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Interpretation of audio forensic information from the shooting of journalist Shireen Abu Akleh

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ABSTRACT

User generated recordings (UGRs) are increasingly presented as evidence in forensic investigations due to the widespread use of handheld cameras, smartphones, and other portable field recording devices. A case study comes from the shooting death of well-known Al Jazeera television correspondent Shireen Abu Akleh on May 11, 2022. Ms. Abu Akleh was killed by a gunshot while reporting from the West Bank city of Jenin during a clash between Israeli Defense Forces and armed Palestinian militants. The fatal gunshot was not captured on video, but the microphones of at least two cameras at the scene recorded the sound of multiple gunshots. In this paper, we describe the acoustic evidence from the incident, including the estimates of the various geometric and physical parameters and the likely range of uncertainty of those measurements, and present a forensic estimate of the distance between the firearm and the recording microphones.

1 Introduction

User Generated Recordings (UGRs) are audiovisual material obtained from unofficial sources, such as smartphones and other devices carried by bystanders, residential and commercial surveillance systems, and from electronic news-gathering teams. The seeming ubiquity of handheld recording devices has steadily increased the likelihood that UGRs may become part of an audio forensic investigation [1, 2].

UGRs in the form of a video recording comprise a sequence of video frames (sequence of still pictures) typically encoded exploiting image frame-to-frame correlation via MPEG video, and a corresponding digital audio recording. The audio encoding generally involves a lossy perceptual audio coder, although some recordings may use uncompressed PCM. If lossy coding is involved, block-based processing may result in spectral modifications and temporal pre-echo effects that may blur the precise timing of waveform features [3, 4].

This paper presents a case study of audio forensic information obtained from UGRs at the scene of the shooting death of Al Jazeera television correspondent Shireen Abu Akleh, on May 11, 2022. (https://www.aljazeera.com/news/2022/5/11/shireen-abu-akleh-israeli-forces-kill-al-jazeera-journalist).

The shooting incident took place on a public street with community bystanders and professional journalists nearby. At least one cell phone video and one recording by a professional videographer are known to exist.

The remainder of this paper is organized as follows. First, we review the acoustical properties of firearm sounds, including the characteristic bang of the ignited gunpowder, and if the ammunition travels at supersonic speed, the shock wave crack of the bullet observed down range. Next, we describe the relevant characteristics of the distinctive sounds observed in the UGRs from the Shireen Abu Akleh shooting incident and summarize the acoustical analysis. Finally, we conclude with some remarks about the usefulness and limitations of UGRs in current and future audio forensic investigations.

2 Muzzle blast

A conventional firearm uses a confined combustion of gunpowder to propel the bullet out of the gun barrel. The hot, expanding gases rapidly pressurize the chamber behind the bullet. The pressure accelerates the bullet down the gun barrel and out the muzzle, accompanied by the jet of combustion gas emitted from the muzzle, the *muzzle blast*. The muzzle blast sound propagates in all directions, but much of the acoustic energy is expelled in the general direction the gun barrel is pointing. The muzzle blast comprises an acoustic shock wave and a brief, chaotic sound lasting only a few milliseconds [5-7].

The muzzle blast sound propagates through the air at the speed of sound (e.g., 343 m/s at 20°C), and like any sound, the acoustic waves interact with the surrounding ground surface, obstacles, temperature and wind gradients in the air, spherical spreading, and atmospheric absorption. A recording microphone located at some distance from the firearm will receive the muzzle blast sound accompanied by multi-path reflections and reverberation. If the direct sound path from the firearm to the microphone is obscured by terrain, buildings, or other obstructions, the received muzzle blast consists only of diffracted and reflected sound [5, 8-10].

3 Shock wave phenomenon

The mechanical properties of regular linear acoustical wave propagation involve a linear balance between the acoustic pressure (p), air density (ρ), and the air particle velocity ($\bar{u}$) at a particular point. The sound wave phase speed (the speed of sound, c) is given by [11]:

$$c = c_0\sqrt{1 + T/273}\ , \qquad (1)$$

where c_0 = 331.5 m/s and T is the air temperature in Celsius.

An object traveling through the air at a rate faster than the local speed of sound creates a ballistic shock wave. Once launched, the shock wave itself moves through the air at the speed of sound. A supersonic projectile that travels through the air creates a shock wave cone that trails behind the bullet's path [5, 7, 8].

