Technology for Artillery Location 1914 - 1970

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Dedication

This little book is dedicated to my wife Mary who has supported me through difficult times and has put up with the piles of "research material" which seemed to follow me round the house!

Preface

Five years ago, someone asked a question on the Wireless-Set-No19 list about a strange looking wireless set which seemed to be related to the Wireless Set No 22 but with far too many tuning knobs. The set eventually turned out to be a Radio Link SR Mk II but in finding that out, I became involved in a research project which took me back to the beginning of the Great War and into some mathematics which I had not visited since university and in some cases, school.

This book is the result of numerous visits to many interesting places such as the National Archive in Kew and the archive of the Royal Regiment of Artillery in Woolwich, not to mention the time spent on reading and discussion with experts around the world by email. However, I am still at something of a loss to explain exactly what it was which piqued my original interest in this, to most, somewhat obscure subject.

The paragraphs which follow are taken from the Preface to earlier editions and give a short summary of the book's contents...

The advent of indirect fire in the Royal Artillery at the beginning of the 20th century brought with it the need to employ technical means for locating targets. These fell under three headings; Survey, Flash Spotting and Sound Location, the latter two of which are considered in this article. It is not intended to be in any sense a mathematical treatise on the principles of artillery location but, of necessity, there is some mention of those principles in general terms. References are given for those readers who may wish to investigate the theories in detail.

Readers with existing knowledge of the subject of artillery location will realise that no mention has been made of the projectile tracking radars which were introduced late in the Second World War. This is quite deliberate as the author feels that a study of this aspect of radar rightly belongs in a larger work on the history of radar. Instead, the entire focus of the book will be on the original methods of Flash Spotting and Sound Ranging and it aims to present such information as is currently known on the technologies which facilitated the use of artillery location in wartime.

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I would like to thank a number of people without whom this book could not have been produced. The list which follows is undoubtedly incomplete and to those who have been missed, my apologies and sincere thanks:

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- Nigel Evans from Australia has a superb site "British Artillery in World War II" at
  http://members.tripod.com/nigelef/index.htm
  essential reading for anyone interested the history, practice and organisation of artillery. Nigel provided the author with numerous nuggets of information and access to some documents which appear to be unavailable in the UK.
- To Paul Evans, the librarian of the Royal Regiment of Artillery in Woolwich Arsenal. Thanks for making my visit interesting as well as useful in filling gaps in my knowledge of the inter-war period.
- Louis Meulstee has been a source of inspiration to all of us with an interest in the history of army communication. Anyone attempting to produce even a modest work like this has to wonder at the dedication which must have gone into the four volumes of *Wireless for the Warrior*. Louis was also kind enough to allow the reproduction of the diagrams and photograph in Section 4.2 on the Radio Link SR Mk.I.
- The photographs of the Radio Link SR Mk.II (Figure 4.5) were provided by Richard Howes, G8DJK of the Pye Historical Collection, to whom my thanks are due. The Pye Telecom Museum web site can be found at
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- Brian A Clarke, VK2GCE kindly allowed the inclusion of the photograph of, and information on his Control Unit, SR Mk.II.
- Chris Suslowicz has made available many signal training documents from which clues and research leads were gleaned.
- Robert Osborne is the author of the website of the 7th Survey Regiment, RA and his father served in that regiment. Robert supplied useful leads to documents in the National Archive and kindly gave me permission to reproduce the wonderful drawing of an SR HQ at work, Figure 3.26.
- The pictures of the Recorder, SR No.1 Mk.II and the Plotter, SR Mk.I are reproduced with the permission of the National Archive.
- Alan Knell supplied invaluable information on the Carrier Link, SR and the SR Radio Link No 2.
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- Keith Watt RN (Rtd.), in providing the inspiration for, and management of the Wireless-Set-No19 web site has created the most comprehensive British military communication document archive in the world:
  www.royalsignals.org.uk
  A number of the documents from this archive have been used in the preparation of this book, along with documents from the author's collection.
- Colin Barratt and Keith Watt kindly proof read this version of the manuscript - all remaining errors are the author's fault!

Chapter 1

Indirect Fire and its Consequences

Up to the end of the 19th century, gunners could always see their targets and engaged them by pointing the gun barrels in the right direction and tilting them upward to achieve the correct range – this is known as *Direct Fire*. However, various technical advances such as the introduction of rifled barrels and more effective propellants, served to increase the range of guns of all types. Consequently, they could be sited further away from their targets and hidden from the enemy (who would, of course, be using weapons with similar ranges to attempt to knock out our batteries). The first example of this was the use of howitzers[1] firing from behind cover such as a crest, during the Boer War.

Firing from out of sight of the target is known as *Indirect Fire* and by 1906 it had been accepted by the British Army as the primary mode of fire. The big problem with indirect fire, of course, is how to point the guns at the target[2] when you can't look down the barrel and see it. The means of achieving this took some time to stabilise and continues to evolve to the present day.

Before the First World War, it was envisaged that future wars would be characterised by movement and that cavalry would play a vital role in exploiting breaks made in the enemy's lines. At this time, the Royal Regiment of Artillery was composed of two separate organisations, mounted (the Royal Horse Artillery supporting Cavalry and the Royal Field Artillery supporting infantry) and dismounted (the Royal Garrison Artillery, providing siege and coastal artillery). During the Great War, the RHA and RFA supplied the lighter guns, while the RGA supplied the mediums and heavies. They were not in fact merged until 1924.

As we now know, World War 1 in Europe was mainly a war of "position" and the methods for controlling indirect fire had to become very sophisticated. Put simply, indirect fire required a great deal of trigonometry and surveying. After all, the target must be definable in some way other than direct view, and the only suitable approach is to have an accurate drawing which covers both gun and target – in short, a map. Hence the trade of surveyor (a Royal Engineer trade at this time) rose to paramount importance.

The other aspect of indirect fire which came to the fore in the Great War was the location of hostile guns. Generally speaking, gun batteries firing indirectly would be out of sight of the enemy and his guns would be out of our sight. However, it was very desirable to be able to fire on his guns to put them out of

[1]Howitzer: A gun which fires its shell on a much higher trajectory than a field gun and has a relatively short barrel (less than 30 times the bore). The plunging trajectory of the shell makes the howitzer an ideal weapon for use against fortifications.

[2]The correct expressions is "laying the guns on the target".

action. The two means developed during the Great War for gun location form the main subject of this paper.

1.1 The Growth of Artillery Survey

When the BEF landed in France in 1914, the British Army's surveying resource was just one map officer at GHQ, followed in October 1914 by a ranging[3] section, initially of one officer and four other ranks, which expanded and became the 1st Ranging and Survey Section RE in April 1915 [1]. Initially this group worked with aeroplanes which, lacking wireless, had to drop a smoke bomb on the proposed target. Observers would then find bearings to the smoke and hence the range but, of course, the observers and the guns had to be surveyed onto the map for this to be usable.

Various procedures for obtaining the position of hostile guns by observation were tried, including the taking of a bearing and measurement of the "flash-to-bang" time for the calculation of range. Unfortunately it was found that to be useful, the timings had to be accurate to much less than a tenth of a second whereas even a trained observer had a reaction time which was more like a fifth of a second. However, this method persisted in the British Army and elsewhere for some time and British observation sections were equipped with stopwatches. It seems that flash-to-bang ranging was used in the Japanese army during the Second World War and Figure 1.1 shows a stopwatch scaled in metres, made by Seikosha for the Japanese army. These devices were commonly known as *Phonotelemeters*.

Figure 1.1: Phonotelemeter

Eventually, a method of taking bearings from several observation posts, described below, was perfected. The perfection of Flash Spotting, as this method became known, is generally credited to Harold Hemming, a Canadian gunnery officer posted to the Ranging and Survey organisation.

In October 1915 a Royal Horse Artillery officer called William Lawrence Bragg was sent to France[2]. Lawrence Bragg (later Sir Lawrence Bragg, CH) was at this time in his twenties and already a Nobel Prize winner for his work on X Rays and Crystal Structure. With others, he developed the method of gun location known as Sound Ranging, using the "gun sound", a pressure wave produced when the exploding propellant emerged from the barrel which could be detected by a suitable microphone. In Bragg's unit was a Corporal Tucker who, before the war, had worked at Imperial College on the cooling of platinum wires by air currents. With this background, Tucker was able to design a microphone specifically for the detection of gun sounds, known thereafter as the Tucker Microphone.

By the end of the Great War, there were thirty four sound ranging installations and more than one hundred Flash Spotting posts covering the Western Front alone[3].

[3] "Ranging" is the term used for bringing our guns onto the desired target and should not be confused with "Location" which means finding the position of enemy guns.

1.2 The Second World War

In 1920, it was decided that survey, flash spotting and sound ranging should be transferred to the Royal Artillery in a single Survey Company, RA. All but one of the officers[4] who had been involved in flash spotting and sound ranging had left the service, most returning to academia. Technical developments slowed dramatically in the inter-war years and the equipment produced for sound ranging was poor – in [4], Bragg notes

> ... when World War II threatened and I was asked to give my opinion on the sound-ranging apparatus as it had been developed in the interim, I was appalled. It was like the World War I set which had grown the most complex whiskers.

It was shortly after this that the Recorder, Sound Ranging No 1 was developed and this was used throughout the war, with a Mark II version introduced in 1940 and a Mark III version later in the war. With the outbreak of the Second World War, Hemming was back in uniform heading Flash Spotting and Bragg had, from the late 30s, been advising the government on Sound Ranging.

In 1939, Survey Regiments were organised with three Batteries, one each for survey, flash spotting and sound ranging but during the war this changed to a two Battery arrangement, each Battery containing three troops for the three duties. The 1943 regimental establishment shows 31 officers, 4 warrant officers, 45 senior NCOs, 124 junior NCOs and 404 gunners/privates – a total of 608 men. There were in addition 14 attached REME other ranks operating a Light Aid Detachment, led by a Warrant Officer[5]. By the end of World War 2, nine Survey Regiments were in action.

1.3 Maps and Grids

It was mentioned above that artillery survey, which formed part of the work of the Survey Regiment, RA, involved map making. It may be useful, before moving on to describe Flash Spotting and Sound Ranging, to spend a few moments considering this in more detail, because surveying was the basis of the rest of the artillery's operations.

The generally accepted geographical framework of measurement is latitude and longitude, but unfortunately this is not particularly useful on the battlefield, in particular because the lines of longitude converge at the poles and are therefore not parallel to each other. The most convenient coordinate system for use by artillery is a rectangular grid overlaid on a standard map. The grid system is defined in terms of a number of parameters including the latitude and longitude of the grid's origin, the units of measurement (yards in the British Army until relatively recently) and the orientation of the grid with respect to North. Note that because of the curvature of the earth's surface, a rectangular grid cannot be sustained over great distances.

For artillery purposes, an error of less than one metre in position and the same in height above some reference (usually mean sea level) is required. But it is no good applying a grid to an inaccurate map, and maps were a problem in both World Wars – in WW1, some of the French maps were based on a Napoleonic survey! However, the German maps of the Western Front were also conveniently inaccurate and in WW2, the British view was that the German

[4] The one remaining officer was from SR and joined the Air Defence Experimental Establishment.

maps of Germany were unsuitable for military operations! Where necessary therefore, new maps had to be created by aerial photography and surveying on the ground, although in 1944, a set of modern German maps of Holland fell into Allied hands and made it unnecessary for further work to be done on the Allied versions.

Artillery survey fixes features on the landscape, as well as the guns, observers, etc., in relation to the grid, allowing any position to be quoted in terms of x and y co-ordinates (known as *Eastings* and *Northings* respectively). This is initially done by regimental surveyors who are part of the artillery regiments, and progressively improved by the men of the Survey Regiment, as time permits. In WW2, it was the job of the Gun Position Officer (GPO) to know exactly where his unit was at all times while on the move, so that his guns could deploy at short notice and with the expected positional accuracy. The aim of the subsequent refinements carried out by the Survey Regiment was to bring all the guns in first a division, then a corps and finally across the whole theatre, into a known relationship. In this way, large concentrations of fire from numbers of batteries could be accurately called down on particular targets.

1.4 Registration and Ranging

None of the principles outlined above sprang into existence fully formed, they evolved over several years, along with a number of other gunnery procedures such as the use of Aiming Points and Bearing Pickets, not described here.

It should be noted that until 1917, attacks by both sides were always preceded by heavy artillery barrages which were intended to remove obstacles (such as wire) in the path of advancing troops, disrupt the enemy defences and silence enemy artillery. Because no accurate means of shooting from the map alone existed, batteries had to "register" their designated targets in advance. This process involved observing the fall of shot (observed by the Flash Spotting posts) during a ranging shoot where corrections to bearing and range were made in increments until the shot fell on the target. The preliminary barrage of course, inevitably warned of an impending attack and the registration meant that the enemy knew what targets would be hit.

The battle of Cambrai in November 1917 is generally known as the first mass employment of tanks in attack but it is possibly more importantly notable for the conduct of the artillery element in the operation. Because of the advances which had been made in location and survey, GHQ were able to lay down three pre-requisites for the successful tank attack[6]:

1. No artillery registration.
2. No attempt to destroy obstacles by preliminary bombardment.
3. Artillery to be directed on guns, not on trenches and wire.

