NOTES & RECORDS OF THE ROYAL SOCIETY

Notes Rec. R. Soc. (2005) **59**, 273–284
doi:10.1098/rsnr.2005.0095
Published online 6 September 2005

LAWRENCE BRAGG'S ROLE IN THE DEVELOPMENT OF SOUND-RANGING IN WORLD WAR I

by

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In 1915, when Lawrence Bragg was a 25-year-old Second Lieutenant in the Royal Horse Artillery, seconded to 'Maps GHQ', he learned that he and his father had shared the Nobel Prize in physics. Lawrence's equation was crucial for winning the prize and he had been wounded by his father's early dissemination of their work with casual attribution to 'my son'. Lawrence was responsible for developing methods for pinpointing the position of enemy artillery pieces by recording the boom of their firing with an array of microphones. It was a simple idea but difficult to implement. Step by step, Bragg and the group he assembled solved the problems and developed a system that worked. Sound-ranging was valuable in the British victory at Cambrai in 1917 and vital for that at Amiens in 1918: the 'black day of the German Army'. He received the MC and the OBE. His Army service manifested both his scientific leadership and administrative skills, which culminated in the demonstrations of the validity of the dream he enunciated in his Nobel lecture: that X-rays could be used to resolve the structure of the most complicated molecules.

Keywords: William Lawrence Bragg; X-ray diffraction; World War I; sound-ranging

Entering the army

William Lawrence Bragg (later FRS) enlisted in a Territorial Force formation, King Edward's Horse, in 1909, shortly after he came up to Trinity College Cambridge to read mathematics.[1] They were mounted infantry, which had been found useful during the Boer War, so they learned musketry and horses. The Horse had been established specifically for training men from the Colonies. Bragg thought that it would be a agreeable way to become acquainted with men like himself: strangers slightly out of place in the ancient university—it was a long way from Adelaide, Australia, where he had grown up. Within weeks he had many friends in the University and felt quite at home; still he found the Horse sufficiently agreeable

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to recommend it to his younger brother Robert Charles—Bob—who came up in 1912. Bob also enlisted. Every year during the long vacation they went off for manoeuvres. Bragg completed his service in the Horse and was discharged in November 1913.

Bragg had taken a First in Part II Physics in 1911. He then started at the Cavendish Laboratory, measuring the velocity of ions in various gases. Despite its renown the facilities were scant, and because of its renown it was jammed with students. It was hard to get things done. Each student had to fabricate needed apparatus. Often glass had to be blown. There was a single foot pump for 40 students, so it was difficult to get to use it. Bragg recalled, 'I was able to sneak it once from the room of a young lady researcher when she was temporarily absent, and passing her room somewhat later I saw her bowed over a desk in floods of tears. I did not give the foot pump back.'

When war broke out in August 1914 Bragg was grateful for his military training. While his friends were frantically trying to join up, Bragg was commissioned as a Second Lieutenant in the Leicestershire Royal Horse Artillery on 26 August. In the French field artillery there was a tradition of serious interest in guns, but in the British and German services the focus was on hauling them into action at a gallop, and then firing over open sights. Tables of logarithms were seldom consulted. It was not Bragg's element. '…my knowledge of horses was not at all extensive and my fellow officers and men were Leicestershire hunting enthusiasts'. The training was monotonous and repetitive, and so was the officer's mess, with seemingly endless discussions of stifles; the months dragged by while they languished far from the front.

Escaping from horses

Out of the blue in July 1915 Bragg was ordered to report to Colonel Coote Hedley, a Royal Engineer (RE) and head of the Geographical Section of the General Staff in London.[2] Hedley told him that on a visit to France he had learned that the French were working on a method to pinpoint the position of German artillery pieces by the sound they produced.[3] Distrusting memoranda, Hedley went directly to General Headquarters (GHQ) in Flanders to buttonhole those in charge about the possibilities. There was 'much apathy and some opposition', but he won. GHQ set up a committee of three, experts on artillery, electricity and topography, to evaluate what the French were doing. The French were exploring three methods: first, having observers at widely spaced points, to measure the interval between a gun flash and hearing the sound with a stop watch; second, to place microphones along the front and record their output on moving smoked paper; and third, to record the output from the array of microphones with a string galvanometer, which the French called the 'Bull–Weiss system'. The committee thought the Bull–Weiss method the most promising. GHQ was not convinced. The committee was sent back to see the methods in action. Again they recommended the Bull–Weiss method. Their recommendation was forwarded to the Experiments Committee at GHQ, who rejected it because it had not been shown to work. The head of the topographical sub-section at GHQ, Lieutenant Colonel Ewan Maclean Jack RE, would not let the matter rest. 'After some discussion' the committee's report was rescinded and a string galvanometer was ordered from Bull. It would be delivered in October 1915.