The ratio of the speed of a moving object, V, to the speed of sound, c, is known as the *Mach number*, $M = V/c$. In the case of an object moving faster than Mach 1 ($V>c$), the air motion is nonlinear, and the object launches a shock wave rather than a linear acoustic disturbance.

Because the shock wave disturbance propagates at the speed of sound, the inner angle of the shock wave cone depends upon the Mach number, M. The ballistic shock wave trailing the supersonic bullet has an inner angle [12]:

$$\theta_M = arcsin\left(\frac{1}{M}\right). \qquad (2)$$

A projectile with speed just barely above the speed of sound ($M \approx$ Mach 1) will have a broad shock wave cone ($\theta_M \rightarrow 90°$), while a fast bullet ($M >>$ Mach 1) will have a narrow shock wave cone ($e.g., \theta_M \rightarrow 16.6°$ when $M = 3.5$, as shown in Figure 1.

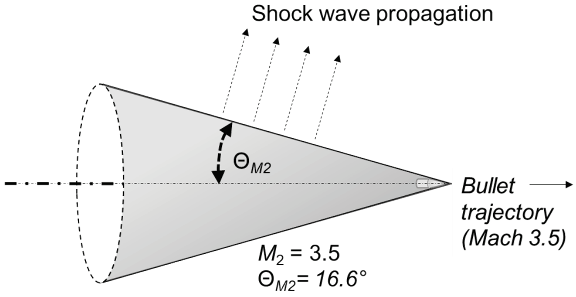

Figure 1: Shock wave cone from a supersonic projectile [7].

A microphone located near the trajectory of a supersonic bullet will detect the shock wave immediately after the bullet passes by. The time of arrival of the shock wave at the microphone depends on the distance of the microphone from the bullet's path and the Mach number of the bullet. A sketch (plan view) is shown in Figure 2. The issue of the position of the microphone with respect to the bullet's trajectory will be discussed further in Section 6.

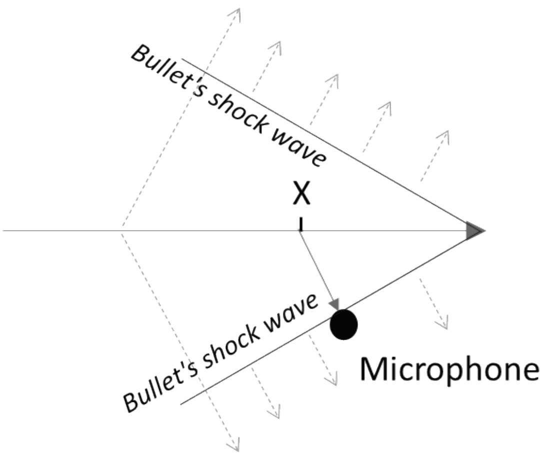

Figure 2: Plan view depicting shock wave arrival at a microphone near the bullet's path.

The bullet decelerates as it travels down range due to friction with the air. The deceleration rate depends in a complicated manner upon the bullet's absolute speed, the mass and aerodynamic characteristics of the bullet (often expressed as a *ballistic coefficient*), the density and humidity of the air, and the presence of wind and other environmental factors. Therefore, the time-of-flight from the muzzle of the firearm to a particular location down range must use an estimate of the bullet's average speed and deceleration profile. An example speed profile is shown in Figure 3.

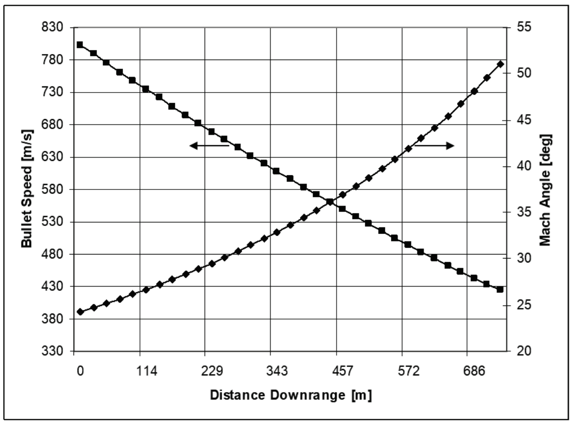

Figure 3: Example of bullet deceleration and shock wave Mach angle as a function of distance down range (V_{muzzle} = Mach 2.4) [10].

4 Relative timing of shock wave and muzzle blast

When a firearm shoots a supersonic bullet, the bullet's ballistic shock wave emanates from the bullet's path as the bullet travels down range faster than the speed of sound, while the muzzle blast of the gun propagates at the speed of sound. This means that the sound of the ballistic shock wave will precede the sound of the muzzle blast at points down range near the bullet's path.

