Battlefield Acoustics in the First World War: Artillery Location

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Introduction and Context

Acoustics have probably been used in warfare for as long as people have been warring with each other. Indeed, in an historical review, Namorato (2000) relates the use of acoustics in warfare from biblical to modern times. The examples he describes through the nineteenth century largely rely on the human ear for hearing or not hearing and for recognizing various sounds associated with warfare.

World War I (WWI) was distinguished from earlier conflicts by technological advancements such as the advent of electricity that took place in the late nineteenth and early twentieth centuries which led to the invention of devices for transmitting, detecting, and recording sound. Other technological advancements in warfare were introduced during this period: the machine gun was invented in 1884, the flamethrower was invented in 1914, poison gas was introduced in 1915, and the tank was invented in 1916 (Meyer, 2006).

However, advancements in artillery, which killed more people in WWI than did any other weapon, led to the development of methods to localize (and ultimately destroy) enemy artillery. In other words, artillery location technologies were developed to counter the recent advances in artillery.

In the early twentieth century, there were two classes of artillery: field artillery and heavy artillery (see bit.ly/2TX2DFZ). Field artillery, such as that used in the US Civil War, was intended for mobile warfare and shot small caliber shells between 7.5 and 8.4 centimeters. The projectiles traveled in flat trajectories at targets within the line of sight, so soldiers could usually see the cannon firing at them. Field artillery continued to be used in the First World War, but it was supplemented by heavy artillery (Meyer, 2006; Storz, 2014).

Heavy artillery was developed in the late 1800s, largely by Germany because field artillery was not able to destroy improvised field fortifications in the Russo-Turkish War (1877–1878). Heavy artillery fired larger caliber rounds with increased muzzle velocities at increased ranges. Then, in 1897, France developed a gun with a long barrel recoil that had a brake mechanism that absorbed the recoil so that the gun did not require repositioning after each shot. In addition, shells combined propellant, warhead, and timing devices into a cylinder that could be quickly loaded into the guns. These developments allowed for an increased rate of fire and subsequently required an increased supply of ammunition.

One example of heavy artillery in use by the German Army in WWI was a 21-cm-caliber Morser Howitzer (**Figure 1**) that had a supersonic muzzle velocity of 393 meters/

Figure 1. *A 21-cm-caliber Morser Howitzer used by the German Army in World War I (WWI). Photo by Balcer~commonswiki, used under the Creative Commons license with attribution (CC BY 2.5). Available at bit.ly/3d75Eem.*

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second and a maximum firing range of 11 kilometers. It could be fired at a rate of 1 to 2 rounds per minute. These guns could be positioned at larger distances from the line of fighting and behind obstacles such as forests or hills.

WWI began as a war of mobility, with seven German armies advancing rapidly through Belgium and into France in August 1914. Their progress was impeded by the French, with the help of the British Expeditionary Force (BEF), before they were able to invade Paris. For the next four years, the Allied and German armies defended lines of demarcation that roughly ran from the North Sea near the border between France and Belgium to the corner between France, Germany, and Switzerland in what became known as trench warfare. Machine guns kept troops in their trenches and the fronts stationary so that the most effective way to inflict injury on the enemy was to lob shells at them from behind one's own line.

Methods of Artillery Location

All sides in WWI recognized the need for locating artillery fairly quickly. Three basic methods were used: aerial location, flash ranging, and sound ranging. Aerial location was performed by using both observation balloons and airplanes. Aerial photography made great strides during this period and provided valuable intelligence for locating enemy positions and for map making. However, these advances came with risks because as airplanes developed, so did antiaircraft artillery. Also, aerial surveillance was not effective in conditions of fog or rain, which were not uncommon. Observation balloons bobbed around in the atmosphere, making it difficult to measure bearings accurately. In addition, each side would hide or camouflage its batteries to avoid detection or set out decoys.