It can be argued that the German counter attack regained nearly all the ground taken by the initial attack, but it is still clear that Cambrai marked a turning point in the conduct of the war. The tanks themselves may have been something of a surprise to the enemy, but the lack of a preliminary barrage and the accuracy of the shooting when the guns did open up must have been devastating.

Although the primary purpose of both flash spotting and sound ranging remained the location of hostile guns, they were equally capable of ranging our own guns and were used frequently for that purpose in both World Wars.

Chapter 2

Flash Spotting

Now we turn to the first of the two original methods of locating enemy artillery, and one which remained unchallenged until the arrival of trajectory following radars late in the Second World War. The dramatically increased speeds of calculation made possible by the electronic computer from the 1960s make it difficult for a modern reader to appreciate just how big the computer revolution has been and to realise that fifty years and more ago, *all* scientific and engineering calculations had to be done by means of the slide rule and printed mathematical tables. The theory and practice of artillery location is of course based on science and mathematics (particularly trigonometry) and generally everything had to be worked out manually and plotted on a variety of charts. And yet, it is recorded that by the end of Second World War, a located hostile battery could be fired on before its shells had fallen[1]!

2.1 Growth of Flash Spotting

Artillery personnel in 1914 were no strangers to the principles of observation since much indirect fire was directed by Forward Observation Officers who nominated targets and guided fire onto them by means of telephone and later wireless communications. Of course the positional warfare conditions in the Great War made this sort of operation less necessary, but the skill and, to a certain extent, the equipment was available.

Early on therefore, it became evident that the fixing of enemy guns (which became known as Flash Spotting) would be crucial and nearly every Corps put in place some means of achieving it[2]. The first such organisation is thought to have been the Flash Spotting Section set up by II Corps Artillery on the front between Hill 65 and the southern outskirts of Armentières. Third Army formed an Artillery Survey Detachment in October 1915, controlled for tactics and administration by the R.A., but for training and technology by the Third Army Topographical Section (R.E.). This dual control was soon abandoned and the Section was put directly under the Army Topographical Section. A total of seven observation posts were placed along the Army front, but this was soon found to be impractical and in April 1916 the Section was split into Groups of three or four posts each.

First Army formed a Flash Spotting Section shortly after the Third Army's Artillery Survey Detachment but in this case, it was not initially successful and may be said to have been formed on unsound principles:

- Personnel were selected from officers and men who had experience of survey instruments in peace time, but included no gunners.

- The instruments used were theodolites which were far more accurate then necessary (reading to 10 seconds of arc) and unsuitably fragile for field use.
- The Section worked in Groups of two observation posts each and there was initially no cooperation between Groups.
- Groups were required to report individual flashes to the R.A., which made the finding of an accurate location extremely unlikely.

It took flash spotting in the First Army at least eighteen months to live down these early mistakes but, by the close of the War, it was as effective as any on the Western Front.

The responsibility of the Royal Engineers for the observation function, as part of Survey, would seem to be illogical in that the information produced by the observation groups was of use only to the artillery. How command and control was exercised in practice is unclear, but (apart from the initial groups in First Army) it seems that considerable numbers of gunners were involved in observation. There must have been some difficulty however, as Winterbotham recommended in [2] that all artillery observation must become the responsibility of the Royal Artillery.

2.2 How Flash Spotting Works

The principles of flash spotting are simple; two or more observers take bearings on a gun flash and, providing the positions of the observers are known and the bearings accurate, a simple trigonometrical calculation (see Appendix A) will fix the position of the gun.

Today, a computer running a suitable program fed with the observer positions and the observed bearings would produce the hostile gun's position in microseconds. However, before computers, these calculations would have been onerous, slow and open to errors. Happily there was a much better way – by plotting. Given a map overlaid with a grid on which the positions of the observers were accurately marked, observed bearings could be plotted and their intersection would identify the hostile gun's position, at least in theory.

Much valuable information on the conduct of flash spotting can be found in the 1937 publication "Manual of Flash Spotting" [7] which, given its date, was probably produced under the guidance of Harold Hemming as the country moved towards rearmament. It is also a reasonable assumption that it contains descriptions of the best practices worked out during WW1 and it is known that it was still current in 1939[1].

Each flash spotting troop could deploy up to four observation posts, but often used three, which was the minimum permitted number. Although the principles are simple, the practice is less so and it was found (no doubt by the First Army Flash Spotting Section!) that using just two bearings was unreliable. Indeed, the observations from up to six posts could be combined, but that appears to have been rare.

Flash Spotting posts had to be manned and with their observers alert twenty four hours a day, seven days a week in action. Given some of the locations suggested, this cannot have been easy.

> . . . it will be evident that the sites which best fulfil the conditions are commanding positions some 1,500 to 2,000 yards from the front line. A flash spotting post requires a large arc of view, if placed further forward than this, it will be difficult to conceal, and the enemy

[1] An amendment dated March 1939 exists.

> will be able to disturb the observer with machine gun and rifle fire. Accurate observation can hardly be expected of an observer under such conditions ... ([7] p 52)

That must rate as one of the greatest understatements of all time!

Whetton and Ogden in [8] tell us that late in the Second World War in Europe, a mobile flash spotting post was brought into service. This consisted of a small platform, capable of holding just one observer, on a vertical telescopic arm mounted on a three ton truck. In use, this device suffered from two serious defects:

- The hydraulic seals tended to leak, which resulted in the platform slowly descending while in use.
- The erection and positioning of the platform was carried out by the vehicle driver on the ground, in telephone communication with the observer. This was a somewhat cumbersome arrangement and the observer would often find himself raised well clear of cover before he could get the driver to stop the operation. It is claimed that this problem was particularly evident when an officer was on the platform!

It is interesting to note that most assumptions in the Manual of Flash Spotting favour positional warfare and there seems to have been little thought that flash spotting could be employed in mobile warfare. For example, on the tactical employment of flash spotting in the advance:

> ... As long as the advance continues without halts, there will be few, if any, opportunities for action by the group ... ([7] p 74)

Observers clearly had to take accurate bearings on the flashes they saw, both in azimuth (in the horizontal plane) and in elevation[2]. Highly sophisticated optical instruments were provided for taking the bearings (see 2.3 below), but the big problem in flash spotting was making sure that all observers were seeing and reporting on the same flash.

It is noted in the Manual of Flash Spotting that posts should not only observe gun flashes, etc., but must take every opportunity to make general observations on troop dispositions and movements in the their area of observation. This information would be passed back to headquarters in regular reports for which a form was provided.

Until well after World War II, artillery propellants produced a muzzle flash[3] which could be seen clearly at night, providing the gun was in view of the Observation Post. Even if the the gun was not directly visible, the flash could often be seen indirectly because it lit the sky above it. Between the World Wars, so-called "flashless" propellant was developed but it was not generally employed by field artillery during the Second World War. In any case, this propellant tended to produce characteristic smoke rings which could be seen during the day. Therefore, the work of the Flash Spotters was normally general observation during the day and flash spotting at night.

2.3 Spotting Instruments

Observation Posts in the Great War were generally supplied with an observing instrument, a telescope, binoculars, a stopwatch, a head and breast set for the

[2] Up to this point, we have assumed that the landscape is flat, but this is obviously not always the case. However, for the fixing of hostile gun positions, height is not an issue as bearings are all that are needed. Some other uses of flash spotting, such as the plotting of air bursts when ranging friendly guns, do require an elevation reading.

[3] In fact, the gun produces two flashes; first a short flash as the burning propellant emerges from the barrel and then a longer, more intense flash as the unburnt gas meets the oxygen in the air.

telephone (of which more later) and a supply of maps and other topographical material. As mentioned above, the stopwatch was for flash-to-bang range estimation and the telescope (usually one of the “signal” pattern instruments) and binoculars were for general observation.

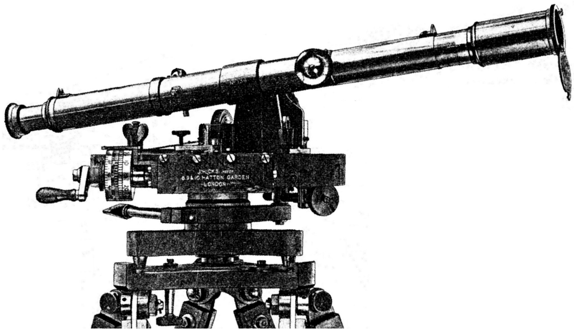


Figure 2.1: Instrument, Observation of Fire.

As mentioned above, the First Army supplied its original Flash Spotting Sections with commercial surveying theodolites, which can be used for determining horizontal angles. However, they soon proved unsuitable for a number of reasons:

- The field of view was very limited and the magnification insufficient (also, the image was normally inverted!).
- The measurement of horizontal angles was too accurate and, coupled with the limited field of view, finding the desired flash was very difficult.
- There was generally no way to disengage the azimuth adjustment screw to allow the instrument to “sweep” across the observation area.
- The theodolite is a precision instrument, quite unsuited to use under combat conditions.

It may however be noted that theodolites were later used on occasion for the measurement of vertical angles in air-burst ranging.

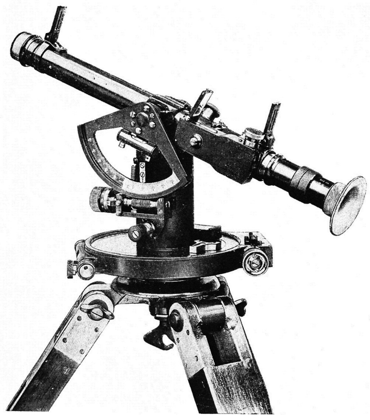


Figure 2.2: Director, No 2, Mark 1.

The first generally available flash spotting instrument was the Instrument, Observation of Fire (Figure 2.1) which had been in the stores of Heavy and Siege Batteries, RA, but which had been found to be too heavy for use by them in the field[9]. This was not a problem for flash spotting posts, where a sturdy mounting for the instrument was a necessity to achieve stable results. The instrument was essentially a telescope designed for rapid and easy measurement of angles, and these particular instruments had been designed for observation, so appeared to be almost ideal for flash spotting use. They had a wider field of view which was the right way up and were relatively easy to train on the desired flash. Their disadvantages were the somewhat limited field of view, the relative inferiority of the optics and the weight. However they were widely and successfully used until replaced by better instruments.

The Artillery Director, in use at all R.A. batteries[4], was found to be attractive in some respects for flash spotting use. An illustration of a director[9] in use at the beginning of the Great War is shown at Figure 2.2 and the similarity to the Instrument, Observation of Fire will be readily appreciated.

Being lighter and more easily handled under combat conditions, although the quality of the optics was perhaps not ideal, directors were preferred by flash spotting personnel except for conditions of static warfare, where the heavy mounting arrangements were an advantage. Of course, directors were difficult to obtain because of the need for them at every artillery unit. By the end of the War, director design had progressed considerably and the standard instrument was the Director No 5, illustrated in Figure 2.3.

Both the British and the French were searching for an instrument more suited to the specialised needs of Observation Groups and a number of designs were produced. The British, in the person of a Major Henrici R.E., produced the "Theodolite, F.S." which was based on a German "Trench Theodolite", a small prismatic telescope. The main characteristics of the Theodolite, F.S. were:

- Both horizontal and vertical angles could be measured, the vertical angle being read from a graticule in the field of view.
- The field of view was about 6.5° and magnification power 6.5.
- A well designed mounting with transit circle reading to one minute of arc.
- It was suitable for use at night.

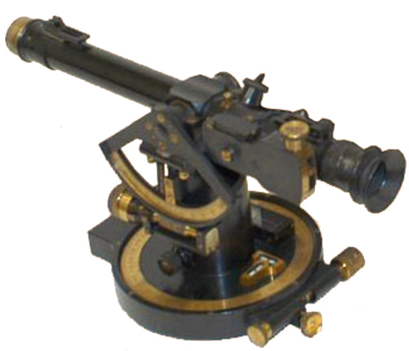


Figure 2.3: Director, No 5.

[4]The Director is used during the initial setting up of guns for indirect fire, to establish the correct initial bearing with respect to some known point.

Unfortunately, no images of either the German Trench Theodolite or the Theodolite, F.S. can currently be found.

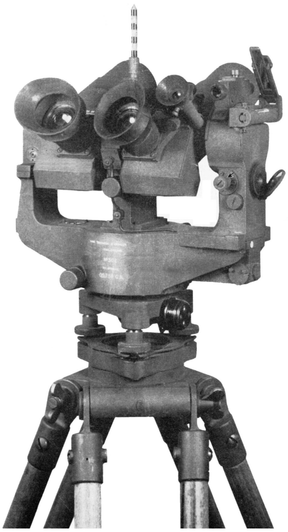
Figure 2.4: Longue-Vue Monoculaire à Prismes

Meanwhile, the French had produced two designs; a binocular instrument for night work and a prismatic telescope, the *Longue-Vue Monoculaire à Prismes* which had been designed for French flash spotters by their army Service Géographique. A large supply of these instruments had been ordered and they were eventually able to supply all British units and, later, the Americans in the field. The Longue-Vue Monoculaire (Figure 2.4) was agreed to be extremely accurate and easy to use – and it fitted on the British mounts which also accommodated the Theodolite, F.S. for night work. Its primary features[10] were its good field of view, accuracy, ease of setting and the triple eyepiece (with magnifications of ×16, ×23 and ×32). One flaw was found in operation – the base (also used for the Theodolite F.S.) proved to be too light for the French instrument and a considerable amount of play tended to develop.