With the speed of sound (c) for the muzzle blast wave front, and an average bullet speed (V) over the path from the muzzle to the microphone, the time difference between the shock wave arrival and the muzzle blast arrival is determined by the relative speed:

$$t_{diff} = \frac{distance}{c} - \frac{distance}{V} \quad . \tag{3}$$

In an audio forensic investigation, it is more typical to observe the time difference between the arrival of the shock wave and the arrival of the muzzle blast from an audio recording, and then estimate the distance of the firearm:

$$distance = \frac{t_{diff}}{\left(\frac{1}{c} - \frac{1}{V}\right)} \quad . \tag{4}$$

The geometry of the sound propagation is shown in Figure 4.

5 Case study: the incident in Jenin on May 11, 2022

The UGRs from the shooting death of Al Jazeera television correspondent Shireen Abu Akleh give an example of audio forensic interpretation from unofficial sources. The shooting incident took place on May 11, 2022, outdoors on a street in the western portion of the city of Jenin. Ms. Abu Akleh and several colleagues were covering maneuvers by Israel Defense Forces (IDF) at the Jenin refugee camp in the West Bank. Their reporting at the location in Jenin took place with both community bystanders and professional journalists nearby.

At the time of the initial bullets passing through the area, a community member happened to have his mobile smartphone making a video recording at the intersection where the bystanders and journalists had gathered. Although the phone's camera was not pointing at the journalists at the moment of the shots, the sound of the initial shots was recorded. After the initial barrage of shots, an Al Jazeera camera operator also began recording audio and video a few steps away from the individual making the cell phone video.

The mobile phone UGR will be referred to as the *Sleem Awad cellphone video*, [16] while the videographer's recording is referred to as the *Al Jazeera video* [17]. The videos were provided by reporters from Bellingcat, CNN, and the New York Times, as part of their investigation of the incident [13-15].

There has been no dispute about the authenticity of these two videos taken near the scene of Shireen Abu Akleh's shooting. However, there were disputing claims about which forces were responsible for shooting the bullets, because both IDF and Palestinian forces were known to be active in Jenin at the time of the incident. The investigating reporters noted that gunshots were audible in the two videos, *and the fundamental question posed by the reporters was whether it was possible to estimate the distance from which the audible shots were fired by analyzing the audio recordings*.

Our initial observation of the gunshot sounds in the audio recordings revealed distinctive *crack-pop* sequences. A crack-pop sequence of sounds is indicative of, first, the shock wave of a supersonic bullet passing the microphone (the "crack" sound), then the arrival of the more distant muzzle blast of the firearm (the "pop" sound).

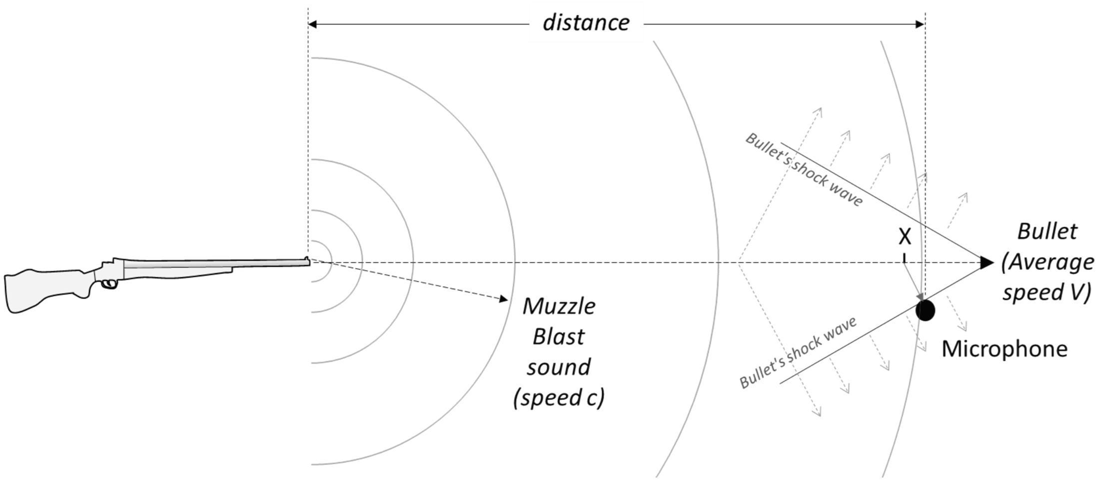

Figure 4: Relative timing of arrival of shock wave and muzzle blast at the microphone for a supersonic bullet with trajectory close to the microphone position.