Flash ranging, developed alongside sound ranging, was another method for locating artillery. Three to four observation posts were ideally surveyed 1,400-1,800 meters from the front lines along a 3- to 4-kilometer base. Efforts were made to conceal these posts from the enemy, but concealment was not always possible. There had to be a sufficient distance between each observer for accurate triangulation. The observer had a survey instrument at his position, similar to a transit or a theodolite, and a phone line hardwired to the switchboard at "Flash Central." The observer would press a key or button that was part of the phone set when he saw the flash from an enemy gun. If multiple observers pressed the key at the same time, the operator at Central could be confident they were observing the same flash. The observers measured the bearings from their position to the flash of the observed gun and reported them to Central through the telephone. On a map board at Central, the observers' positions had been accurately plotted. The operator at Central stretched catgut strings from the observers' positions on the board along the corresponding bearings so that the intersection of the strings from the different observation posts provided the location of the gun or the battery. Captain (later Colonel) Harold Hemming, a Canadian gunnery officer posted to Ranging and Survey, is credited with the development and advancement of flash ranging. Flash and sound ranging were developed at the same time and complemented each other (Bragg et al., 1971; Mitchell, 2012).

Beginnings of Sound Ranging

When the war started, Charles Nordmann was a professor of astronomy at the Paris Observatory in Meudon, France. He was serving at the front in the French Army in 1914 when he conceived the idea of sound ranging and obtained permission to test it. He sought the assistance of Lucien Bull, who had been developing galvanometers for electrocardiography at the Institute of Marey in Paris (Van der Kloot, 2005; Mitchell, 2012).

Nordmann determined that a gun could be located by measuring the time differences of arrival of the sound from a gun to different observation positions. Nordmann and Bull conducted sound ranging experiments to test this idea in late November 1914. Two guns were located in St. Cloud, a village located on the west side of Paris. In one approach, human observers, "tappers," would press a key similar to the ones used by the flash-ranging observers when they heard the guns fire. They also used stopwatches to record the time from the flash of the muzzle to the time they heard the sound. In a separate approach, four microphones placed along a baseline of 4,500 meters recorded the signals. The tests proved successful, and the guns were located with an error of 40 meters in range and 20 meters in bearing. The human observers were within 0.05 second of the microphones. The "tappers" were deployed to Arras, Belgium, near the British line, to establish sound-ranging (SR) sections. Because the method was subjective and lacked precision, the French continued to develop and improve systems using microphones (MacLeod, 2000).

The Geographical Section of the General Staff in London had learned about the French efforts to locate artillery by sound. The head of the topographical subsection at the General Headquarters (GHQ) in Flanders, Belgium, Lieutenant. Colonel Ewan Maclean Jack, Royal Engineers (RE), recruited Second Lieutenant William Lawrence Bragg to put a system in operation.

Bragg was a student of mathematics and physics at Trinity College Cambridge in 1909. After taking a First in Part II Physics in 1911, he started working at the Cavendish Laboratory. In November 1915, he and his father, William Henry Bragg, were jointly awarded the Nobel Prize in physics "for their services in the analysis of crystal structure by means of Röntgen rays." W. L. Bragg, who was 29 years old at the time, is still the youngest laureate to have won the Nobel Prize in a scientific category.

Bragg had enlisted shortly after the war began and was commissioned as a Second Lieutenant. In the fall of 1915, Lieutenant Colonel Jack offered Bragg the opportunity to put SR into operation. Bragg accepted, happy to have a scientific job in the war, and recruited an assistant, newly commissioned Lieutenant Harold Roper Robinson, a lecturer in physics at London University where he worked with Ernest Rutherford (MacLeod, 2000; Van der Kloot, 2005).

Bragg and Robinson traveled to a section of the front in the Vosges Mountains in the Alsace region of France where the French had set up their SR apparatus. The French sound rangers instructed the British officers over the next couple of weeks. However, the front during that time was very quiet and they didn't see much action. Bragg and Robinson left to establish the first SR section on the British front in Flanders, five miles southwest of Ypres, Belgium, which was being held by the Canadian Corps of the British Second Army. Bragg and his team struggled through 1915 and the first part of 1916, producing inconsistent results due mainly to the type of microphone they were using (discussed in ***Microphones***).

Despite the lack of progress, Lieutenant Colonel Jack agreed to start up additional SR sections. Bragg recruited new sound rangers by attending unit parades, where he would order "all Bachelors of Science step forward" (Van der Kloot, 2005). By June 1916, 16 SR sections had been recruited, trained, and deployed to areas along the front (one of these recruits was Lance Corporal William Tucker).