Now they needed an officer who knew something about sound and electricity to put the method into operation. Would Bragg be interested? Indeed he was. Bragg left the interview overjoyed with his liberation; it made him 'walk on air'.[3] He was seconded for special duty on 19 July, to the topographical sub-section—which was known even on official documents as 'Maps GHQ'.[4]

I do not know how Bragg was chosen for the job, though there is no doubt about his credentials and they could not have found a better man. That year he and his father, William Henry Bragg, who was then Professor of Physics at Leeds, had published their book *X-rays and crystal structure*.[5] In May 1915 father and son were jointly awarded the Barnard Medal of Columbia University, given at five-year intervals, which was reported prominently in *The Times* as an 'American Medal for British savants'.[6]

He went over to Paris for a briefing by the French on what they were doing. A leading spirit was Charles Nordmann, a Professor of Astronomy from Paris, who had the idea while serving at the front in 1914 and had obtained permission to give it a try. He teamed up with Lucien Bull, an Irishman at the Institute Marey, who had been making 'string' galvanometers to record the electrocardiograph. The string in the galvanometer was a fine wire that ran through the gap in a powerful magnet. When an electrical current flowed through the wire it moved in the magnetic field. The wire's shadow was recorded on a moving strip of photographic film. For the sound-ranging enterprise Bull increased the number of strings; now they were inserting six. From Paris, Bragg travelled up to GHQ to report to Colonel Jack.

In the first months of the war Maps GHQ was a tiny operation. The Army expected a short war; they had excellent Belgian maps on hand. They had only two surveyors with theodolites to take bearings on smoke bombs that British aircraft would drop over German batteries. When the Army settled into trench warfare, Maps GHQ expanded to provide the detailed maps that were needed for France. Since then they had started to use flash-spotting to pinpoint German guns. Now they would add sound-ranging. Jack authorized Bragg to go to England to sign on another officer to help out. Bragg decided on a newly commissioned Second Lieutenant: Harold Roper Robinson (later FRS), of the Royal Garrison Artillery.[7] He had worked been working at Manchester University on β-rays emitted from metals struck by X-rays.

Early in September they travelled together to the front in the Vosges Mountains, where the French were working with their apparatus. It was a peculiar introduction to battle. During their first two weeks not a single gun on either side was fired. Things were so quiet that the French used their gun emplacements to lay out their washing. Finally German guns fired. The sound-ranging sometimes gave a position for the gun, but usually they did not have any other evidence that it was where deduced. In October Bragg and Robinson picked up the heavy galvanometer in Paris and hauled it by lorry up to the Fifth Army area in Flanders, where they were to start operations. Carbon–graphite microphones and wire came from Britain. The unit had been expanded by the addition of a lorry with driver and mate to carry the massive galvanometer, one lineman and one NCO, and two drivers of Singer cars for the use of the two officers. Bragg had escaped from the horses.

News from home

Then Bragg had bitter news. His brother Bob died of wounds on 2 September at Suvla Bay on Gallipoli, serving as a Second Lieutenant in the Royal Artillery in the 11th Division. Their sister, Gwendolen, eight years old at the time, described how the news reached her at the family home near Leeds: 'But one morning as I was standing by the shallow stone sink in the kitchen, looking out into the garden, my father unexpectedly passed the window, came in, said to me quickly in a low voice "Bob's gone" and then went upstairs to my mother. I heard her cry out.'[8] Soon thereafter Bragg heard that his closest friend from Trinity College been severely wounded; he died two years later.

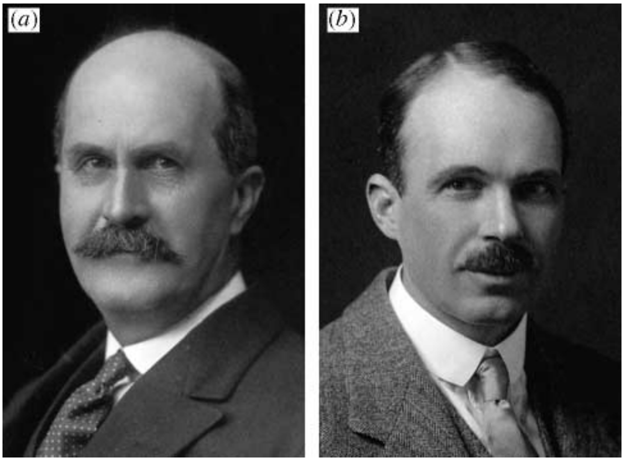

Figure 1. The Nobel laureates in Physics 1915. (*a*) William Henry Bragg. (*b*) William Lawrence Bragg.