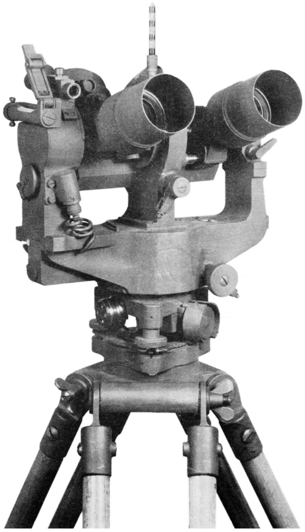
In the autumn of 1917, a Sergeant Coles, working in a field survey battalion, designed an instrument with a direct reading bearing scale which was visible through the instrument's eyepiece. This was a major advance and Sgt. Coles was sent to England in May 1918 to work with a leading instrument manufacturing company, Messrs. Watts & Son, on the development of the device. Unfortunately, production difficulties meant that the Coles Instrument did not go into service in the Great War.

It is also thought that there was an device known as the "Watkins Instrument", but whether this was based on the Coles design or not is currently unknown. Hemming does not mention the Watkins instrument in [4].

The optical instrument used by flash spotters throughout the inter-war years, WW2 and later was essentially a set of accurately calibrated binoculars known as the Instrument, Flash Spotting No 4[11] made in England by Messrs. Cooke, Troughton and Simms. Whether the No 4 was derived from the Coles or Watkins instruments and what the Numbers 1, 2 and 3 instruments might have been, are unknown. Figures 2.5 and 2.6 show this instrument, of which each observation post was equipped with two. Aside from accuracy and the ability to exactly calibrate bearing and elevation, the instrument had quick release arrangements which would allow the observer to easily swing it to a different bearing to begin making detailed observations on another gun. It also has an extremely sophisticated prismatic optical system which projects illuminated graticules into the field of vision, allowing readings to be taken directly, day or night. The Firepower Museum in Woolwich holds a post-World War 2 example of the No 4, Mark III instrument.



(a)



(b)

Figure 2.5: Instrument, Flash Spotting, No 4 Mk.III

(a)

(b)

Figure 2.6: Instrument, Flash Spotting, No 4 Mk.I with Stand

2.4 Communications

Flash spotting posts were connected to the flash spotting headquarters by line. The process of surveying a post into the grid was presumably fairly lengthy but, of course, essential for operation of the post, so there would have been at least a certain amount of time to lay lines. The Manual[7] lays stress on the use of what appear to be fairly permanent structures for observation posts and their construction would have added to the preparation time, allowing even more time for line laying. This is borne out by accounts of spotting in the Great War, but it is clear from various sources that even when wireless became available in World War II and afterwards, line remained the primary means of communication.

In May 1916 Hemming, knowing that the most essential feature of successful flash spotting was to ensure that all observers were concentrating on the same flash, invented the arrangement which was to be used for the rest of the Great War and for some time thereafter. He realised that each observer could be given the ability to signal to HQ whenever a flash was seen, by means of a telegraph key, using the existing telephone lines from the posts to the HQ. Bragg suggested the means by which this might be achieved, a sensitive relay, and while on leave, Hemming bought some relays, keys and buzzers in London's High Holborn. He returned to France after only four days of a fortnight's leave (his fellow officers thought he was mad) and constructed a prototype device. Subsequently, the GPO produced the design as the "Flash and Buzzer Switchboard" which was used with a modified standard "buzzer" field telephone.

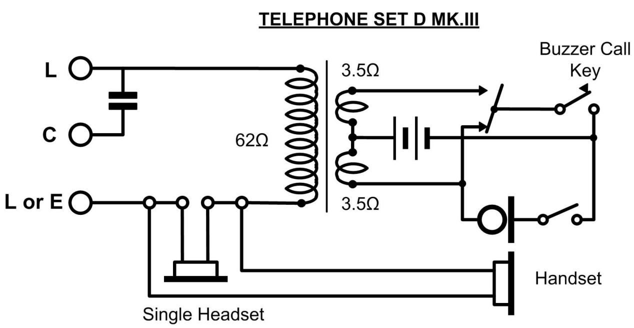


Figure 2.7: Telephone Set D Mk III, Circuit.

It should first be explained that buzzer telephones were field telephones without a bell which used a simple buzzer at the calling end to make a noise in the headset or receiver of the telephone at the receiving end (generally a single headset called a "watch receiver" was provided, in addition to the handset). The telephone initially used in flash spotting was a modified version of the Telephone Set, D, Mark III [12]. The circuit of the unmodified "D III" telephone is shown at Figure 2.7 and the telephone with the flash spotting modifications is shown in Figure 2.8.

The modifications were:

1. A "flash key" was fitted between the L and C terminals of the telephone. This was originally a spring loaded bell push type of switch as shown in Figure 2.8, but it will be seen from the picture of the Instruments, Flash Spotting in Figure 2.6 that a toggle switch is fitted to the instrument stand and this could be substituted for the bell push. The function of

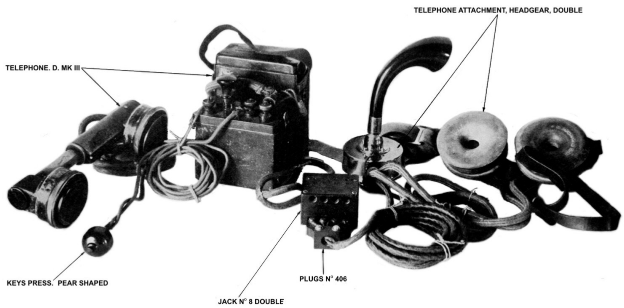
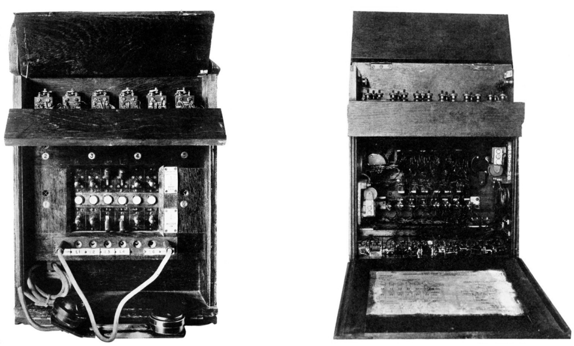


Figure 2.8: Flash Spotting Post Telephone Equipment

the flash switch was to complete the DC circuit through the telephone by shorting out the blocking capacitor which was wired between the L and CL terminals. This operation is further explained below.

2. In the standard DIII telephone, the handset and the watch receiver are wired directly to terminals on the main unit. For the flash spotting version, the watch receiver is directly wired, along with a double four-pin jack socket, the Jacks, No 8, Double. The hand set is supplied with the appropriate four-pin plug, the Plug No 406 (used in numerous later telephones).
3. An additional headset (Telephone Attachment, Headgear, Double) was plugged into the other socket in the double jack. This headset, which carried a breast microphone, was normally worn by the observer.



(a) Front (b) Rear

Figure 2.9: Flash and Buzzer Switchboard

The buzzer telephones at the observation posts were connected to the Flash and Buzzer Switchboard (see Figures 2.9 and 2.10) which, apart from use as a standard six line exchange, allowed the observation post to indicate to the Flash Spotting HQ exactly when a flash was observed. Each of the switchboard's six lines were equipped with:

- A watch receiver, also known as a "hooter" to receive an incoming buzz call.

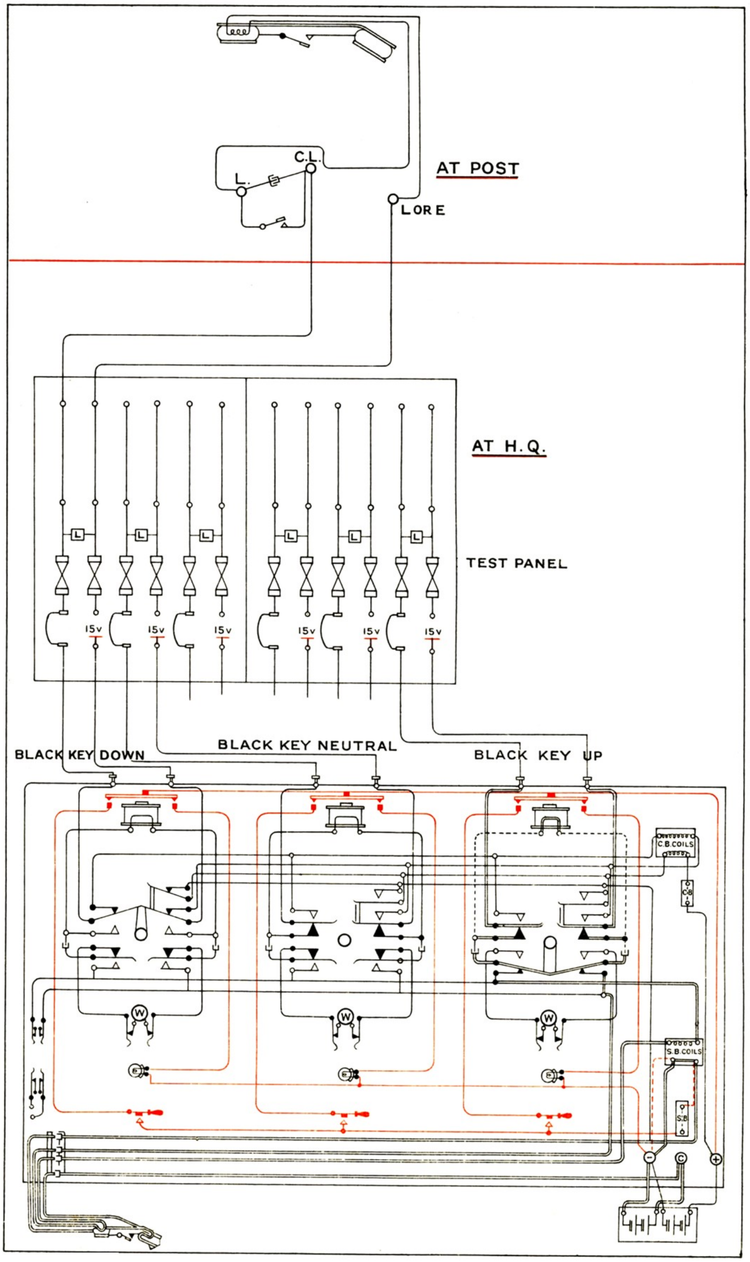


Figure 2.10: Flash and Buzzer Switchboard - Circuit

- A black, three position speak and ring key.
- A red flash buzzer key.
- A 15v battery and flash relay.
- A 4v lamp.
- An audio jack socket for connecting an observation post circuit to an external line.

In addition, the switchboard contained a handset and speech circuit with battery, a battery for operating the lamps, a sending buzzer for calling posts, a receiving buzzer operated by the flash switch at any post and terminals for connecting an external line or, more usually, a standard switchboard.

The operation of the switchboard was similar to that of normal switchboard if the black key only is considered. The normal position of the key is horizontal, when an incoming buzz call would operate the appropriate hooter. To answer the call, the operator would lift the black key, connecting the speech circuit and disabling the hooter and lamp. To call a post from the switchboard, the black key would be pressed down against its return spring and released. This action would send a buzz call from the sending buzzer to the post. Finally, to connect several posts together, their black keys would be lifted.

The red keys had a simple function related to the reception of flash calls - only when a post's red key was down would operation of the flash switch at the post cause the appropriate flash relay to close, lighting the lamp and operating the receiving buzzer.

2.5 Flash Spotting in Action

The operation of flash spotting communications will best be described by outlining the procedure used to obtain a position. The following is paraphrased from [7] and represents the situation at the beginning of World War 2 while the Flash and Buzzer Switchboard was in use. First, the two main plotting tools, the Concentration Board and the Parallel Ruler Board[5] must be mentioned.

The Concentration Board was a rectangular map board with either a map or a standard grid mounted on its surface. On the map or grid were plotted the accurate positions of the flash spotting posts in use, as well as all hostile positions already found, all suspicious areas, etc. Each observation post was plotted in a different colour and corresponding to each post, a coloured pre-printed arc was stuck to the board, extending 10 degrees on each side beyond the field of view of the post[6]. A pin was carefully driven into the board at the location of each post and a thread (normally gut) was attached it. The other end of the gut thread was attached to a lead weight, coloured to match the post's colour, so that the thread could be stretched across the board to indicate a bearing on the post's arc. The intersection of bearings from several posts gave the location of the hostile gun or battery – provided that all the posts had been observing (or "concentrating" on) the same flash. The purpose of the Concentration Board was to ensure that happened, as described below. An example of a concentration board is shown at Figure 2.11.

The Parallel Ruler Board (see Figure 2.12) was again a map board with a standard grid ruled on it, but this time a circle of as large a diameter as

[5]There was a third board, the Large Scale Plotter, but as this was only used for very accurate location and followed on from the use of the other boards, it is not covered further here. A full description of its theory and use is given in [7].