During this period, Bragg promoted the exchange of ideas: "At intervals of two months or so, we had a meeting at some central point such as Doullens to which each section sent an expert. They swopped stories, schemes, and boasts of their achievements and I am sure emulation made everything go much faster. The meeting generally ended with a binge of heroic magnitude" (Bragg et al., 1971, p. 38).

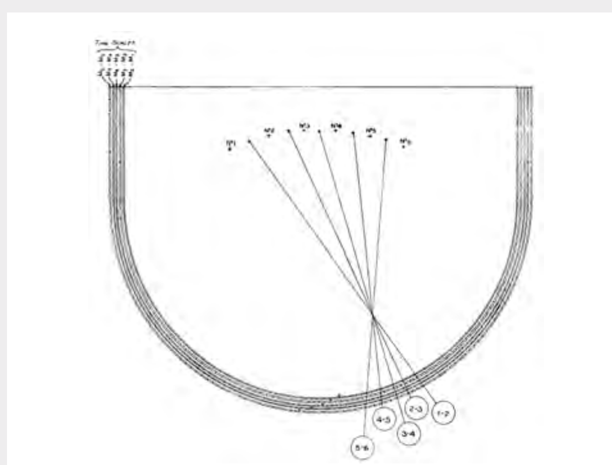
Method and Apparatus

Hyperbolas

As mentioned in **Beginnings of Sound Ranging**, acoustic location was based on determining the differences in the times of arrival of the sound from a cannon to different observation positions or microphones. The difference in time was used to determine the direction of travel of the sound by considering that the gun was located on the asymptote of a hyperbola while the pair of microphones that detected the sound was located at its foci. The time difference would be constant for any gun located along this asymptote. Thus, the time difference established the direction of arrival of the gun wave. Time differences from other pairs of microphones produced their own asymptotes or bearings. The intersection of these bearings determined the location of the gun.

Thus, the sound rangers devised graphical techniques to determine the gun locations. After being surveyed,

Figure 2. *Plotting board used with sound ranging.* ***Nos. 1-6****, microphone positions. The timescales between adjacent microphones are within the border that runs from the top left, underneath, and to the right of the array (although difficult to read at this scale). From Mitchell, 2012. See text for detailed explanation.*



the positions of six or seven microphones were plotted on a plotting board (**Figure 2**; Mitchell, 2012). A catgut string was pinned at the midpoint between adjacent microphones; the strings stretched from this point to their corresponding time difference on the timescale. In **Figure 2**, the string is represented by the lines running from the midpoints between the microphone positions to the circles with numbers (the circles are not part of the plotting board but are only included to identify the microphones corresponding to that bearing). For example, the bearing determined from the No. 1 and No. 2 microphones is represented by the line that runs from the corresponding midpoint to the circle containing "1-2." The intersection of the strings indicated the gun location. In practice, a reliable location required three or more asymptotes.

When surveying the microphone positions, the SR team would try to maintain equal spacing between the microphones, which were separated by approximately 1,500 meters, so that the entire array had a length of roughly 7,500 meters. As the war progressed, the SR teams learned that they could distinguish individual guns when fired simultaneously by placing the microphones on the arc of a circle facing the enemy line, as depicted in **Figure 2**. The radius of the arc was the estimated distance of the enemy batteries. Bragg initially thought this was "fussy" because of the extra complexity in laying out the line, but he later recognized the benefits. A captured German order forbade any battery to fire alone, thinking that multiple batteries firing at the same time would confuse the Allied SR systems. But Bragg claimed that they could locate "almost any number of guns firing at once, the more the merrier" (Bragg et al., 1971), obviously a hyperbole.

Microphones

Initially, both the French and the British used carbon microphones for SR. These were invented independently in England and in the United States around 1877. A recent article by Thompson (2019) in *Acoustics Today* contains an excellent description of these devices.

Three different sounds were produced by the firing artillery and recorded by the SR apparatus. The first sound was the muzzle wave, referred to as *onde de bouche* by the French, which was produced by the explosive charge propelling the projectile from the cannon. This sound was of primary interest to the sound rangers because it radiated from the cannon. The second sound, although detected first because the projectile was supersonic, was the ballistic shock wave or shell wave recorded by the microphones as the supersonic projectile traveled over them on its way to its target. This was referred to by the French as *onde de choc* and is basically a minisonic boom radiating from the projectile. The third sound recorded by the microphones was the explosion of the shell as it impacted its target. The carbon microphones were sensitive to the shell wave, which was higher in frequency than the muzzle wave. This issue frustrated the BEF sound rangers in their early efforts because it complicated the interpretation of the signals because the shell wave was dependent on the caliber of the gun and varied with the range and direction of fire.