As described earlier in this paper (Section 4), a supersonic bullet travels down range faster than the speed of sound, so its shock wave is observed in the vicinity of a down range microphone a time t_{diff} before the arrival of the gun's muzzle blast traveling at the slower speed of sound (see Eqn. 3).

5.1 First barrage

The pertinent section of the Sleem Awad video begins with the first audible close gunshot just after 7 minutes file elapsed time (FET): 7:06.918. Shortly before the first audible gunshot, the video shows several journalists wearing helmets and protective jackets starting to walk south on a road in Jenin later identified to be New Camp Street, while perhaps a dozen bystanders watch and engage in casual conversation (see video frame shown in Figure 5).

The first barrage has six audible shock wave + muzzle blast sequences. Figure 6 shows the recorded audio waveform and four video frames from around the time of the first shot, with manually inserted labels indicating the bullet's shock wave arrivals (SW1 and SW2) and the corresponding muzzle blast arrivals (MB1 and MB2).

The observed timing between the arrival of the first ballistic shock wave (SW1) and the arrival of the corresponding muzzle blast sound (MB1) is 310 ms. Using an estimated air temperature of 18° C, the speed of sound, c, would be 342 m/s. The average speed of the bullet cannot be determined from the audio recording, but sources knowledgeable about the firearms and the type of ammunition most likely to have been in use in Jenin that day indicate that projectiles were from a 5.56 x 45 mm NATO cartridge. A diagram depicting the bullet velocity for several example 5.56 cartridges is shown in Figure 7.

The muzzle velocity of the 5.56 cartridge examples range from 2,750 to 3,300 ft/s (838 to 1,006 m/s), with the projectile slowing to 2,250 to 2,600 ft/s (686 to 792 m/s) by 200 yards (183 meters). If we consider the average velocity from the muzzle to 200 yards to be 762 to 884 m/s, and $t_{diff} = 0.31$ s, we can use Eqn. 4 to provide an estimate of the distance from the firearm to the recording microphone: *173-193 meters*.

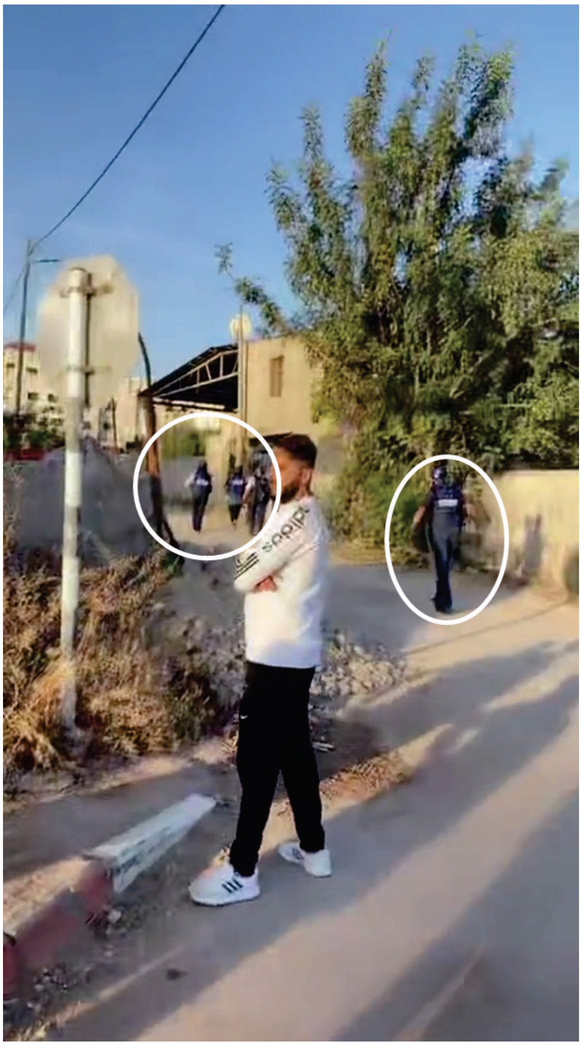

Figure 5: Frame from Sleem Awad video at approximately 7:06.2 FET showing reporters in blue jackets labeled "PRESS" walking south on New Camp Street, while bystanders casually converse.

