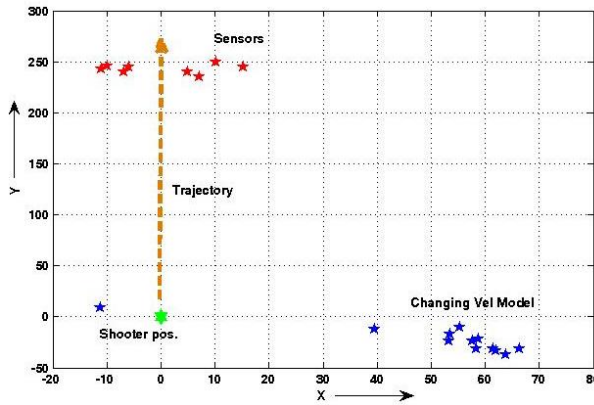
In Figure 5 the red stars denote the location of the single microphone sensors, the black stars indicate the estimation of the sniper location using the constant velocity model, and the blue stars indicate the location of the sniper using the changing velocity model.



(a) 3D view of estimated sniper locations



(b) 2D view of estimated sniper locations with constant vel. Model



(c) 2D view of estimated sniper locations with changing vel. model

Figure 5: Results of the algorithm

Table 1 presents the average values of X, Y, and Z coordinates and their variances for the sniper location using both models.

| Coord. | Shooter position | Mean (Const. vel. Model) | Std (Const. vel. Model) | Mean (Chng. Vel. Model) | Std (Chng. Vel. Model) |
|--------|------------------|--------------------------|-------------------------|-------------------------|------------------------|
| X      | 0                | 37.1                     | 27.6                    | 51.8                    | 25.8                   |
| Y      | 0                | 8.6                      | 11.9                    | 21.0                    | 12.7                   |
| Z      | 0                | 31.0                     | 42.3                    | 29.7                    | 7.4                    |

Table 1: Statistics of estimated sniper location by both the models

We are able to localize the sniper position to within 60m for the case where the sniper fired the gun from a berm on the ground. These estimate appears to be biased estimates. In the future work we plan on investigating the reasons for the bias.

### 3. Conclusion

In this paper we have presented a sniper localization algorithm using single microphone sensors. The algorithm is based on the time difference of arrival of muzzle blast and shock wave which can be measured at each microphone accurately without necessitating time synchronization among the sensors. This feature makes the approach more readily usable for man-wearable sniper localization system.

We presented two models for estimation of the sniper location. The merits of the two will be explored further in later work.

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