During this time, Bragg was billeted in a farmhouse at La Clytte in Flanders. The privy, located in an annex just off the kitchen, was sealed except for the hole beneath the seat: "one sat on the only aperture between interior and the outer air" (Bragg et al., 1971). When a British 6-inch gun, located a quarter mile away, fired, "anyone sitting on the privy was slightly, but perceptibly, lifted off the seat" (Bragg et al., 1971). This led Bragg and his colleagues to conclude that the gun sound produced a large amount of low-frequency energy that could be exploited for SR (Mitchell, 2012).

Corporal Tucker's experiences led to a solution. Tucker had joined Bragg's section on Kemmel Hill from the Physics Department at Imperial College, where he had been performing experiments in the cooling of very fine hot platinum wires, called Wollaston wires (see bit.ly/3d5u5Jf). The tarred-paper shack in which he was staying at the time, with Bragg and others, had holes or tears in it. When the guns fired, jets of cold air annoyed him as he lay on his bunk. Tucker had the idea of using these jets of air to cool Wollaston wires. The first successful experiment involved stretching a thin wire over the opening of an empty rum jar and blowing on it. Then they obtained "proper wire" from England and stretched it across a hole they had drilled in a discarded ammunition box. The new microphone worked; the shell wave "hardly made the galvanometer quiver" while the gun wave "gave an enormous kick" (Bragg et al., 1971; Mitchell, 2012).

The final form of the Tucker microphone consisted of a 23-liter (5-gallon) tinplate cylinder with conical ends, manufactured in England by the Cambridge Instrument Company. One end of the cylinder was closed. A short, open tube was inserted into the other end. The hot wire grid consisted of fine platinum wires stretched across a square opening (4.5-centimeter aperture) in a mica disk, which screwed into the end of the open tube (Tucker and Paris, 1921). The original devices worked poorly due to resonances, but the problem was mitigated by drilling four small holes in the side of the cylinder. Tucker microphones were provided to all British SR sections, whereas the French continued using systems with microphones.

The Tucker microphone is essentially a Helmholtz resonator; the low-frequency, long-wavelength muzzle wave caused the pressure of the volume of air in the cylinder to change uniformly as the acoustic wave passed over the microphone. This vibration caused the air in the tube or neck to move into and out of the container, cooling the platinum wires. Air moving in either direction cooled the wire, which had the effect of "rectifying" the signal by producing a current that was always positive (Bragg et al., 1971). Its resonance frequency was probably between 30 and 50 Hz, based on the cited dimensions. The four drilled holes would have dampened and broadened the resonance. Bragg reports that the characteristic frequencies of the guns were between 10 and 25 Hz, with larger guns at the lower frequencies. Tucker's microphone was less sensitive to the higher frequency, smaller wavelength shell waves.

Harp Galvanometer

SR required that the signals produced by the microphones be recorded so that the time differences could be determined. These signals were recorded with different styles of galvanometers. In one arrangement, referred to as the *télégraphe militaire* (TM), electric signals from carbon microphones "would actuate marking pens on smoked paper" (MacLeod, 2000), probably in a way that is similar to a strip-chart recorder.

Lucien Bull designed and developed a recording device based on the string or Einthoven galvanometer, which had been invented in 1901 by Willem Einthoven. Bull's version contained six wires, each connected to a different microphone. This was referred to as the "harp" galvanometer. The wires were arranged in a plane parallel to one another and a half centimeter or so away from a plane containing 35-mm movie film. A light source projected images of the wires onto the film, which advanced at a constant speed. A magnetic field was applied in the direction perpendicular to the plane of the wires. Electrical current from a microphone, in the presence of the magnetic field, caused the corresponding wire to deflect, which was recorded on the film.