In total, the first barrage of audible gunshots in the Sleem Awad video includes six audible shock wave + muzzle blast sequences during the approximately 2.5 s interval from 7:06.918 to 7:09.416 FET, as shown in Figure 8.

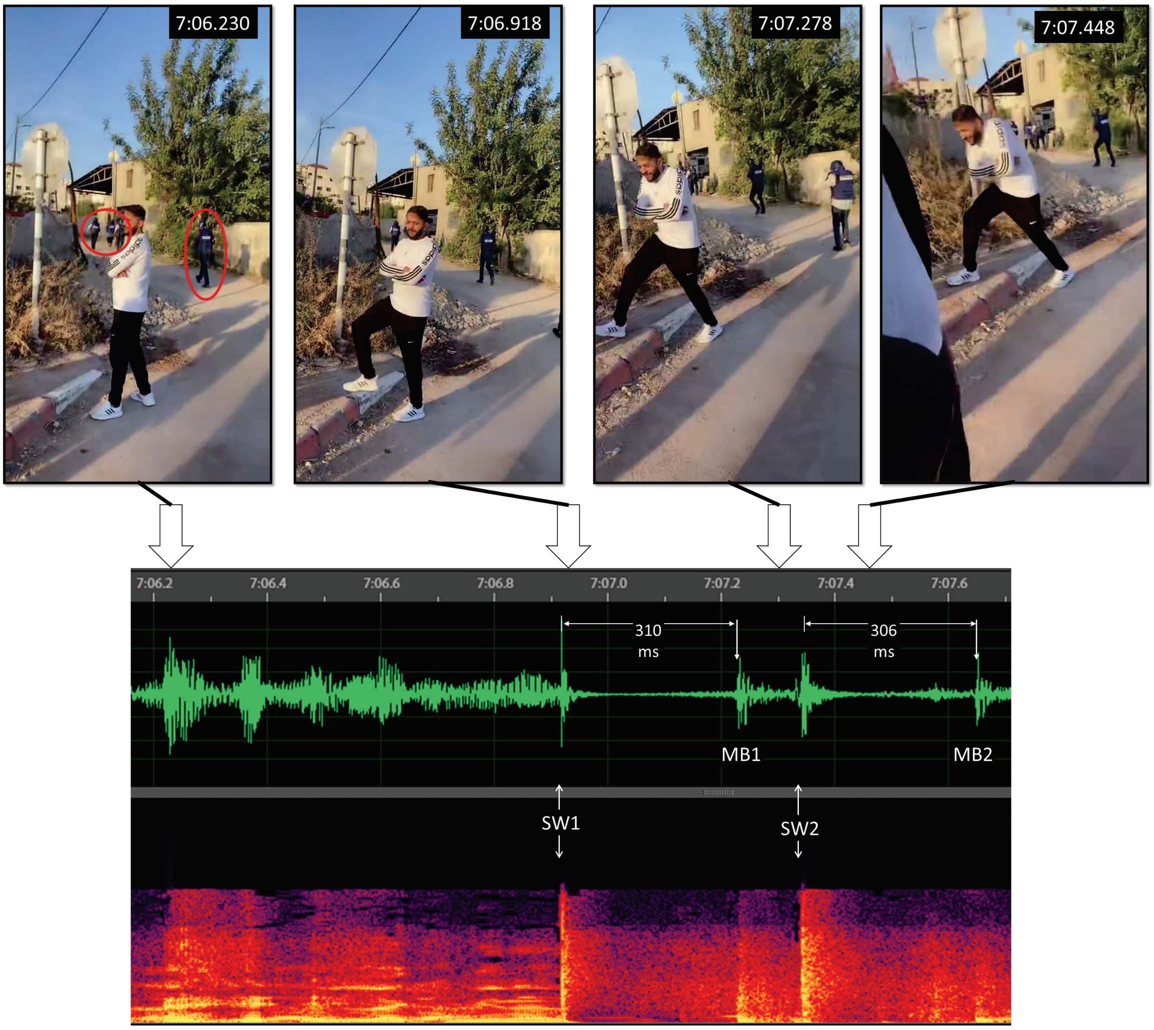

Figure 6: Sequence of video frames and audio from the Sleem Awad recording at the moment of the first distinct gunshots.

The amplitude and timing of the successive shots varies, and at least part of the variation appears to be the movement of the recording cell phone as Mr. Awad and the other bystanders react to the sound and run a few meters to the east, presumably out of what they perceive to be the line of fire.