[6]These pre-printed arcs were subdivided to 10 minutes of arc and were provided in 50cm, 60cm and 70cm radii, so that they could be arranged to avoid too much crossing on the board. Once positioned, the arcs were labelled every 5 degrees, with zero corresponding to grid North.

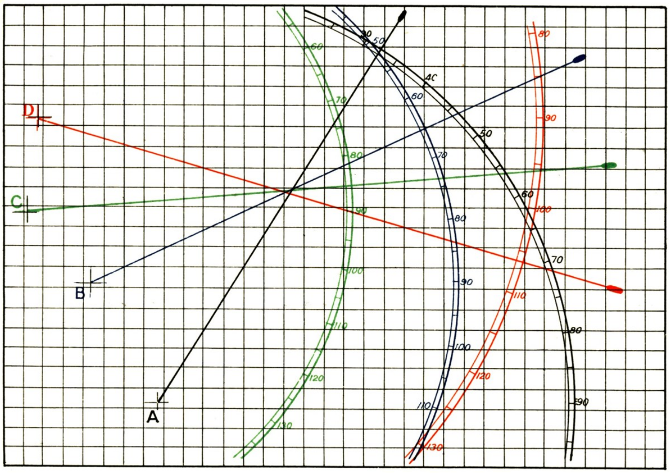


Figure 2.11: Concentration Board

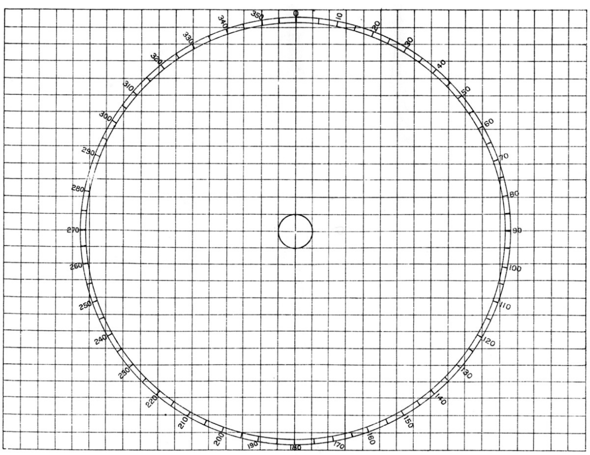


Figure 2.12: Parallel Ruler Board

possible and divided every 10 minutes of arc, was added. The positions of the posts were accurately plotted, but no pins or threads were used. Instead a parallel (or "rolling") rule was used to set a post's observed bearing from the centre point of the circle and the rule was rolled across to line up with the post's position. Thus the bearing from the post could be accurately plotted without the use of individual arcs. Obviously, the intersection of bearings from several posts gave the location of the hostile gun or battery – provided that all the posts had been observing (or "concentrating" on) the same flash. The purpose of the Concentration Board was to ensure that happened, as will now be described.

The initial setup on the switchboard when engaged in spotting was all black keys up and all red keys down. When an observer saw a flash, he laid his optical instrument on it and reported it by pressing his flash switch, giving a buzz and a lamp signal at HQ. The HQ operator would request the bearing which would be laid out on the concentration board. If the thread passed through a known position, the plotter would direct the other posts to watch on the bearings from their posts to the position. If the thread passed through more than one known position, the plotter would direct at least one post to watch each known bearing. Then, if the position was indeed known, this would be confirmed by the simultaneous[7] lighting of more than one lamp.

Alternatively, if only one lamp was lit on each round, the position was previously unknown and a search procedure was initiated. Each post, other than that reporting the flash, would be given a sector to watch, based on an approximation of the range from the first post, from the "flash to bang" time – not at all accurate, as mentioned earlier. The post originally reporting the flash would then "lead" the operation and all red keys, except the key for that post, would be raised to the horizontal position. This disabled the flash keys at the other posts, but allowed them to hear the first post's flash report as a buzz.

If this had been properly controlled, one of the other posts would soon see a flash corresponding to the original report and would send bearings to HQ. The red keys would then be returned to the down position and synchronisation could be checked by the HQ. Assuming the plot on the concentration board indicated that a concentration had been achieved, the bearings would be transferred to the parallel ruler board to give an accurate location for the hostile gun or battery[8].

2.6 World War 2 and Later Developments

The Telephone Set D Mk.III was a design which dated from the end of the Great War and although it was in common use between the wars, it was replaced by later marks which were more sophisticated. It is not at present clear when the modified D Mk III was replaced by the Telephone Set, F.S. Mk I which is shown at Figure 2.13(a). It is certain from relevant EMER[9] [14] that the Mk I telephone was replaced by the Mk II by March 1945, and a photograph of an example of this instrument is shown at Figure 2.13(b).

[7] In fact, the lighting might not be quite simultaneous, particularly if observing smoke puffs during the day as the smoke could be affected by wind.

[8] In many cases, the plotting accuracy was sufficiently good that individual guns in a battery could be located.

[9] Electrical and Mechanical Engineering Regulations were the technical manuals used by the Royal Electrical and Mechanical Engineers (after 1942) when servicing equipment. A discussion of the EMER system will be found in the author's article "EMERs - A Valuable Resource"[13].

(a) Telephone Sets, F.S. Mk I

(b) Telephone Sets, F.S. Mk II

Figure 2.13: Telephone Sets, Flash Spotting

The Telephone Set, F.S. was similar in construction to a number of wireless control units and somewhat larger than the D Mk V telephone set, apparently because extra depth was required to accommodate the three, rather than two, line terminals. Compare Figure 2.13(b) with the photograph of the Control Unit S.R. No 2 Mk I below at Figure 3.25(b). The latter instrument is built in the same case as the Telephone Set D Mk V, and has only two line terminals.

Examination of the photographs in Figure 2.13 will reveal that the Mk I instrument has a Morse key mounted to the upper left, but the Mk II has nothing there. The key was used in place of the "flash key" in the instrument based on the the D Mk III and provided the DC path used by the flash relays in the Flash and Buzzer Switchboard. Both marks generate buzzer calling using the push switch in the centre of the instrument and the Buzzer 'T' Mk I, which doubles as the Anti-Sidetone Induction Coil (ASTIC) as may be seen in the circuit diagram of the Mk II at Figure 2.14. However, the Mk II does not provide any DC signalling and the EMER makes it clear that when this version was introduced, the Flash and Buzzer Switchboard was obsolete.

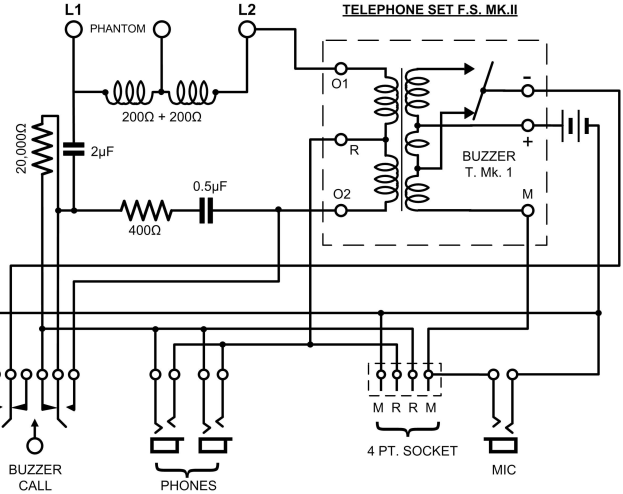


Figure 2.14: Telephone Set F.S. Mk II - Circuit

Exactly when that happened is not documented, but it can be inferred that it was around the beginning of the Second World War. The Manual of Flash Spotting [7] in the author's collection is dated 1937 with 1939 amendments and this contains full information on the Flash and Buzzer board, along with instructions in its use. However, a 1938 publication [15] which contains details on numerous pieces of equipment used by Artillery, does not contain any reference to the Flash and Buzzer Switchboard.

So at some point, probably around 1939, it was decided to move away from the use of the procedure for concentration outlined above. The reasons for this are not stated[10], as it would have been simple and cheap to design a replacement for the Flash and Buzzer Switchboard[11]. However, this change approximately coincided with the rise of Wireless in the army and [7] includes a very short appendix on "Use of Wireless" which mentions that wireless can be used in mobile warfare when there is insufficient time to lay lines; unfortunately no detail is given.

There is correspondence in the National Archive which indicates that during the procurement process of the Radio Link, SR Mk I (see 4.2), this equipment was also to be used for Flash Spotting wireless communication. Thereafter, it must be assumed that the successor system, Radio Link, SR Mk II was also used for Flash Spotting. It is clear from [16] that line was the main means of communication from Flash Spotting Observation Posts to the plotting centre, but that a wireless net was used until the lines were ready. The wireless net was then closed down, but tested regularly so that it could be brought back into service if the lines failed.

2.7 Conclusion

Flash spotting was, with hindsight, the most obvious development in artillery location once indirect fire became the norm. It was based on simple scientific principles which made it a particularly accurate tool – once proper instruments were designed and procedures worked out.

Some time after the end of World War 2, Flash Spotting was abandoned, probably for a number of reasons including better flashless propellants, longer ranges, the use of radar and, possibly, the advent of fire and run mobile artillery operations. In 1948 [19], two Flash Spotting or "Observation" troops, each capable of fielding four OPs, were part of the Corps "Observation Regiment", as the Survey Regiment was then known. In a document of 1955 [20], a Flash Spotting troop is noted as part of the Locating Battery of the Corps Locating Regiment, in another change of name. In both cases, the regiment also contained Survey, SR and Radar units.

However, in the Royal Signals Pocket Book of 1954 [21], there is no mention of flash spotting in the Corps Locating Regiment wireless diagram, which may be explained by the following quotation from the "RA Notes" issued in October 1957:

[10] Training pamphlets from 1951 [16], 1954 [17] and 1956 [18] describe the full R/T and line procedure used during Flash Spotting operations and it is clear that R/T procedure was feasible because the OP operators wore headsets in action. Thus any type of line switchboard could be used because the OPs were simply linked at the switchboard when operations commenced and thereafter the lines were used exactly like an R/T net. The simplicity of this approach and the need for only one set of training are probably the answer.

[11] As the US Army had done - see Chapter 7.

> **Firm Policy - Flash Spotting**
> The FS troop is [wartime establishment] in a corps locating regiment, not [peacetime establishment] of the two regiments nor on the TA orbat. Techniques have been kept alive at the School of Artillery by FS instruction (6 weeks) to Long CB Staff Courses. The technique is low priority and will no longer be taught, [wartime establishment] will be amended.

and in a 1964 Artillery Training pamphlet [22], only radar and sound location are mentioned. We must therefore assume that during the late 1950s, Flash Spotting disappeared.

Chapter 3

Sound Ranging

The location of hostile guns from the sound they produce when fired is, in comparison to flash spotting, more complex in both theory and practice. To begin with, consider the sound itself, actually one of three sounds made by a firing gun:

- Gun Sound – the noise made by the expanding hot gas, product of the ignition of the propellant, as it bursts from the barrel immediately behind the shell. Gun sound travels at the speed of sound (337.6 metres per second) and is the sound used in sound ranging.
- Shell Sounds – noises made by the shell as it flies through the air. If the shell is travelling supersonically, there will also be a shell wave or "sonic boom". Because the shell does not travel at a known speed, any attempt to use shell sounds for ranging will fail.
- Shell Burst – the noise made by the exploding shell. Somewhat similar to gun sound, it can confuse the situation. The shell burst may, of course, be used for ranging friendly guns.

Unlike the gun flash, which is light and travels almost instantaneously from gun to observer, gun sound is a pressure wave which travels much more slowly. This is both the most useful feature in that the whole sound ranging operation relies on measurable travel time differences, and the source of a good deal of complication.

3.1 Fundamentals

The boom of the gun sound travels as an expanding spherical pressure wave at a nominal speed of 337.6 metres per second. However, this speed only applies in still air of average humidity at a temperature of 50 degrees Fahrenheit.

For the moment we will assume that the speed of sound is a constant. The momentum achieved by the gases emerging from the barrel is such that the gas bubble will expand past atmospheric pressure and will then "recoil" back through atmospheric pressure and would continue to oscillate for ever, were it not for the fact that the wavefronts produced carry away energy. In practice, it takes only one or two cycles of compression and rarefaction for the oscillations to die away. The result is a highly damped oscillation with a very low fundamental frequency – below 20Hz, down to perhaps 2 or 3Hz. However, the energy contained in the wavefront is very large.