Better news came in a later letter from father. On 12 November 1915 they had been jointly awarded the Nobel Prize in physics. Bragg was the youngest laureate ever and they were the only father–son team ever to share a prize (figure 1). When he received this news he was billeted in the home of a Curé, who proffered a bottle of *Lachryma Christi* in celebration.

The basis for the award was the 'reflection' idea that had come to Bragg one day in 1912 when he was walking in the backs along the river Cam. His insight led to the Bragg equation, the elucidation of the nature of X-rays, and the use of X-rays in determining chemical structures. Bragg and his father remembered it as '…a glorious time when we worked far into every night with new worlds unfolding before us in the silent laboratory'. In his Nobel lecture, which he finally delivered in 1922, Bragg suggested, 'there seems to be hardly any type of matter in the condition of a true solid which we cannot attempt to analyse by means of x-rays'.[9]

The prize also helped to ease Bragg's feelings towards his father, which had been shaken during their collaboration, as we know from his own testimony in later life. Father had reported some of their joint work in two letters to *Nature* that gave credit to 'my son' for the equation but did not even give his name.[10] In 1913 father had been invited to the Second Solvay Conference, along with Einstein, Laue, Rutherford and other luminaries of international physics. In his presentation father described his son's results, giving him the credit. Einstein and other distinguished attendees sent Lawrence a postcard of congratulations.[11] Lawrence felt that his father had been unjust in not permitting him to describe his idea first. Father had acted unthinkingly, not maliciously, and subsequently went out of his way to make amends.[12] Still the incident was '…remembered 60 years later with pain'. Surely this contributed to Bragg's lifelong vigilance to see that credit was always given where due—a key element in his successes as a scientific administrator.

A usable microphone

Sound-ranging was not working well. They located their first enemy gun in November 1915, but successes were rare. The firing of cannon produces very-low-frequency sound waves: a field gun booms at 25 Hz, and larger artillery pieces produce sound at 10 Hz. The diaphragms on their microphones scarcely moved in response to such low tones, and hence the signal recorded by the string galvanometer was almost undetectable on the photographic film. It was especially frustrating because there was abundant energy in the sound waves from the guns. In Bragg's billet in Flanders the latrine was in a small window-less chamber off the kitchen; when the door was closed the only opening to the outside was beneath the seat. Every time that a British 6-inch gun fired from its emplacement about a quarter of a mile away, Bragg's bottom was elevated perceptibly off the seat, even though often he heard nothing at all. They needed a detection system sensitive to low frequencies. Another problem was that high-velocity guns make two sounds, a loud 'shell-crack' generated when the projectile breaks the sound barrier—loud, but useless for accurate gun location—followed by the dull, barely audible boom, the 'gun-wave'. The microphone diaphragm was still vibrating in response to the crack when the boom came, so the boom could not be distinguished on the film. They called this 'washout'. In contrast, the microphones were all too sensitive to rifle shots, buzzing insects, nearby bad language and the like. They did not solve this problem for months.

Nonetheless, Colonel Jack, with his 'unfailing kindness and gaiety', thought the results 'just satisfied requirements', so he started up additional sections. Bragg was authorized to attend unit parades, where he would order: 'all Bachelors of Science step forward'. He would pick the most likely, who usually were willing to volunteer and more than satisfied after they joined up. Like any research group, Bragg's outfit had periodic meetings to thrash out successes, failures, bits of gossip, and so on, followed by what Bragg described as a 'binge of heroic magnitude'.

Each sound-ranging section had 3 officers and 18 others: 1 Sergeant, 1 instrument repairer, 1 photographer, 3 linemen, 2 telephonists, 3 forward observers, 3 batmen and 4 motor transport drivers. The first was designated 'W'—presumably for 'Willy', as Bragg was generally known in the Army as he had been in the family. Bragg was promoted to Lieutenant, 'to remain seconded', on 20 June 1916, and appointed 'Acting Captain whilst holding a special appointment' on 3 September 1916.[13] At first the new men were trained by Bragg at his section. As the expansion continued he set up a school at Merlimont-Plage, 25 miles south of Boulogne. The sound-ranging sections were incorporated into Field Survey Companies, which also included flash-spotters and topographers. Each Army had a Field Survey Company, but remarkably they were all commanded by Maps GHQ. By the end of the war the Field Service Battalion had 5000 men. There were Companies in France, Italy, Salonica and Palestine.