5.2 Second barrage

Following the first barrage, there are no audible shots for several seconds. During that interval the Al Jazeera videographer began filming at the scene. The first few seconds of the Al Jazeera video show producer Ali al-Samoudi, who had been struck in the shoulder by one of the bullets in the first barrage, walking north in a slightly stooped-over posture toward a waiting automobile (see Figure 9). At approximately the same instant, the sound of a second barrage of shots begins: seven audible shock wave + muzzle blast sequences in 2.31 seconds (between 7:17.847 and 7:20.163 FET in the Sleem Awad video, and 1.478 and 3.792 FET in the Al Jazeera video).

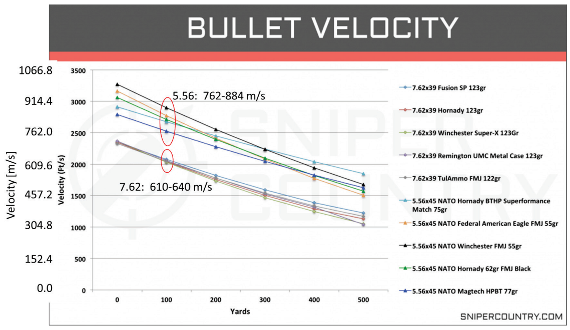

Figure 7: Example velocity chart for 5.56 caliber ammunition (from snipercountry.com) [18].

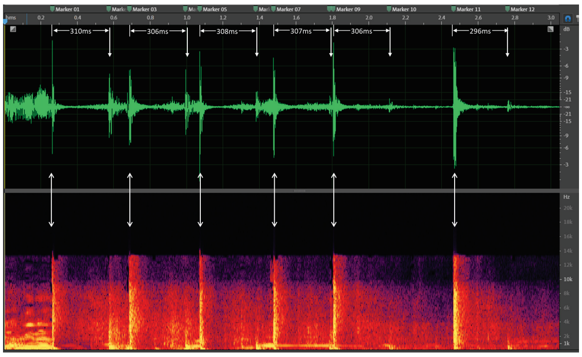

Figure 8: First barrage sequence of six shots in the Sleem Awad video, 7:06.918 to 7:09.416 FET.

Figure 9: Initial frame from the Al Jazeera video, showing injured producer Ali al-Samoudi heading toward a waiting automobile.

As observed in the audio waveform shown in Figure 10, several of the shots in the second barrage are sufficiently close together in time that the muzzle blast of one shot coincides with the shock wave of the next shot. For the shots in which the shock wave and muzzle blast combinations can be identified, the time differences are similar to what was observed for the first barrage: approximately 300 milliseconds.

Producer Ali al-Samoudi was struck by a bullet during the first barrage, as he is already seen (Figure 9) moving north away from the scene toward the waiting automobile when the second barrage begins. However, it is not clear at what moment Shireen Abu Akleh was struck.

One clue is that there is a brief glimpse showing a tree and wall forming the west side of New Camp Street in the Sleem Awad video at the time the second barrage commences (see Figure 11). Mr. al-Samoudi has already moved farther to the north at that time (right of the view in Figure 11), and the other journalists, including Ms. Abu Akleh, must still be on the street to the south (left of the view in Figure 11).

After the seven audible shots of the second barrage cease, the Al Jazeera videographer moves into a position providing the view shown in Figure 12. In that frame from the Al Jazeera video, Ms. Abu Akleh's body can be seen lying face down, with freelance journalist Shatha Hanaysha standing near the wall and tree and in the location previously seen as vacant in Figure 11. Thus, it appears likely that the shot that struck Ms. Abu Akleh was from the second barrage.

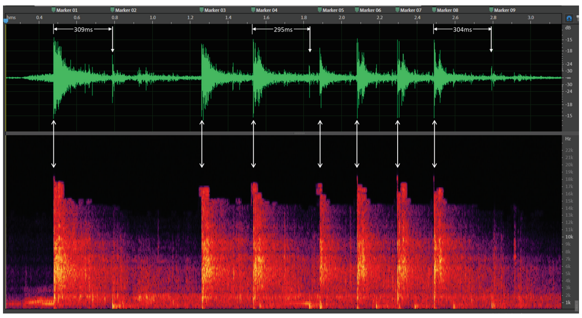

Figure 10: Second barrage consisting of seven audible shots, 7:17.847 to 7:20.163 FET.