Sound Ranging relies upon measuring the differences between the times of arrival of the gun sound at a number of accurately surveyed microphones (see above). The general arrangement is as in Figure 3.1 which shows four microphones laid out roughly in a line, a sound ranging HQ, where the computation

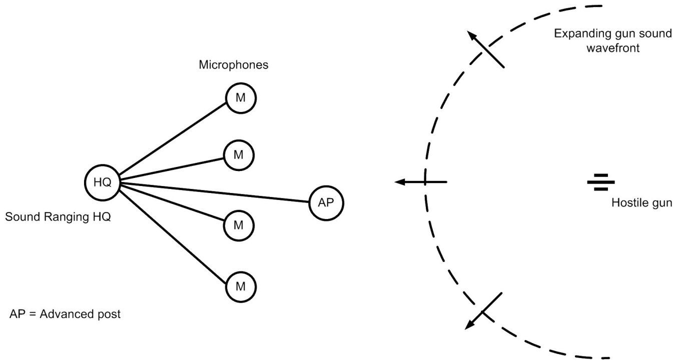


Figure 3.1: General arrangement of SR microphones.

and plotting are done, and an Advanced Post which controls the observation, as will be described later. The line of microphones is known as the "base" and the distances between individual microphones are known as the "sub-bases". If the lengths of each sub-base are the same (in either a straight line or a curve), the base is known as a "regular base". Regular bases were preferred because they made reading the recordings easier.

The following explanation of the principles of SR is based on the information given in the Manual of Sound Ranging (1937) [23] and elsewhere. Those readers who wish to investigate the mathematics in detail should read the Manual or any instructional work dating from before around 1960. After that date, and particularly in more modern times, a different principle will most likely be found. This later arrangement, the three microphone array, can find only bearing, so that more than one microphone group must be used to find range, and hence location[1].

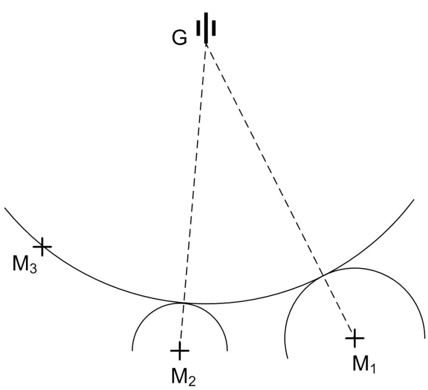


Figure 3.2: Arrival timings

[1]Even this arrangement was tried successfully in the Great War. Three SR groups cooperated to locate the "Courieres Gun", 11 miles behind enemy lines, using bearings only (the distance precluded the production of ranges by SR).

Consider a simple arrangement of just three microphones as shown in Figure 3.2. The sound from the gun G arrives first at microphone M_3, then at M_2 and finally at M_1. If the speed of sound is V, the arrival time at M_3 is T_3 and the arrival time at M_2 is T_2, then M_3 is closer to G than is M_2 by $V(T_2 - T_3)$. Similarly using M_1 and T_1, M_3 is closer to G than M_1 by $V(T_1 - T_3)$. Graphically, as in Figure 3.2, circles showing these differences in distance may be drawn around M_2 and M_1. Now it is clear that G must lie at the centre of the circle which passes through M_3 and touches the two difference circles, as shown.

Unfortunately, drawing the circle centred on G accurately is not so simple in practice. Having drawn the difference circles to scale on tracing paper, it is possible to graphically find the circle centred on G with a set of concentric circles drawn on a sheet of paper, placed under the tracing paper. This method was used experimentally, but may not have been particularly accurate and was certainly quite cumbersome.

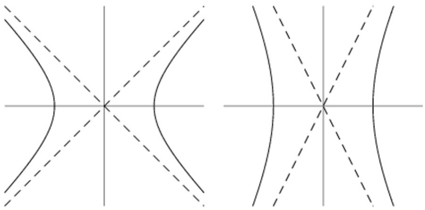


Figure 3.3: Hyperbolas

There were other, more accurate methods, most of which relied on some more complicated geometry. If we consider M_3 and M_2 only, there are an infinite number of circles which pass through M_3 and touch M_2. However, the centres of these circles lie on a hyperbola which is a "*plane curve such that the difference between any point on the curve and two fixed points is a constant*". This complicated statement describes a curve which looks like those in Figure 3.3. The foci of the hyperbola, incidentally, are the positions of the two microphones. The circles defined by M_3 and the difference circle have centres which lie on a different hyperbola and the gun is located at the intersection of the two hyperbolas. In practice, at least three hyperbolas (four microphones) were required to provide an accurate location, mainly because localised atmospheric irregularities would produce small errors.

There were several plotting methods based on hyperbolas, but the one most commonly used in both World Wars involved asymptotes. These are the straight lines to which the hyperbola approaches, but never meets, even if extended indefinitely. They can be regarded as tangents to the curve at infinity and are shown on Figure 3.3 as dashed lines. Since the distance from the microphones to the gun is normally much greater (typically four or five times greater) than the length of the sub-base, the appropriate asymptote can be used as an approximation to the hyperbola for each sub-base. Being straight lines, the asymptotes are much easier to work with than hyperbolas.

The principle behind the production of asymptote scales is outlined in Appendix B. In practice, the angle made by the asymptote to the line of a sub-base is dependent upon the difference in sound arrival time for the microphones at each end of the sub-base. A gridded board was set out with the surveyed positions of the microphones and around the edge of the board, a set of time difference scales, one for each sub-base. A string (normally gut) was pinned

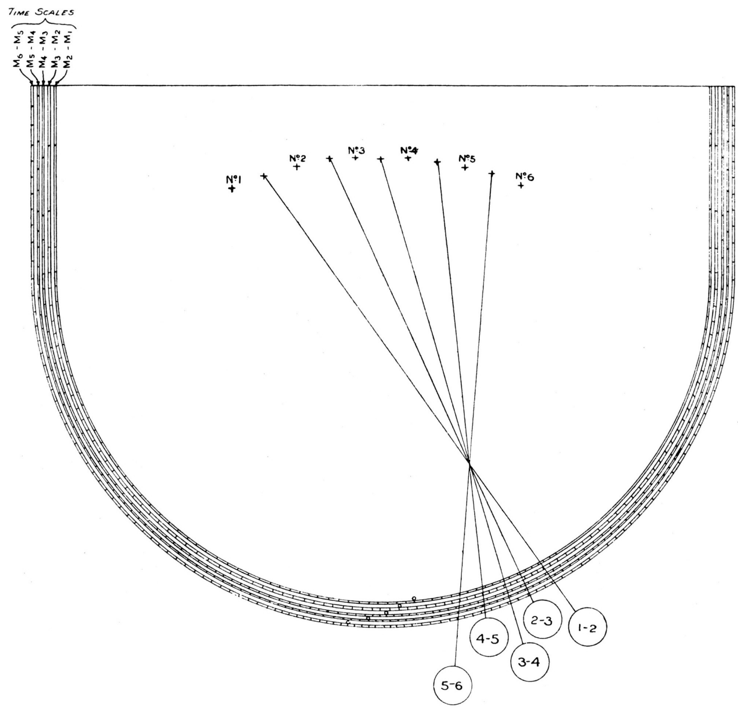


Figure 3.4: Asymptote Plotting Board.

to the centre point of each sub base and a lead weight was attached to the other ends of each string. The strings could then be laid across the appropriate points on the scales and the intersection would give the gun location. A World War 1 example set out for a six microphone, curved, regular base is shown at Figure 3.4.

3.2 Corrections

At this point we must return to the speed of sound and the reasons why it cannot be assumed to be constant. A number of meteorological factors must be taken into account and in Sound Ranging, as in all artillery, regular and accurate met. reports (commonly referred to as "meteor" reports) are essential[2]. Since the measured time differences were inversely proportional to the actual velocity of sound, corrections were converted to, and applied as a percentage of the differences.

[2]The flight of a shell is affected by a large number of factors, from the wear on the barrel's bore to the temperature of the propellant. However, most of the corrections made are based on the meteor report and meteorologists have long been essential to the operation of artillery units. The theoretical basis for meteorological corrections in sound ranging was originally published in early 1918 by Harry Bateman, one of Bragg's colleagues[24]. In modern times, automated met. stations provide continuous meteor data to the gun control systems.

The factors which must be included in the corrections are listed below.

3.2.1 Humidity

The density of the air varies with humidity and a correction to the speed of sound should therefore be made for humidity. However, the correction would be very small and in practice it was customary to take 337.6 metres per second as the velocity in still air at 10°C, rather than 337.16 metres per second, which is the velocity in dry air at that temperature. This assumed that the air has a constant humidity, but errors introduced by this assumption were negligible[3].

3.2.2 Temperature

Sound travels faster in warm air than cold, the speed of sound being proportional to the square root of the absolute temperature. Appendix E provides the theoretical basis for the use of a time difference correction of +0.18% per degree Centigrade above 10° and -0.18% per degree below that temperature. In Fahrenheit, these approximate to ±0.1% per degree above/below 50°F.

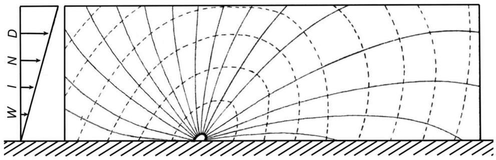


Figure 3.5: Effect of Wind

3.2.3 Wind

Sound, being a pressure wave, can be affected by wind – for example, a uniform wind blowing in the same direction as the sound is travelling from gun to microphone will increase the sound velocity by an amount equal to the speed of the wind. But, of course, such a uniform "following" wind will only act in this way for one microphone - the others will experience a lesser effect. In addition, not only are winds not normally uniform, but they vary with height, resulting in an effect shown in cross section in Figure 3.5 which, as will be readily appreciated, is complex.

In the Great War, the complexity of wind correction calculations was evidently realised and Bragg mentions in [4] that "Wind Sections" were set up to carry out regular measurements of the arrival times of test detonations. Winterbotham in [2] describes the set up of these sections as:

> ... a S.R. Section which has a series of microphone bases established on concentric semi-circles of different radius, such as 5,000, 7,000 and 9,000 yards. By exploding a bomb at a central point the rate at which the sounds spreads from this point can be measured in all directions in which the sound from an enemy gun is likely to travel.

[3]This explanation comes from [23] and it is likely that in 1937, when it was written, no account was taken of operation in very dry (e.g. the Western Desert) or very humid (e.g. Burma) conditions. As yet, no evidence on this has come to light.

Wind Sections were, of course, slow and costly to install, and immobile – they covered about 35 square miles and consumed 48,000 yards of air line cable! However, although they were only in operation for six months, a large amount of data was collected by the Wind Sections and used to construct temperature and wind correction tables. They also established that the effective wind speed and temperature for use in S.R. corrections are those at an altitude of between 250 and 500 feet.

3.2.4 Barometric Pressure

Providing the temperature remains constant, Boyle's law states that the product of the volume of a given mass of gas and its pressure is a constant. The velocity of sound (V) is given by:

$$V = \sqrt{\frac{kP}{d}}$$

where k is a constant, P is the atmospheric pressure and d is the density of the air.

So from Boyle's law, a change in pressure is accompanied by a change in density such that the changes cancel out and thus barometric pressure changes make no difference to the velocity of sound.

3.3 Microphones

Location by sound had been discussed for some time before the outbreak of the Great War and the French army had some experimental sound location groups in the field in 1914. They used large carbon microphones to detect the sounds (it is recorded that the wooden diaphragms, about a third of a metre in diameter, had to be tapped with a mallet every morning to break up aggregations of carbon granules)[6]. Unfortunately, these microphones were insensitive and could not distinguish between the three types of sound generated by the gun, or from local sounds such as rifle fire or even conversation!

Bragg's section was first billeted in a farmhouse at La Clytte which was equipped with the normal French sanitary arrangements, a board seat with a hole, located in an annex. When one sat on the seat, one sealed the only connection with the outside world. There was a six inch gun located about a quarter of a mile behind the farmhouse and when it fired, the shell wave made a highly audible noise as it sped overhead. However, Bragg and his colleagues noticed that after the shell noise passed, anyone sitting in the privy was slightly, but perceptibly, lifted from the seat. This led to the conclusion that this gun sound contained a large amount of energy which could be exploited in location.

Tucker provided the next part of the solution, noticing that the pressure wave caused an icy blast to blow in his face while he was lying on his bunk. This was found to be coming from two holes in the wall (possibly made by mice). Using his earlier work on the cooling of platinum wires and a principle known as the "Helmholtz Resonator" he designed the prototype "Tucker Hot Wire Microphone" (see Appendix C) and constructed it from an empty wooden[4] ammunition box with a wire stretched across a hole in its lid. He used the wire in a bridge circuit, feeding it with a small electrical current, and the Helmholtz

[4]It was fortuitous that he used a wooden box as it was later found that the early metal production model suffered from self-resonances which confused the signals.

principle limited its response to low frequencies, thus eliminating shell sound and extraneous noises local to the microphone. The prototype was successfully tested at Kemmel in 1916.

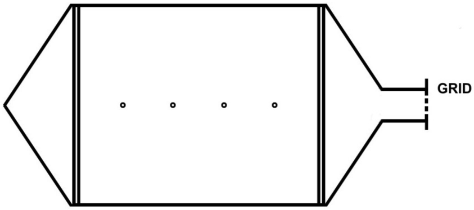


Figure 3.6: The Shape of the Tucker Microphone

The Tucker microphone went into quantity production and all SR units were equipped with them. The final form of the microphone was a tinplate cylinder with conical ends which had a volume of 5.8 gallons (roughly 23 litres). In order to solve the problem of self-resonances, four small holes were drilled in the side of the cylinder as shown in Figure 3.6. One end of the cylinder was closed and the other carried a short, tapped tube into which screwed a holder carrying the hot wire “grid”, a mica disk with a square aperture, across which was mounted a small porcelain rod and about 4.5 cm. of 0.1 mm. diameter platinum wire was looped through holes in the rod.