The sound-rangers worked closely with flash-spotters, who used a flash board devised by Lieutenant Henry Harold Hemming.[14] It eliminated observer suggestibility. When they started to locate a gun each post heard a buzzer when the lead observer had seen a flash. If they had also seen a flash they buzzed also. When all posts were buzzing together, the buzzers to the posts were cut off. If the controller still received simultaneous signals from all observers he knew that they were on the same target. Bragg helped with the electrical implementation of the flash board and he and Hemming—a Canadian—became friends and collaborators, which was especially useful when the Germans took to setting off false flashes that made no sound.

The microphone problem was solved by Corporal W. S. Tucker, who had studied physics at Imperial College, London. During the winter he slept in a tar-paper shack. There was a hole near where his head lay on his pillow. Now and again he was annoyed by a chill puff of air against his cheek—a pressure wave from a cannon. It reminded Tucker of an apparatus used to measure wind velocity. He passed the idea on to Bragg, who always gave Tucker full credit. Air currents were measured by taking advantage of the fact that cooling a wire raises its electrical resistance. To measure wind velocity a length of wire was heated by running an electrical current through it. The wire was one limb of a Wheatstone bridge. The voltage drop through the wire was balanced by adjusting a variable resistor in the opposite arm of the bridge so that no current flows through the galvanometer. If airflow cools the wire, the bridge is unbalanced and current flows through the galvanometer.

They tried it with a thin strand of wire stretched over the opening of an empty rum jar. It worked nicely when blown on. To do it properly they needed thin platinum wire. When proper wire came from England they picked up an empty wooden ammunition box, which were lying about everywhere. They ran the platinum wire the length of the box and drilled a hole in the cover for the pressure waves to enter. ‘I will never forget the thrill of seeing the first record, in which the shell-wave hardly made the galvanometer string quiver, while the gun-wave gave an enormous kick’. Most other battlefield noises had no effect because they were higher frequency.

Still there were problems. Gusts of wind cooled the wire and distorted the recordings. They tried covering the hole in the box with wrappings. Most either blocked the air movement or did not stop the wind. Persisting, they found that wrapping the box in several layers of standard issue camouflage netting did the trick. Later in the war the Germans experimented with a similar detection system but they never solved the wind problem. Then there was an unexpected but more readily soluble problem. Small insects liked the warmth, but when they settled on the thin wire it would break. The answer was to put copper screening over the aperture to the box. To their amusement the screens officially became ‘protector, Earwig, Mark I’ on the army stores list.

Sound-ranging in practice

They remained at the mercy of nature; no sound-ranging system would work well when the wind was blowing toward the German lines. As Bragg wrote, ‘due to the “principle of maximum cussedness” the wind in Flanders and Artois was usually westerly’. Sound is thrown upward by a head wind, so it passes above the microphones. When the wind blows toward the observer, sound is deflected downwards and arrives with a ‘sharp crest’. Misty weather was ideal: little wind and uniform temperature. Sound curves over hills and buildings, so they do not interfere.

They shifted the making of Tucker microphones to England. The manufacturers did a professional job, stringing the wires through neat metal boxes. The elegant apparatus worked poorly. Just as the performance of a high-fidelity speaker depends on its enclosure, by chance the ammunition box had just the characteristics needed. So there were no more metal containers. The first 20 string galvanometers were from Bull; after that they were made by the Cambridge Instrument Company.

The typical setup for a sound-ranging unit was to have six microphone stations and two observation posts in front of them. The observers would push a key when they saw a gun flash or heard a boom; their signal would turn on the film transport in the galvanometer. Each setup required about 40 miles of low resistance, well-insulated wire—of higher quality than telephone wire. The wires were run on stakes above ground, so they were exposed to destruction by enemy fire and to pilfering—Australians were considered a special menace.