Figure 11: View of wall and tree on west side of New Camp Street at the start of the second barrage: no individuals are north (right) of the tree at that point.

5.3 Final barrage

Following the uninterrupted flow of the Al Jazeera video, after the last shot in the seven-shot second barrage, approximately 1 minute and 59 seconds elapses, followed by one isolated shock wave + muzzle blast sequence. That shot is observed at a point in the Al Jazeera video in which an individual in a white shirt and jeans is crouching near Shireen Abu Akleh's body (see Figure 13). This is followed by a gap of about 23 seconds before another shot is heard, and a final shot is heard about 2.5 seconds after that.

Counting the audible shots with the shock wave + muzzle blast signature, the total is 16: six from the first barrage, seven from the second barrage, and three in the final barrage. The relative timing of the videos and shots is summarized in Figure 14.

Figure 12: After second barrage, a frame from the Al Jazeera video shows freelance journalist Shatha Hanaysha standing next to Ms. Abu Akleh's body, lying prone on the ground.

Figure 13: Al Jazeera video frame when one isolated audible shock wave + muzzle blast sequence occurs (1:59 after the second barrage).

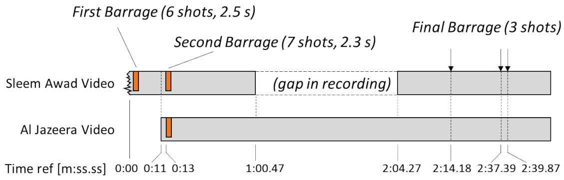

Figure 14: Time sequence of events in the two videos, referenced to start of first barrage.

6 Interpretation and uncertainty

The audio forensic interpretation of the shock wave + muzzle blast sequences based upon the observed time difference of arrival of approximately 300ms at the position of the recording microphones leads to the conclusion that the firearm was likely between 167 and 186 meters away, using $t_{diff} = 0.3$ s and a plausible range of average bullet velocities (see Section 5.1). However, there are several uncertainties about the detailed circumstances of the incident captured in the UGRs that must also be considered.

6.1 Unknown trajectory of each bullet

As noted in Section 3, the observed shock wave phenomenon is due to the arrival of the bullet's ballistic shock wave "cone" at the position of the microphone. If the trajectory of the bullet passes some distance, *d*, from the microphone position, the time-of-arrival of the shock wave at the microphone position is delayed by the time required for the shock wave to travel at the speed of sound from the bullet to the microphone, as sketched in Figure 15.

The portion of the shock wave cone that impinges upon the microphone is generated when the bullet has not yet reached the microphone's position, as shown in Figure 16. Referring to the geometry depicted in Figure 16, this means that the arrival of the shock wave sound depends upon the bullet's time-of-flight at average speed *V* from the muzzle to position "*X*", plus the time required for the shock wave to travel from *X* to the offset microphone at the speed of sound, *c*. Furthermore, the Mach Angle Θ_M of the shock wave cone (see Eqn. 2) will be determined by the bullet's speed in the vicinity of the microphone, which will be slower than the average speed over the entire path from muzzle to the scene.

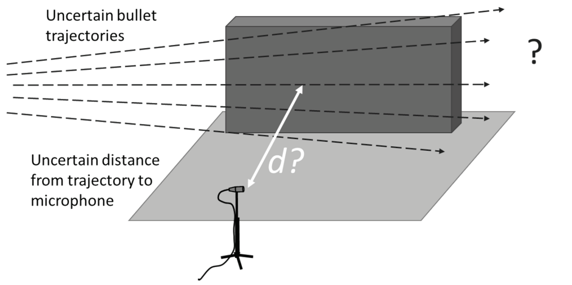

Figure 15: The uncertainty of the geometric relationship between the bullets' trajectories and the location of the recording microphone.

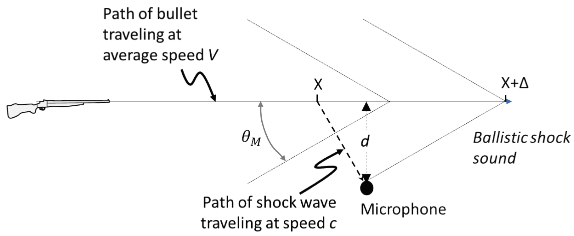

Figure 16: Geometry of shock wave path to microphone with offset bullet trajectory.