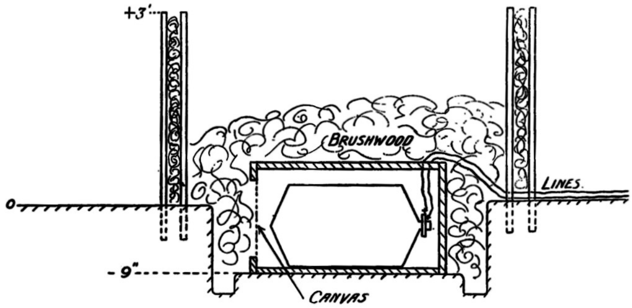


Figure 3.7: Deployment of the Tucker Microphone

The Handbook for the Sound Ranging Instrument[25] describes how the microphone was to be deployed in the field, so as to minimize the pickup of wind noise (see Figure 3.7):

> The microphone is placed in a wooden box, one end of which is made of canvas, the other end being a hinged inspection lid. This box, which is not standardized, having in the past always been made locally by the sound ranging section, is placed with the canvas end towards the enemy’s guns, and the container is placed in it with the grid facing away from the enemy. The box is sunk into the ground to about half its height, and provision is made for drainage. The whole is covered with brushwood, furze or camouflage, and if time permits a 3 ft. hedge of hurdling, brushwood, etc. is placed round

it. If this screening is kept loose, the wind is broken up so that the gusts do not reach the microphone, but the sound is not appreciably deadened.

An interesting sidelight is that because the microphone wire was always warm, the mouth of the microphone became a popular location for insects. For this reason small wire grids – Protectors, Earwig, Mark I – were added to the Vocabulary of Army Ordnance Stores!

Microphone designs evolved over the years (a process which continues to this day) and in the Second World War, it is reported that the microphone was

"... similar in size to a dustbin, but double skinned ... dug in with just the lid protruding, covered with coco matting and [with] earth sprinkled on top" [26].

This description probably referred to what was called the Standard 25 Litre Microphone, which is known to have been in use until 1942. In 1941, the transport allocated to SR units was reduced[27] and it was necessary to reduce the size and weight of all its equipment. Early in 1942, Captain G.G. Scarrott of the Survey Wing of the School of Artillery designed a new hot wire microphone which appears to have remained in use until around 1960, see Figure 3.8.

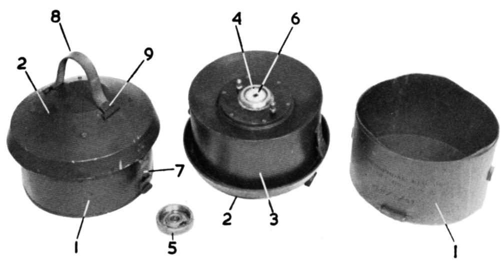


Figure 3.8: Microphone, Linear, SR, Mk.1

The microphone consisted of a container (1), container cover (2), resonator (3) and grid holder (4). The resonator was permanently fixed to the underside of the container cover and was thus held free of the sides and bottom of the container. Centrally, in the base of the resonator, was a circular tray into which a microphone grid (6) fitted, the tray being covered by a cap (5) which, when screwed up, both held the grid in position and completed the electrical circuit. To secure the cover and resonator to the container, two sliding catches (7) were fixed to the sides of the container on opposite sides. A leather carrying handle (8) was held by brackets (9) on the top of the container cover. Because of its construction, the microphone had to be installed in an upright position.

The Scarrott pattern microphone would seem to have been a very successful device and was in use for at least 25 years. This did not mean that other designs were ignored and during the 1950s several patterns of moving coil microphone were investigated. Directions for the Use of Artillery Instruments, Pamphlet 8[28] from 1959 notes that moving coil microphones were not currently available, although at around the same time, the Recorder, Sound Ranging No.5[5], was able to use moving coil microphones. The No.5 Recorder was equipped with channel amplifiers, required to drive the pen recorder, and this may be significant, since moving coil microphones were quoted as one fifth as sensitive as the hot wire type.

[5] See below.

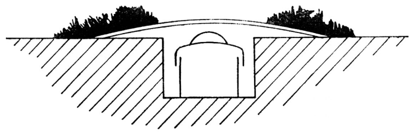


Figure 3.9: Wind Screen SR, No 1 Mark 1

As noted above, one disadvantage of the hot wire microphone was its sensitivity to local noises and, particularly, wind noise. A number of arrangements were used for shielding the microphone from the coco matting to little canvas tents, but the essential feature was that it had to be protected from the direct affects of moving air, which would have tended to desensitise it or add “noise” to the wanted signal. Figure 3.9 shows a microphone dug in and covered by the Wind Screen SR, No 1 Mark 1.

Figure 3.10: The RF Capacitor Microphone

The final evolution of the sound ranging microphone was the RF Capacitor Microphone which was supplied as part of the Sound Ranging Set, Radio Link No 2 (See Section 6.3) and the principles of which are described in Appendix D. A photograph of this microphone is shown in Figure 3.10.

3.4 The S.R. Instrument

Up to now, it has been made clear that sound ranging relies on the differences in time between the appearances of the gun sound at each microphone in the SR base, but there has been no indication of how these differences were measured. The instrument used by the British army in the Great War was designed by Lucien Bull and Charles Nordmann at the Institut Marey in Paris and manufactured there by their mechanic M. Kelsen, although production was later taken up by Cambridge Scientific Instruments. The apparatus had at its heart a six-string harp galvanometer.

The “string”, or “Eindhoven” galvanometer was invented by Willem Eindhoven, professor of physiology at the University of Leiden and was originally used for the display of rapidly occurring transient changes of current, such as produced by the heart muscles[6]. The instrument used a conductive "string" under tension in a magnetic field which, when a current was passed through it, would deflect. Expanding the concept produced the "harp" galvanometer where a number of thin wires under tension (six in SR) were placed in a strong magnetic field. When a current passed through any of the wires, it would deflect and this deflection could be made to interrupt a beam of light.

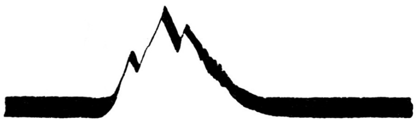


Figure 3.11: A "Break".

In practice, light was focussed through a slot, past the wires of the harp and onto a moving, light sensitive film, which showed a set of six straight lines when no current passed through the wires. If the microphones of the SR base were connected to the wires of the harp, the arrival of a gun sound would be seen on the recording film as a deflection of the image of the harp wire, known as "break" – see Figure 3.11. If the film travelled at a known, constant speed, then there was a direct relationship between length on the film and time. Therefore the time differences could be read as lengths between deflections on the recording film. In addition, the shape of the break could be used to provide other information such as an estimate of calibre.

There are indications that the original experiments used the galvanometer strings connected at the balance point of a bridge containing the microphone (which is essentially a variable resistor) with a balancing resistor and two sources of EMF as shown in Figure 3.12. This is consistent with the frequent use of the Wheatstone Bridge for measurement and the connection of galvanometers in bridges during the early part of the 20th century.

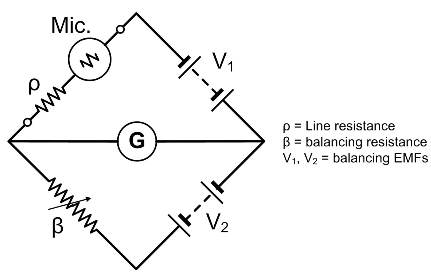


Figure 3.12: Bridge Connected Microphone

It seems that the bridge arrangement was used throughout the first World War but in 1921, perhaps with the use of wireless in mind, a transformer was designed to provide a more stable and easily adjusted connection. The microphone's varying resistance in the presence of gun sound gave rise to an alternating current at the balance point of the bridge, albeit a very low frequency

[6]Eindhoven was awarded a Nobel Prize for his work on the electrocardiogram in 1924.

AC, requiring careful transformer design [29]. Figure 3.13 shows the use of a transformer (part of Recorder, SR No1 Mk II).

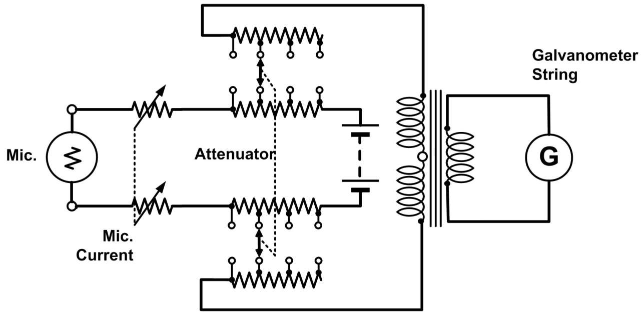


Figure 3.13: Transformer Connection

The current in the microphone (normally set to between 30 and 40mA) was dependent upon the battery voltage and the resistances of one leg of each section of the attenuator, the line current adjustment potentiometer and the combined resistance of the microphone and the line. Current in the primary of the transformer was kept approximately constant by the arrangement of the attenuator sections and the whole circuit was balanced.

Returning to the situation in 1916, clearly some apparatus capable of recording the times of arrival of the gun sound at the microphones and allowing the the timing differences to be measured was needed. As mentioned above, the only suitable kit was that in use by the French and when used with the British hot wire microphone, it was known as the "Bull-Tucker System". A handbook for the instrument in the form used at the end of the War and dated 1921 exists – the Handbook of the Sound Recording Instrument[25], but includes no photographs.

It has been found impossible to obtain detailed information on the early version of the instrument but it is known that in its original form, it used 35mm cine film as the recording medium, onto which was projected the lit image of the six galvanometer strings, six dark dots on a white background which became lines as the film moved along. An electromagnetically maintained tuning fork supplied pulses to drive a synchronous motor at a constant speed, rotating a wheel carrying ten "spokes" which were arranged to interrupt the illumination of the galvanometer strings. This produced bars across the record at fixed intervals (of one hundredth of a second, with a wider bar every tenth of a second) which permitted the timing differences to be read. A real example which comes from the Bayliss Archive[30][7] is shown at Figure 3.14. The age of the document has reduced the contrast between the dark and light areas, but it should be possible to make out the six microphone traces with the breaks and the tenth second marker bars. Less easy to see are the hundredth of a second marker bars. Note also that there are "ticks" every half second – these are a

[7]The Bayliss Archive is a set of documents belonging to Lieutenant Carol William Bayliss of the 1/7 Welsh Regiment, collected during his service with a S.R. unit from 1917. The archive consists of a set of hand written training notes, a number of aerial and panoramic photographs of the Western Front and some original S.R. recordings, annotated with information on the guns observed, etc. As far as is known, these are the only extant examples of contemporary S.R. recordings. The archive is published on the web site of the Wireless-Set-No19 Group at http://www.royalsignals.org.uk/articles/SRS/bayliss.html

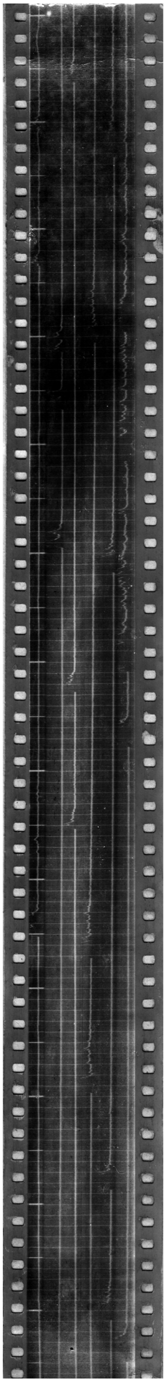


Figure 3.14: A Great War S.R. Recording from 21^{st} September 1918

feature of the later instrument and it is not known if they were provided by the original Bull-Tucker system. Incidentally, the recording shows the sounds from a 105 mm howitzer shelling Hill 201 on 21^{st} September 1918 at 0828. Incidentally, the temperature was 74° and the wind was 6 mph at 356° when the recording was made!

It is unfortunate that the Handbook[25] contains no photographs of the instrument and the author has been searching for photographs for several years. A small number of pictures purporting to be of the French system have come to light, but careful examination casts doubt on their authenticity. For example, the early French system is known to have used 35 mm cine film, which was found to be impossible to develop automatically. One of the first modifications was therefore to use photo-sensitive negative paper strip[8] of the same size and punching as cine film which could be developed automatically. Some early instruments would therefore have had a feed taking the film through a light tight slot into the dark room area. Those fitted with the auto-developing camera would feature a long rectangular box out of which the developed and fixed tape appeared. None of the pictures found to date match either of these configurations completely so they have not been included in this book.

3.5 Recorder, Sound Ranging, No 1

A great deal more is known about the instruments used in the Second World War. Right through that War and beyond, the recording equipment was the Recorder, SR No 1 [31]. The Mark I version of this device was developed in the early 1930s and the Mark II appeared in 1940, in turn being replaced by the Mark III later in the war.