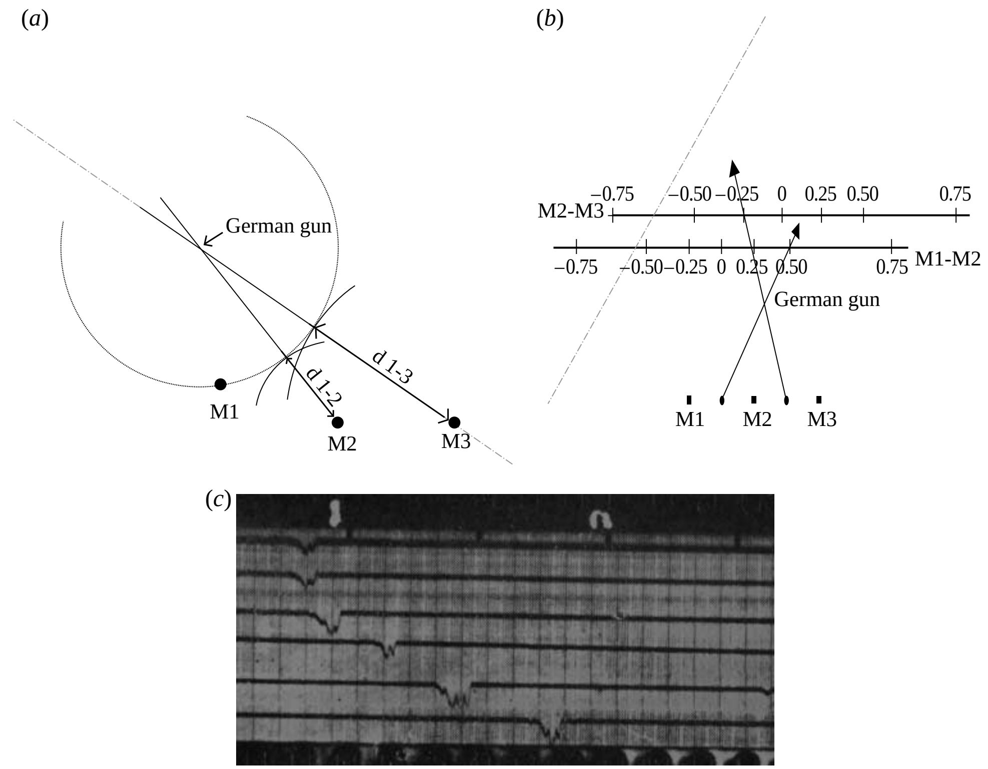

Figure 2. Sound-ranging. (*a*) The basis of the method. The sound first reaches microphone 1 (M1). From the difference in time required for the sound to reach M2 and M3 the distances are calculated that the wave travelled during these intervals. Arcs with these distances as the radii are drawn on the map. The position of the gun is calculated by determining the centre of the circle that runs through M1 and touches the arcs drawn from M2 and M3. (*b*) A simplified view of Bragg's method for ready computation of the gun's position. The arrows represent strings that the operator positions on the scales at the top according the time differences between the arrivals of the sound at each pair of microphones. The gun is where the strings cross. (*c*) A section of a string galvanometer recording of the signals from six Tucker microphones when a German gun fired. Time differences as short as 5 ms were determined from the records.[24]

The microphones were usually about 4000 yards behind the front line, along a 'base' of about 9000 yards. Eventually the microphones were spaced 'at absolutely equal intervals on the arc of a great circle facing the enemy line'. At first Bragg rejected this 'fussy and artificial ideal', which was a challenge to the surveyors, proposed by Lloyd-Owen and Gray. However, the advantage is that with this configuration the pattern on the film from the firing of a gun has a regularity that is readily recognized, so that a trained interpreter could pick out the deflections from a single gun when several were firing (figure 2*a*).

Figure 2*b* illustrates how the position of a gun could be determined. The method is cumbersome, so in practice the method shown in figure 2*c* was used. It merely required the interpreter to position cat-gut strings fixed on a local map at the midpoints between the microphones onto a scale on the upper part of the map. The gun is where the strings cross. The accuracy was usually within 100 yards. Then the camouflaged gun position often could be pinpointed from aerial photographs. With time the analysis became more sophisticated. The records also showed the shell-crack from a high-velocity gun and where the shell exploded. From this information the calibre of the gun could be estimated. This could be verified by sending someone out to the shell hole to pick up the fuse from the exploded shell. Bragg pointed out that 'for determining the calibre of a gun "local information" on this point is also useful, if one remembers to divide by two the estimate of the calibre formed by those on the spot from the explosion'.

Sound was also used for ranging the British counter-battery fire. According to Jack, 'An ingenious mechanical plotter was devised by Bragg whereby the necessary corrections could be supplied to our gunners in a very short time, in terms of yards short or over, minutes right or left'.