To understand the sensitivity of the firearm distance estimate to the offset distance, *d*, between the bullet's trajectory and the microphone location, we can express the time-of-arrival of the shock wave in terms of the unknown distance, *X*, from the firearm, the estimated average bullet speed, *V*, the speed of sound, *c*, and the estimated Mach Angle, Θ_M, for the bullet traveling at its decelerated speed near the microphone:

$$t_{shock\_arrival} = \frac{X}{V} + \frac{d}{c} \cdot \frac{1}{\cos\theta_M} \ . \qquad (5)$$

Assuming *X*>>*d*, we can approximate the arrival of the muzzle blast sound as

$$t_{muzzle\_arrival} = \frac{X + \frac{d}{\cot\theta_M}}{c} \ . \qquad (6)$$

The observed time difference of arrival is therefore $t_{diff} = t_{muzzle\_arrival} - t_{shock\_arrival}$, and solving for the estimated distance *X*, we have

$$X = \frac{t_{diff} - \frac{d}{c}\left(\frac{1}{\cot\theta_M} - \frac{1}{\cos\theta_M}\right)}{\left(\frac{1}{c} - \frac{1}{V}\right)} \quad . \tag{7}$$

Note that Eqn. 7 reduces to Eqn. 4 if $d \rightarrow 0$. The estimated distance from the muzzle to the microphone is given by:

$$X_{tot} = X + d/\cot(\Theta_M) \quad . \tag{8}$$

Using t_{diff} = 300 ms, c = 342 m/s, the average bullet speed V between 762 and 884 m/s, and the decelerated bullet speed in the vicinity of the microphone between 689 and 776 m/s (giving the Mach Angle between 28.76 and 26.15), the estimated distance from the firearm is shown in Figure 17. Thus, we may estimate that the uncertainty about the distance to the firearm is approximately +2 meters for each +1 meter of microphone offset.

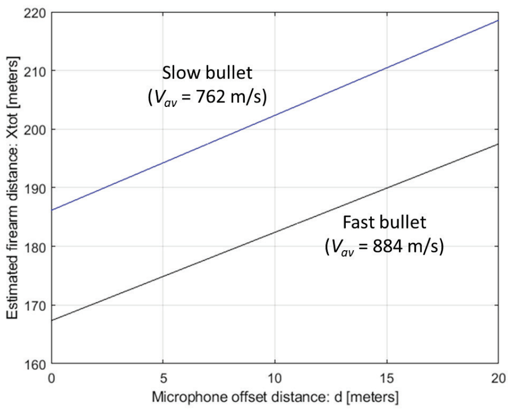

Figure 17: Estimated distance to firearm with t_{diff} = 0.3 s, as a function of d, the microphone offset distance from the bullet trajectory.

6.2 Other aspects of uncertainty

Some other contributing factors to uncertainty in the firearm distance estimate based on the shock wave + muzzle blast timing include temperature, wind, and other meteorological effects that may cause a change to the speed of sound. A ±1° C change in temperature results in a change of approximately ±0.6 m/s in sound speed, which causes about ±0.6-meter change in the estimated firearm distance. Similarly, a light breeze of 2 m/s (Beaufort wind force scale of 2) parallel to the bullet trajectory would cause a ±2-meter change in the estimated distance.

Thus, the uncertainty of the firearm distance is primarily attributable to the uncertainty about the bullet speed, and secondarily attributable to the uncertainty about the microphone offset distance from the bullet's trajectory. The meteorological effects appear to have minimal effect upon the estimated distance from the firearm to the microphone.

It is also important to note that while the shock wave + muzzle blast timing analysis shows approximately the same $t_{diff} \approx 0.3$ s, the analysis does not provide information about whether *all* of the observed shots were from a single firearm, or from two or more different firearms at approximately the same distance.

7 Conclusion

The tragic shooting incident that resulted in the death of Shireen Abu Akleh was observed by two unsynchronized User Generated Recordings (UGRs) obtained from unofficial sources present at the scene. The availability of these UGRs is an example of the increasing likelihood that such recordings may become part of an audio forensic investigation. While a complete and authoritative investigation of this shooting incident requires more than just the audio forensic evidence, the audio analysis does provide several objective observations about the estimated distance of the firearm(s) from the microphone that would not be available solely from eyewitness testimony or post-incident collection of physical evidence at the scene.

This case study also demonstrates several of the challenges associated with audio forensic analysis of gunshot sounds, such as uncertainty about the precise location of the recording microphone(s), uncertainty about the number of firearms, the bullet speed and trajectory, and the potential effects of wind, terrain, and temperature.

8 Acknowledgements

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