The Recorder, SR No 1 was a complicated device which clearly shows its roots in the early Sound Recording Instrument. It contains the following elements:

- Transformer unit. This contained six interface circuits for connection to the microphones.
- Galvanometer. Six-string Eindhoven type using 20μ copper wires mounted on springs for easy replacement and with gaps between the strings of just 0.67mm. A permanent magnet produced a field at ten degrees to the plane of the strings and the optical axis so that a deflection of more than 0.67mm would not cause a string to touch its neighbours.
- A timing motor driven by a tuning fork and amplifier. The motor produced marks on the recording at precise intervals which could be related to distance via the corrected velocity of sound, allowing measurement of time differences between breaks to be accurately performed.
- Optical path. A lantern provided the illumination which allowed the movement of the harp strings to be projected on to light sensitive film in a camera. The optical path was complex, since it provided magnification of the harp and the addition of the timing marks.
- Automatic developer. The "film" used appears to have been fairly standard bromide photographic paper in a roll which, after exposure in the camera, passed to a one pint developing bath containing a solution of Metol, Sodium Sulphite and Caustic Potash. From the developer, the film passed to a fixing bath containing six pints of a solution of Hypo and Metabisulphite. There was even an electrically operated knife to cut the film!

[8] The Bayliss recordings are of this type.

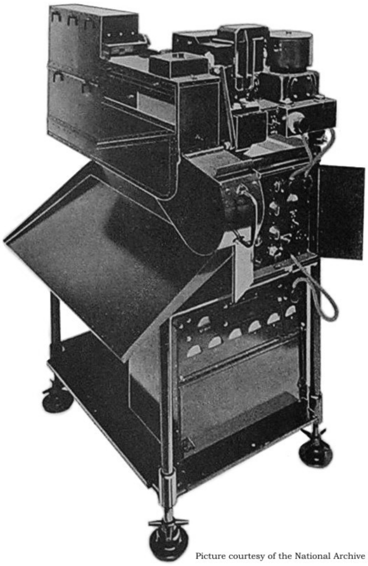


Figure 3.15: Recorder, SR, No 1 Mark II

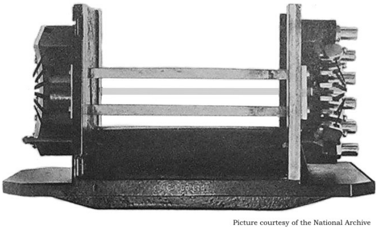


Figure 3.16: Galvanometer Harp Unit

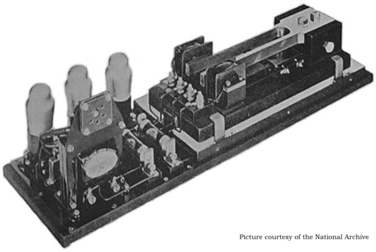


Figure 3.17: Tuning Fork and Amplifier

Figure 3.18: Recorder, Sound Ranging, No 2

3.6 Recorder, Sound Ranging, No 2

In 1944, the Recorder, Sound Ranging No 2 was introduced and this simplified the process considerably because it used a pen recorder and a plain paper roll. See Figure 3.18 for a regrettably poor quality picture of the No 2 Recorder which comes from the the instructional pamphlet[9] of 1947 [32]. A pen recorder is, of course, much less sensitive than a string galvanometer and whereas the No 1 recorder used line current directly, the No 2 had to use amplification to produce readable deflection. There is some indication that a six pen device was tried but proved insufficiently sensitive and the No 2 recorder was a four pen system. However, it is clear that the No 2 Recorder as introduced into service was not designed as a replacement for the No 1 Recorder, but had a different role. According to a training pamphlet of 1948 [19], SR Troops were equipped with one Recorder, SR No 1 and two Recorders, SR No 2, the former used for long base operations (up to six microphones) and the latter for short base (four microphones) location of mortars and guns at shorter ranges. This is confirmed by Whetton and Ogden in [8].

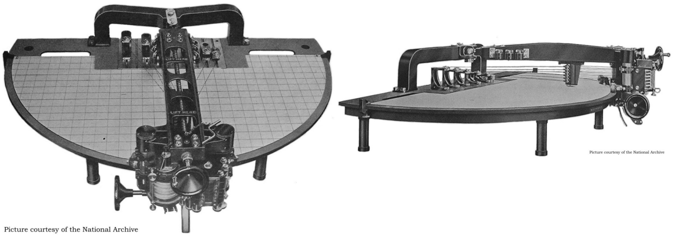
The No 2 Recorder remained in use through the 1950s, although it had been replaced in 1954 by the Equipment, Recorder, Sound Ranging (Long and Short Base), No 5 (see section 6.2 below). This is known because in 1955, the line termination unit was replaced by the Test Unit, Lines, Mk I which was part of the No 5 Recorder and a Data Summary EMER[33] for the unit was issued.

3.7 Plotter and Comparator

It was assumed in Section 3.1 above that gun locations based on the differences between arrival of the gun sounds were found by plotting and this does seem to have been generally true. However, in the early 1930s an instrument was devised to do the calculations automatically, the Plotter, Sound Ranging[34]. This device (see Figure 3.19) was a highly complex precision mechanical instrument which could be used with any sort of microphone base, regular or irregular, provided that the ratio of location range to base length was no more than 3:2.

Before the arrival of the digital computer, various other mechanical devices have been issued for performing tasks associated with location by sound, the most well known of which was used in the ranging of friendly guns. This was the SR "Comparator" [28] which made a semi-automatic comparison between hostile battery position as found by SR and the positions where shells fired at the

[9] Directions for the Use of Artillery Instruments No 12. This is one of a very long series of pamphlets which describe the operation of the instruments.



(a) Front View (b) Left Side View

Figure 3.19: Plotter, Sound Ranging, Mk I

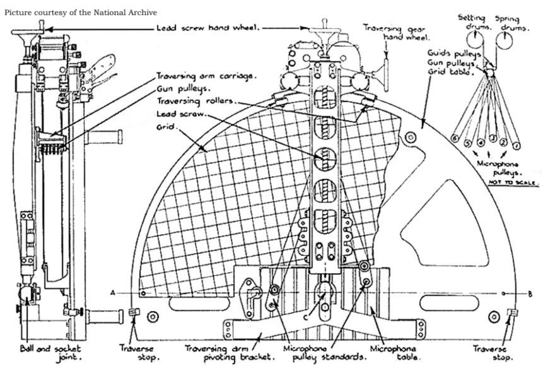


Figure 3.20: Mechanical layout of Plotter

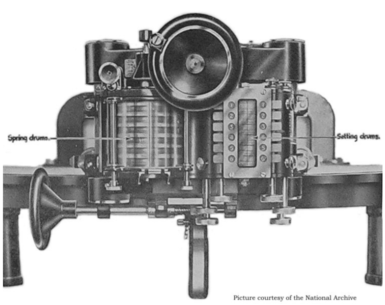


Figure 3.21: Plotter Settings

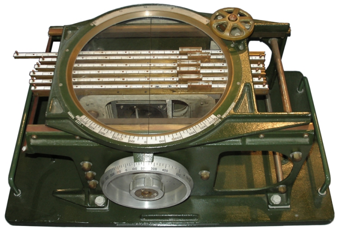


Figure 3.22: SR Comparator Mark IV

battery burst. Clearly the objective was to bring the shell bursts onto the hostile battery position. An excellent example of the Comparator, Sound Ranging Mark 4 is currently on display at the Firepower Museum (see Figure 3.22).

3.8 Deployment

Establishing a sound ranging unit in the field involved laying out the line of four to six microphones normally about three to five kilometres behind the front line. In most cases, the base would be sited behind friendly artillery, thus halving the interference they produced, since the microphones could not pick up their shell waves, only their gun sounds. As mentioned above, there are advantages to using a regular base, but many other layouts are possible and in any case, the topography may preclude a regular base. In general, the longer the base, the greater the location range, but there are complications. Thus, a 3km straight base had a range of 12km with an area of location which can be described as a segment of a circle of 12km radius, centred on the middle of the base[10]. With an 8km straight base, the range is 15km directly in front of the base, but the shape is different, as shown in Figure 3.23.

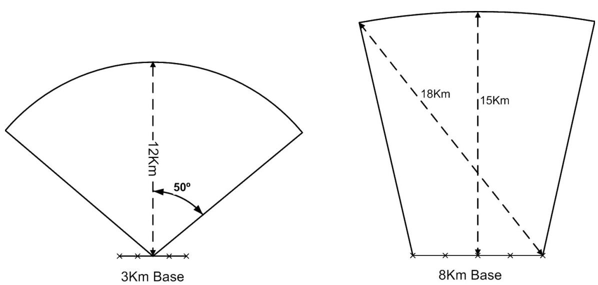


Figure 3.23: The effect of base length

Regular, straight or curved bases were not always possible, as mentioned above, and many arrangements were used to suit the terrain and the tactical situation. Curved bases produced greater accuracy forwards, at the expense of flank performance, and it was possible to use a cross shaped base where flank location was required.

[10] The ranges quoted here are from World War 2 and are much greater than was achieved in the Great War.

The Advanced Post (AP) played a vital role in sound ranging, controlling the whole operation. At least one AP was manned round the clock and when an enemy battery fired, the AP heard its gun sound and started the recorder at the SR headquarters. It was necessary for the AP to be sufficiently far in front of the microphone base to hear the gun sound a few seconds before it reached the base, so that the recorder could be started in time to give a clear record of the breaks from each microphone.

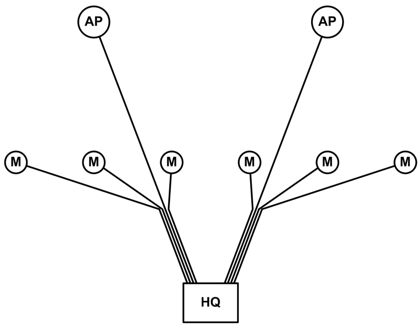
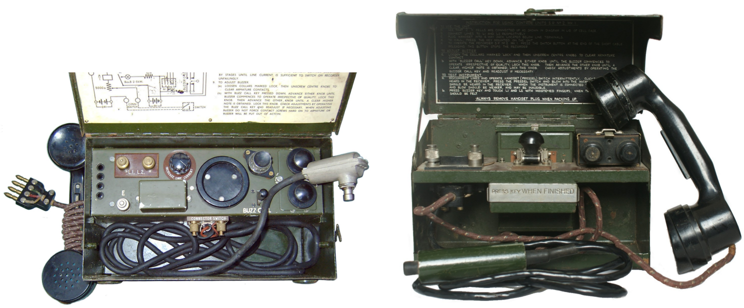


Figure 3.24: Possible line connection arrangement

From the inception of SR, line communication was used to connect microphones and APs to the SR headquarters. Wireless connection became possible once radio telephony developed, but by far the most common means of connection remained line. So with microphone bases of five kilometres or more and APs perhaps five kilometres in front of the base, a considerable amount of field cable had to be laid. An important additional requirement for the line connections was that they had to be "two wire" lines for technical reasons and the use of single wire, earth return circuits was impossible.



(a) Control Unit, SR MK.II (b) Control Unit, SR No.2 Mk.I

Figure 3.25: SR Control Units

3.9 Control Unit, SR

There is no information to hand as to what AP equipment was used in the first World War and it is not even certain that early APs were able to start the recorder. Possibly they simply reported the sound to HQ by telephone.

The Control Unit, SR MK 2[11], which probably entered service between the Wars, is essentially a modified buzzer telephone, similar in size and construction to the Telephone Type D, Mk V, and appears to have several components, such as the handset and the buzzer, in common with that unit. It was not however, a modified Tele D Mk V. Reference to the circuit (see Appendix F) shows that it uses "phantom" signalling to operate the relay in the Recorder at SR Headquarters, while operating normally as a telephone (which the Flash Spotting telephones could not do). Current to operate the Recorder relay is derived from a 24v. battery via the switch plus a variable line current resistor and applied between earth and both legs of the line. A centre tapped bridging inductance removes AC (speech and buzz) from the Recorder switching circuit and a 0.5μF capacitor blocks the switching voltage from the telephone.

It is not clear when the Mk.2 Control Unit left service and it may indeed have remained in use until the late 1960s when the SR Radio Link No 2 (see below) appeared. However, around 1944 when the Recorder, SR No 2 appeared, a different, simpler unit, the Control Unit, SR No 2[12] went into service. Unlike the Mk 2 Control Unit, this was a modified Telephone Set, D Mk V and was intended to be used with the Recorder, SR No 2 which had no phantom switching facility. Control of the recorder was effected by a switch which shorted the two line terminals. Thus the No 2 Control Unit had the advantages that the control switching supply was with the recorder and it could be used on a single wire, earth return circuit, but the disadvantage that it could not be used for speech while the control switch was operated.

A fitting conclusion to this section is Figure 3.26, the wonderful caricature of D Troop Headquarters, 7th Survey Regiment, RA in action by Gordon Brown. Gordon was officially a film reader and the unit's photographer, but his artistic talents are clear from this work, one of a series which can be seen at the regiment's web site.

[11] Also known as the AP Control Unit No 1.
[12] Also known as the AP Control Unit No.2.