Their calculations required a value for the velocity of sound, which varies with air temperature and wind direction. At first they used tables to correct for atmospheric conditions. Later they fired charges at a position behind the British lines that was surrounded by a ring of microphones. From these measurements they could calculate the sound velocity at the time and also corrections for prevailing winds.

They knew that they were succeeding when a German order was captured: 'In consequence of the excellent Sound-ranging of the English, I forbid any battery to fire when the whole sector is quiet, especially in east wind. Should there be occasion to fire, the adjoining battery must always be called on, either directly or through the Group, to fire a few rounds'. The joke was that the British knew that firing the additional guns would not bother their recordings in the slightest. When they captured German positions they found that they had failed to find less than 5% of the battery positions.

The Germans also worked with sound-ranging, but the best apparatus they developed relied on skilled listeners, who would try to get the bearings by auditory location from amplified signals. They could locate howitzers, but not high-velocity guns. They captured some of the British apparatus in an attack on 30 November 1917,[15] but as mentioned above there were still problems they could not solve. One of the physicists working on the German side was Max Born (later FRS), who was awarded a Nobel Prize in 1954. He wrote little about sound-ranging and seems to have given as much time as he could collaborating with colleagues in his unit on calculations of the internal energy of ionic crystals.[16]

On one of his home leaves Bragg found that his father was working on underwater microphones to listen for submarines. Bragg pointed out that they might also be used for locating underwater explosions; the sound waves travelled much further under water. His idea was taken up and used in the seas around naval bases. Father's major contribution to the war effort was initiating an echo system for locating submarines (ASDIC).

For accurate firing, guns must be calibrated: the muzzle velocity must be known. Some of this was done at the front. Bragg measured muzzle velocity at a test firing range near the channel, where a test shot could be fired off to sea. The shell ripped through two webs of wire a known distance apart, generating an electrical signal that would be recorded on the galvanometer film, from which the velocity could be measured. Often the muzzle velocity was then painted on the gun barrel.

Sound-ranging in British attacks

At Passchendaele in 1917, the artillery commanders overseeing the offensive insisted on pushing the flash observation posts up close to the line. Hence it was impossible for them to keep their phone lines working through the heavy German fire, and they were almost useless. The sound-rangers did much better. They located 190 enemy guns in the first 20 days of the

British offensive. The British artillery fire smashed and cratered the Flemish countryside into a morass in which men drowned on their way up to face the German machine guns in their concrete pillboxes.

The achievements of field survey and the maturing of the British Army were brilliantly displayed on 20 November 1917 along the Hindenburg line west of the German-occupied city of Cambrai. The operation was proposed by the tank commanders Fuller and Elles as a raid.[17] Surprise was crucial, there would be no advanced gun registration and no preliminary bombardment; the tanks would crush the German barbed wire. Then GHQ transmuted the raid into a breakthrough. At dawn the British guns unleashed an intense bombardment, with a majority of the shells falling on the German gun line. The German guns had been accurately pinpointed by the flash-spotters and sound-rangers. The British fire was effective because they could accurately set calibrated guns from map coordinates alone, because they had precise surveys of the positions of their guns and one or more precisely surveyed stakes or 'bearing pickets' in front of each battery, from which they set the angle on which to lay the gun. Each battery had an 'artillery board', a map with a string coming from the position of the gun. When the string was extended to the target the angle between the bearing picket and the target could be read from a scale. The German artillery was suppressed.

Then a barrage crept across no-mans-land; it consisted of one-third high explosive, one-third shrapnel and one-third smoke. The noise, the smoke and the heavy morning mist concealed the 381 tanks treading across no-mans-land toward the defenders. The Germans counted on their trenches to stop any tanks; they were 12 feet wide, which a tank could not span, but the British bridged them with bundles of brushwood. Most of the German infantry did not wait to confront the attackers; they hurried back to the second and third trench lines. The major problems that the attackers faced were a few anti-tank guns and their intrepid crews, dug in near the German front, which did not ordinarily fire and consequently were not on the British artillery maps. On the first day the British advanced two to four miles, sustaining about 4000 casualties. They took as many prisoners. The church bells rang in London.

The breakthrough was to be exploited by five cavalry divisions that Field Marshal Haig had allocated for that purpose. They failed in part because, as the British Official History, quoting an American, put it: 'You can't make a cavalry charge until you have captured the enemy's last machine gun'.[18] The British artillery had to be moved forwards, and once there they were less effective because the new positions were not yet surveyed. The advance stalled. On 30 November the Germans launched a hurricane bombardment of the British positions, with many gas shells. Then came the counterattack, with storm troops in the van. They slipped through the weak points in the British line and fanned out into their rear.[19] The Germans recovered most of what they had lost and even took part of the old British line.