The motor of the harp galvanometer contained a wheel with spokes that would interrupt the illumination of the film at fixed intervals. This placed lines on the film at evenly spaced intervals, which permitted the time differences to be accurately and more easily read. The type of record, reproduced from film, showing signals produced by German guns and detected with Tucker microphones,

Figure 3. *A record reproduced from film of a German gun firing. S, shell wave arrivals; G, muzzle (gun) wave arrivals. From Trowbridge, 1920. See text for details.*

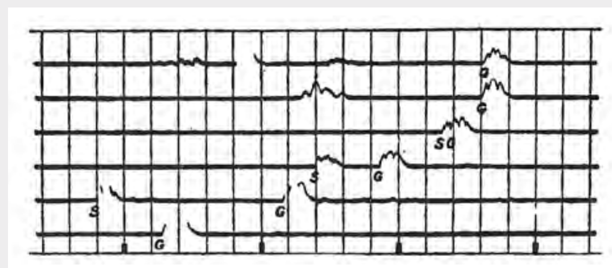
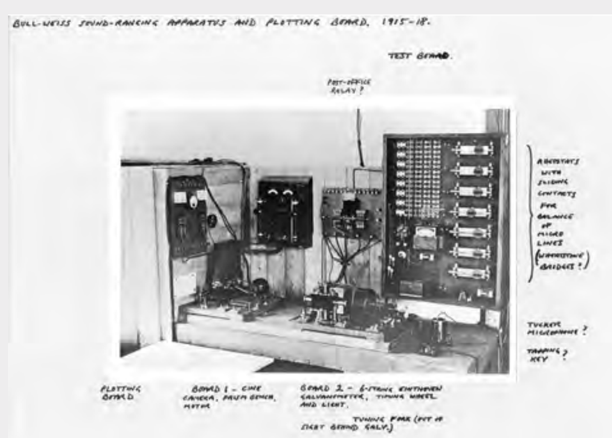


Figure 4. *An SR apparatus such as that used in WWI. Annotations in the border indicate that the plotting board was located at the* ***bottom left****. Just above this was the camera with the galvanometer to its right at the* ***bottom center****. The rheostats (****right****) were used to balance the circuits containing the Tucker microphones. Available at militarysurvey.org.uk. See text for detailed explanation.*



is shown in **Figure 3**. In addition to time differences, the analyst could determine the caliber of the gun by noting the duration of the signal, which was an indication of its frequency; lower frequency signals produced by larger guns had a longer duration. The system designed by Bull, which had a faster response time than the stylus system used in the TM, was able to determine time differences to within 0.01 second (Bragg et al., 1971).

Bull made the first 50 galvanometers, whereas later versions were manufactured by the Cambridge Instrument Company. A complete SR apparatus with galvanometer, camera, and plotting board is shown in **Figure 4**. Each Tucker microphone was connected to a wire of the harp galvanometer through a circuit containing a Wheatstone bridge that contained rheostats used to modify resistances to balance the bridge; this particular system would have accommodated seven Tucker microphones.

The United States Enters the War

The United States officially entered the war on April 6, 1917. General John J. Pershing became the Commander in Chief of the American Expeditionary Force (AEF) in May 1917. He arrived in France in June, where he was introduced to the flash- and sound-ranging efforts of Britain and France. The newly formed US National Research Council recommended Augustus "Gus" Trowbridge, professor of physics at Princeton University, to organize the flash- and sound-ranging services. Trowbridge became a Major in the Signal Corps Reserve before being transferred to the Corps of Engineers in October 1917, where he served under Colonel R. G. Alexander, chief of the Topographical Section (Kelves, 1969).

Trowbridge met with the French in July where he was introduced to their SR systems. In the meantime, Colonel Alexander had been investigating the British and French systems with the help of Lieutenant Charles B. Bazzoni, an American physicist who had volunteered while on a research fellowship in London. Bazzoni preferred the British system, referred to as the Bull-Tucker; although not as sensitive as some of the French devices, it was less delicate and not as difficult to use under demanding battle conditions. The AEF adopted the Bull-Tucker, and the British supplied the first systems (Kelves, 1969).

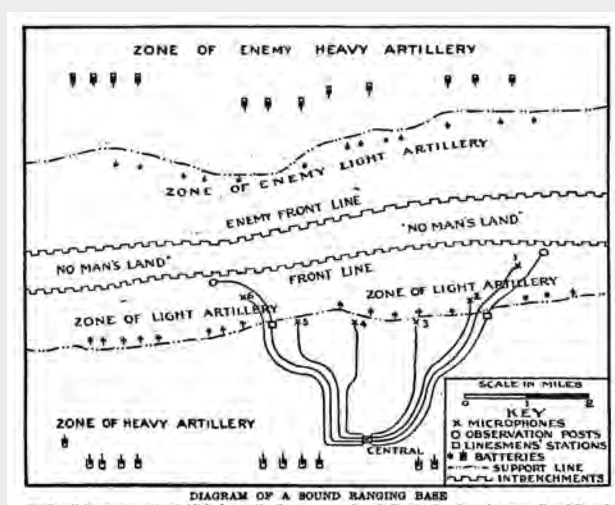
Theodore Lyman, a distinguished Harvard physicist, joined the team as a captain in the Signal Corps Reserve. He and Trowbridge sailed to Europe in September, eager to start training and deploying flash- and sound-ranging sections knowing that the German Army would be concentrating its forces on the Western Front with the surrender of Russia in the east. They recruited officers from the Ambulance Service and troops from the Army Engineers who had already arrived in France. Lyman and Bazzoni set up a school for flash and SR at Ft. de St. Menge, near Langres, (see bit.ly/3d0vJvE) early in January 1918 where they trained and fielded four flash and four SR sections by the end of the war.

Sound Ranging in Practice

A schematic of a typical SR base is shown in **Figure 5**. Numbers 1-6 represent the positions of the microphones, each of which was connected with a low-resistance wire to the apparatus shown in **Figure 4** at the Central position. The distance between microphones 1 and 6 in the figure is approximately 7 kilometers (4.3 miles), requiring the use of approximately 64 kilometers (40 miles) of low-resistance wire. Although the vacuum tube amplifier had been invented in 1911, it was not used in SR until after WWI, thus requiring the use of thicker gauge, i.e., low-resistance, wire.

Observation posts were located on the right and left sides of the base near the front line. The observer would

Figure 5. *Schematic of a typical SR station.* ***x1-x6****, Positions of the microphones, each of which was connected with a low-resistance wire to the apparatus shown in* ***Figure 4*** *at the Central position.* ***Open circles****, observation posts located at the right and left sides of the base near the front line. From Hinman, 1919. See text for detailed explanation.*



push a key or button when he heard or saw guns fire. This signal would initiate the film to start recording at Central, which would run for 20-30 seconds. The film record contained the muzzle blast, at times the shell wave, and the explosion from the bomb's impact. The film was developed, the time differences plotted on the plotting board, and the results delivered to the artillery section, all within 10 minutes. If the strings on the plotting board intersected at a single point, the location was deemed accurate and less accurate if they intersected in more than one point. The SR sections were able to determine the location of the gun, the location of impact, and the time of the round in air. This information aided in determining the caliber of the gun. They would send scouts to scavenge shell fragments to confirm the caliber and type (not an enviable assignment!). According to Bragg, "a typical report gave the caliber, number of guns, and target on which the battery had registered" (Trowbridge, 1920; Bragg et al., 1971). The reports were provided to the artillery who used the information to target the enemy batteries.

In the BEF, a "sound-ranging section had 3 officers and 18 others: 1 sergeant, 1 instrument repairer, 1 photographer, 3 linemen, 2 telephonists (telephone switchboard operators), 3 forward observers, 3 batmen and 4 motor transport drivers" (Van der Kloot, 2005). Although efforts were made to conceal their posts, the observers were often in vulnerable positions, being located close to the front line. In addition to pressing the key to start the film at the time at which a gun was fired, they would estimate the location and caliber of the enemy batteries. If possible, they would also provide other intelligence, such as the location of machine guns and troop movements. Linemen were the most vulnerable. They laid out the wire from Central to the observation posts and the six microphones. When wires were damaged, they would have to repair and splice or, if beyond repair, replace them, often under adverse conditions. Surveyors established the locations of the microphones so that their positions could be accurately placed on the plotting board. The soldiers at Central performed several functions: they developed film, measured time differences and plotted them on plotting boards, maintained and repaired instrumentation, and reported the results to the artillery. Central was also vulnerable, often setting up in wrecked houses located within the range of enemy artillery.

A report on SR issued by the General Staff in March 1917 claimed that the error from a single good observation was usually within 50 yards, dropping to less than 25 yards when several observations were averaged. The report also claimed that a single SR section obtained 260 locations of German batteries in the two-month period of December through January.