The most spectacular demonstration of the capability of sound-ranging was locating a giant German gun firing at the Canadian troops on Vimy Ridge from the shelter of a woods 11 miles behind the lines. This was more than twice the distance that a section could detect. Therefore they used three sound-ranging sections, and by coordinating their records they managed to pinpoint the target.

Bragg and Hemming were transferred to GHQ in April 1918 to coordinate the work of all of sound-ranging and flash-spotting units. Bragg was 'appointed Temporary Major whilst specially employed' on 14 June 1918. One of their first improvements came when they learned that German fliers observing the fall of shot would issue the order to fire by wireless. When this order was received at the sound station the film transport was immediately turned on. The short length of exposed film was developed within 15 seconds and they could locate the gun.[20]

The British attack on 8 August at Amiens came after a week of fog and mist that grounded air reconnaissance. The Germans spent the week shifting their artillery to new positions. The sound-rangers had followed their movements, so when the attack began it was Cambrai all over again, the German artillery was swamped by counter-battery fire, unable to stop the tanks that rolled forwards to tear through their wire. As Ludendorff said, it ‘was the black day of the German Army’.[21] But after the first surge forwards, the British did not repeat past mistakes. The infantry stopped at set lines, defended themselves against counterattacks, making only small, spoiling attacks, while the artillery moved up, was surveyed into their new positions and issued new maps. Then they were ready for the next surge forwards.[22]

Conclusion

When the war ended, Bragg was a Major with the OBE and the MC; he had been mentioned in dispatches three times. Hemming was also mentioned in dispatches three times, had the MC and was also a Major, as was Tucker. Hemming’s additional reward was £100 from the Board of Inventions and Research for his flash-spotting board. He found it a godsend for starting back in civilian life. Bragg had a complimentary review from the Board but no money.

Hemming became a successful banker. Jack retired as a Brigadier General and then for 10 years directed the Ordnance Survey. Histories of the Great War often mention outstanding German Staff Officers. On the British side, Jack deserves more attention. As he wrote, ‘I think we are justified in questioning whether there is any branch of the Army which in proportion to the numbers engaged had a greater effect on operations’. Bragg continued his outstanding scientific work and also was an extraordinarily successful developer of scientific programs, using the administrative skills he had honed in the Army. In 1962 four Nobel laureates were named for work performed at the Medical Research Council Unit in the Cavendish Laboratory, which Bragg had formed, obtained funds for, advised, and cheered on. This was a conclusive demonstration of how correct Bragg had been with his idea that X-rays could be used to determine the structure of complicated molecules such as haemoglobin, myoglobin and DNA.[23]

When the war broke out in 1939 Bragg was aghast to see the useless frills that had been added to the sound-ranging equipment, and set some backs up with his outspoken criticisms. Then he watched contentedly as they were discarded one by one.

Acknowledgements

I am grateful for the assistance of T. M. C. Van der Kloot, Judy Samarel and the staffs of the London Library, the British Library, the Wellcome Library, the Public Record Office, the Imperial War Museum, the Library of The Royal Society, and the Royal Engineers Library.

Notes

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5 W. H. Bragg and W.L. Bragg, *X-rays and crystal structure* (G. Bell & Sons Ltd, London, 1915).

6 *The Times*, 20 May 1915, p. 5.

7 He became a Captain, and at the end of the war was the Adjutant of the First Field Survey Battalion. Subsequently he had a distinguished career in physics and then was the Vice-Chancellor of the University of London from 1954 to 1955. E. N. da C. Andrade, 'Harold Roper Robinson 1889–1955', *Biogr. Mems Fell. R. Soc. Lond.* **3**, 161–179 (1957). Among others whom Bragg recruited to sound-ranging were E. N. da C. Andrade (later FRS), Sir Charles Galton Darwin (later FRS), Joseph Alexander Gray (later FRS) and Alexander Russell (later FRS).

8 G. M. Caroe, *William Henry Bragg 1862–1942* (Cambridge University Press, 1978).

9 http://www.nobel.se.