Another report from 1918, prepared by an artillery information officer of the AEF, compared the locations of artillery batteries provided by flash and SR. In the first case, flash ranging outperformed SR during a period of mobility where the allied forces were advancing and the enemy forces were retreating. Out of 425 locations, flash sections reported 79% while sound sections reported 21%. However, during a period when the front was stationary, SR outperformed flash ranging; out of 392 locations, flash reported 46% while sound reported 54%. The flash sections outreported the sound sections during periods of mobility because the flash sections required less equipment, enabling them to pick up and set up more quickly in mobile conditions, while the sound sections performed much better during periods of stationary warfare. The SR locations were also more accurate.

Weather affected SR in several ways. The first is temperature because sound travels faster in warm air than in cooler air. The time differences are inversely proportional to the speed of sound: an increase in sound speed makes the gun appear closer.

Wind was also a big factor. When the wind blew toward the enemy lines, the microphones were sometimes unable to detect the muzzle wave. The wind speed is lower near the ground than at higher altitudes, with the result that the effective speed of sound decreases with altitude. This causes the sound to refract upward. Bragg complained, "due to the 'principle of maximum cussedness' the wind in Flanders and Artois was generally westerly" (quoted in Van der Kloot, 2005). When the wind direction was from the enemy guns, the effective speed of sound increased with altitude, causing sound propagating in this direction to refract toward the ground, sometimes distorting the signals due to ground reflections but providing measurable signals. SR worked best for the Allies when the winds were light and the temperature uniform and in foggy weather, not an uncommon condition in Flanders (Bragg et al., 1971).

To determine the wind and temperature corrections, the BEF set up "wind sections" behind the front lines. A "pound or so of explosive was set off at intervals of a few hours and the sound was recorded by a series of microphones" whose positions were accurately known, thus determining the effects of temperature and wind.

Wind also produced turbulence as it flowed over the microphone. This cooled the wire and was a source of noise, referred to as wind noise. The early sound rangers experimented with several methods to mitigate this. Wrapping the microphone in camouflage netting helped, as did putting a thick hedge around the microphone (Mitchell, 2012).

A secondary use of SR was to register or correct the fire of friendly artillery since the microphones were able to detect the bursts of shells fired on enemy targets. The SR record of friendly fire was compared with the SR record of the enemy gun. The SR section would be able report to the artillery that the shell had fallen so many meters short or to the side of the target. Corrections would be made until a direct hit was achieved. This practice was independent of wind and weather because the record from the gun and the shell bursts were made under the same conditions.

The Battle of Arras near Vimy Ridge in April 1917 provided a specific example of the effectiveness of flash ranging and SR. Before the attack, three SR sections coordinated their results to locate a giant German gun 11 miles behind the front lines (Van der Kloot, 2005). Other locations provided by flash ranging and SR enabled Canadian artillery to take out 83 German batteries. Having dealt with the enemy artillery, Canadian troops attacked under a creeping barrage, shells fired by the artillery approximately 200 yards in front of the advancing infantry, designed to keep German machine gunners in their trenches. Other tactical adjustments that had been learned over three years of warfare had been made. The Canadians took and secured the ridge at the cost of 10,000 men. This compares with the 200,000 troops the French had lost in three previous attempts between 1914 and 1916. The Germans lost similar numbers defending it (Finan and Hurley, 1997; Meyer, 2006).

Concluding Remarks

The armistice went into effect on November 11, 1918, at 11:00 a.m. A sound recording was produced from a film strip recorded from 10:59 to 11:01 a.m. on the American Front near the River Moselle at the end of the war (see bit.ly/38p2ekk).

The cannons fired right up to the time of the armistice, and it was so quiet immediately after that one could hear birds singing. The Imperial War Museum website has other information of interest (see bit.ly/2OGoyOV).

SR was not the only application of acoustics to warfare in WWI. Namorato (2000) describes the efforts at using acoustics to detect and track aircraft and to detect tunneling. There were also advances in underwater acoustics that was used to detect and track German submarines. A previous article by Muir and Bradley (2016) in *Acoustics Today* also describes the efforts in underwater acoustics. Incidentally, William Henry Bragg, William Lawrence Bragg's father, contributed to this effort (Van der Kloot, 2005).

Acknowledgments

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