10 The sequence of the letters to *Nature* seems curious, especially because it was not uncommon for letters to be signed by several authors. The first letter was W. H. Bragg, 'X-rays and crystals', *Nature* **90**, 219 (1912): 'The rule has been suggested to me as a consequence of an attempt to combine Dr. Laue's theory with a fact which my son pointed out to me, viz. that all of the directions of the secondary pencils in this position of the crystal are "avenues" between the crystal atoms.' Then came W. H. Bragg, 'X-rays and crystals (response to letter from Dr Tutton)', *Nature* **90**, 360 (1912): 'In a paper read recently before the Cambridge Philosophical Society my son has given a theory which makes it possible to calculate the position of the spots for all dispositions of the crystal and photographic plate.' The first mention of W. L. Bragg by name was in 'Summary of papers presented at Cambridge Philosophical Society on Nov 11', *Nature* **90**, 402 (1912). Finally came W.L. Bragg, 'The specular reflection of X-rays', *Nature* **90**, 410 (1912), in which he reported 'the strong reflection of x-rays by a mica plate, in accord with idea that x-rays reflected from parallel planes in a crystal on which the atom centres may be arranged.' He carefully gave credit for the idea of using mica to Mr C. T. R. Wilson (later FRS; P. M. S. Blackett, 'Charles Thompson Rees Wilson', *Biogr. Mems Fell. R. Soc. Lond.* **6**, 209–295 (1960)).

11 I call William Lawrence simply Lawrence throughout to avoid confusion with his father William Henry. When he was knighted he chose to be addressed as Sir Lawrence Bragg.

12 In the preface to W. H. Bragg and W. L. Bragg (*op. cit*., note 5), father wrote, 'I am anxious to make one point clear, viz. that my son is responsible for the "reflection" idea which has made it possible to advance, as well as for much the greater portion of the work of unravelling crystal structure to which the advance has led.'.

13 Public Record Office: WO 374/805. He was awarded the Military Cross (London Gazette, 1 January 1918) and appointed an Officer of the British Empire (London Gazette, 15 March 1918). He was mentioned in dispatches on 16 June 1916, 4 January 1917 and 7 July 1919.

14 Public Record Office 389/6. Memoirs of Lieutenant-Colonel H. H. Hemming. Imperial War Museum Documents PP/MER/155.

15 Memoirs of G. Prouse, Imperial War Museum Documents 84/26/1.

16 Born, M. *My life and views* (Charles Scribner's Sons, New York, 1968); N. Kemmer and R. Schlapp, 'Max Born', *Biogr. Mems Fell. R. Soc. Lond.* **17**, 17–52 (1971).

17 Captain B. H. Liddell Hart, *The tanks. The History of the Royal Tank Regiment and its predecessors Heavy Branch Machine-Gun Corps, Tank Corps and Royal Tank Corps*, vol. I, *1914–1939* (Frederick A. Praeger, New York, 1959). A. F. Brooke, 'The evolution of artillery in the Great War', *J. R. Artill.* **51**, 359–372 (1925–26).

18 Captain Wifried (compiler), *Military operations in France and Belgium 1917. The battle of Cambrai* (HMSO, London, 1948).

19 For a vivid description of the counterattack from the viewpoint of a German company commander see E. Jünger, *Storm of steel* (transl. M. Hoffmann) (Allan Lane, London, 2003), pp. 204–218.

20 Prouse, *op. cit.* (note 15).

21 E. Ludendorff, *Ludendorff's own Story. August 1914-November 1918* (Harper & Brothers, New York, 1919), pp. 326–333. Six or seven German divisions were 'completely broken' and 21 000 prisoners taken. It was the number surrendering that so shook Ludendorff and it should be noted that before the attack he was aware that the German Army was 'Zur Hö betrübt' (depressed down to hell). Brigadier J. E. Edmonds, *Military operations in France and Belgium 1918*(Macmillan, London, 1935), vol. 4, p. 38.

22 This narration of the sequence of events at Amiens, which is not laid out in most histories, is in Innes (*op. cit.*, note 3), pp. 13–31.

23 The Chemistry prize was shared by Max Ferdinand Perutz FRS and John Cowdery Kendrew FRS 'for their studies of the structures of globular proteins'. Perutz had determined the structure of haemoglobin and Kendrew that of another oxygen-carrying protein, myoglobin. Francis Harry Compton Crick FRS and James Dewey Watson (later ForMemRS) shared the Physiology and Medicine prize with Maurice Hugh Frederick Wilkins FRS from King's College, London, for solving the structure of DNA.

24 Lt-Col, E. M. Jack. 'Survey in France during the war'. *R. Eng. J.* **30**, 1–27 (1919).

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