Figure 3.26: SR Troop HQ in action - by Gordon Brown

Chapter 4

The Use of Wireless

As has been mentioned above, Flash Spotting and Sound Ranging historically used line communications and of course, when they were being developed, the available wireless technology was insufficiently advanced to permit its use in either location technique[1]. As it turned out, wireless experiments were first carried out in SR, and FS was left to follow on later, using the same equipment as was provided for SR. There is no clear evidence indicating why SR should have been the first in this field, but it may be that the FS technology was so well developed by the end of the Great War that there was thought to be no need to experiment with wireless.

Returning to the First World War, because of the relatively static nature of war on the Western Front, SR bases had no need to move at short notice and therefore the time taken to lay the lines was not a problem. As we know, at the end of that war, the mobile conditions which had been expected at the beginning did return. By the end of the war also, CW wireless was commonly in use and radio telephony, although in its infancy, was clearly going to be important in military communications. A wireless connection could be set up in little more than the time it took to drive to the desired location and it must have been clear that if the principle could be applied to SR, the set up time (a minimum of six to twelve hours) could be avoided.

4.1 Early Attempts

In 1922, experiments into the use of wireless instead of line to connect the microphones to the recorder were carried out by the Signals Experimental Establishment (SEE) [35]. A five microphone base of 15,000 yards (13.72km) was set up with a recorder some 10,000 yards (9.1km) from them, and used to attempt the location of large calibre guns at ranges of 30,000 to 40,000 yards (27.43 to 36.58km). A Major Fuller, RE – undoubtedly the officer who invented the Fullerphone – had designed a 'Turner' trigger circuit operated by the Tucker hot wire microphone and arranged to transmit a dash on a frequency of 1300m. The string galvanometer at the recording station responded with a similar dash.

The report states that this arrangement proved unsuitable because of the loss of information conveyed by the normal break and that a close approximation to the actual sound must be transmitted. However, a transformer capable of dealing with the very low frequency components of gun sound had

[1] For the first half of the Great War, wireless communication used spark transmitters with hand-sent Morse. Continuous Wave transmitters were gradually introduced, again with Morse, and telephony did not appear until the end of the war.

been designed[29], as mentioned above, and this could be used to modulate the transmitter.

Over subsequent years, developments clearly occurred and it seems that a 195 metre radio link was used in the late 1920s, but unfortunately no further information on the system is currently available. In 1931, another SEE report[36] documents a proposed new link to replace the 195m system, evidently because that wavelength had been allocated to other services (probably broadcasting). The range requirement for the new link was 4,500 yards (4.1km).

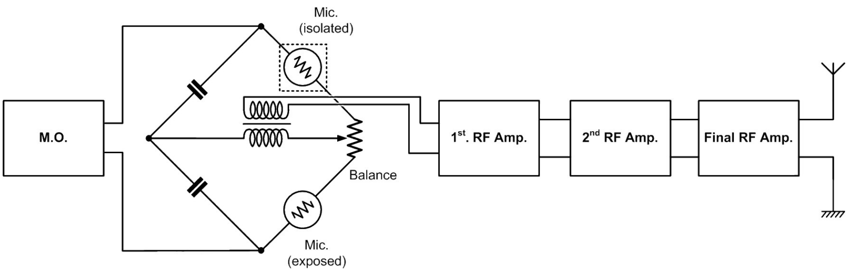


Figure 4.1: SR Link Transmitter for 1931 Trials

The equipment used is described in some detail in the report:

Wavelength 650–2000m (460–150Khz)

Microphones The standard Tucker microphones were used, but at each microphone position there were in fact two microphones, one exposed to gun sounds and the other isolated from noise. This appears to have been done to achieve balance in the bridge modulator used in the transmitter.

Transmitter (See Figure 4.1). Hartley M.O. driving a bridge amplitude modulator. This fed three RF amplifier stages; a pair of S625 tetrodes in push-pull then a single AT26 triode and finally a pair of AT50 triodes in parallel.

Receiver 2-stage T.R.F. with controlled regenerative detector and a step down transformer driving the galvanometer string.

The trials of 11th February were successful, giving ranges of more than 6,000 yards (5.5Km) and the report notes that the now Colonel Fuller was in attendance. Various recommendations were made in the report:

- R/T communication is required between AP, microphones and recording station. It would appear that the AP had to call the shot, instructing the microphone stations to switch to transmit and the HQ to start the recorder. It was noted that one possibility was that a modification to the microphone transmitter might work, but could possibly need a separate R/T receiver.
- A more selective receiver was needed and a superhet with "simple controls" was recommended.
- The sender should be boxed with the microphone and its resonator (this recommendation does not appear to have been adopted).

The next development took place around 1937 when the Air Defence Experimental Establishment[2] produced a system operating in the frequency range

[2]Between the wars, SR seems to have been treated as an inter-service matter. The Admiralty in particular had a stake in SR, generally at sea, and many documents exist on the subject of ranging by sound above and below the surface. Although the Signals Experimental Establishment had a major role, as might be expected, the ADEE were also

1.5 – 2 Mhz [37] also known as “Radio Link, Long Base”, for which no detailed information is currently available. It is not known if this equipment went into service and there is no evidence in the available correspondence [38] that any wireless equipment was on general issue before the Radio Link, SR Mk I (see below). However, it is known from [3] that

> “...sound ranging equipment that was remarkably ponderous, cumbersome and troublesome ... was abandoned on the continent at the Dunkirk evacuation...”

Most likely however, this refers to large microphones and complex line-connected recording equipment.

4.2 Radio Link, SR Mk I

In 1938, following a suggestion from S.E.E. that a higher frequency might be more suitable for SR radio links, trials were carried out using a modified Wireless Set No 11, the standard vehicular HF set at that time and, indeed, during the first half of the second World War. The tests were successful, and a decision to proceed was made on 11th November 1938, with an initial contract placed with E.K.Cole in May 1939. One set consisting of eight senders and one multi-channel receiver was delivered in October 1939. This system was further developed up to early 1940 and a production design was tested at Larkhill, culminating in a successful demonstration in February at Foulness. The Radio Link, Sound Ranging Mk I entered production later that year[3].

Refer to Figure 4.1 which shows the deployment of a five microphone base using the Mk I link. Each location (AP(s), Microphones and HQ) was equipped with a Wireless Set No 11SR, a WS11 modified to cover the frequency range 5 – 8.5Mhz (the standard WS11 covers 4.2 – 7.5Mhz) for normal R/T operation. The WS11SR could also be coupled to a Sender SR, No 1, for use at the microphone sites. The Sender SR, No 1 was very similar in appearance to the WS11 and used many of the same components. However, it was a transmitter only, with a special DC modulator to reduce timing instability and distortion of the low frequency gun sounds, and it covered the 7.5 – 8.5Mhz range allocated for SR. A line drawing of the WS11SR/Sender SR, No 1 is shown at Figure 4.3.

The remaining element in the Radio Link, SR Mk I was the multi-channel receiver known as the R105 (see the photograph and line drawing at Figure 4.4). This device contained an aerial pre-amplifier or ‘buffer’ which distributed the incoming signal from the aerial to five identical receivers covering the 7.5 – 8.5Mhz range of the Senders SR, No 1. Each receiver could drive either headphones via a transformer or one input of the Recorder, SR.

The transformer unit attenuators in the Recorder SR described above each had an additional direct connection position (not shown in Figure 3.13) marked “Radio” for connection to the recorder output of a receiver unit. Because this was provided at each attenuator, a combination of line and radio link could be used; particularly useful when a base was being initially set up and not all lines had been laid, or when a line was put out of service by enemy fire.

In operation, the WS11SR net was set up to give communication between all locations and then each channel of the R105 was netted to its microphone

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involved in ranging by sound (the Dungeness sound mirrors, made redundant by RDF (radar), are a testament to the importance of sound ranging in air defence). Remember also that the one remaining WW1 SR officer had joined ADEE.

[3]The correspondence covering the procurement still exists in the National Archive [38]. Further detailed information may be found in Wireless for the Warrior Volumes 1 and 3 by Louis Meulstee [39], to whom the author is indebted for information on the Radio Link, SR Mk II and permission to reproduce the figures in this section.

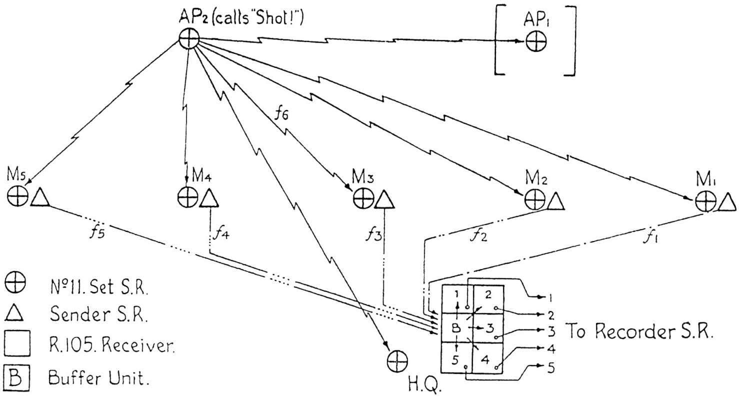


Figure 4.2: SR base deployed using the Radio Link, SR Mk I

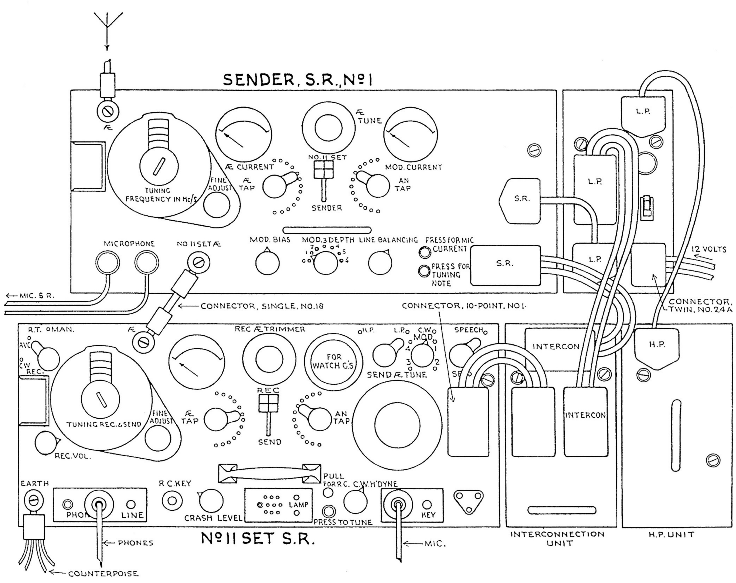


Figure 4.3: WS11SR with Sender SR, No 1

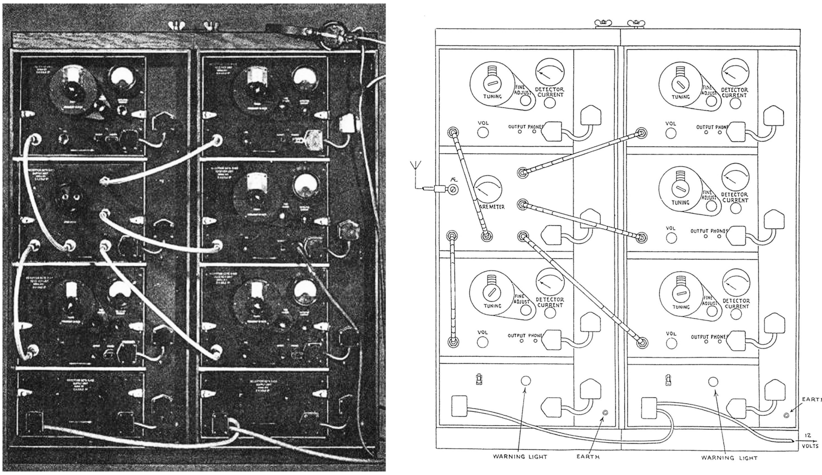


Figure 4.4: Receiver SR, R105

sender. At this point, the switches on all the Senders SR, No 1 were set to "No 11 Set". When an enemy gun was heard by the AP, he would call "Shot" on the R/T net, all the microphone site operators would switch to "Sender", powering the sender, and the HQ operator would start the recorder. After an agreed interval, the recorder would be switched off and the Senders SR, No 1 returned to "No 11 Set".

4.3 Radio Link, SR Mk II

In 1943, a new set of radio link equipment, the Radio Link, SR Mk II was introduced and issued to SR units in time for the Normandy invasion[8]. In many respects this equipment, which was manufactured by Pye, was a great improvement over the Mk I. The size, weight and battery drain were all reduced considerably as only one unit plus power supply was needed at each site.

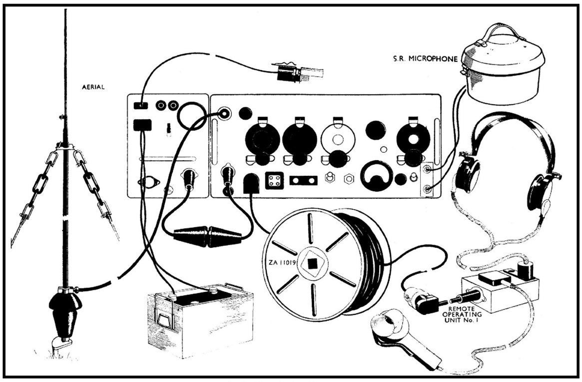
There were two types of set, the Wireless Set SR OS (the microphone site or "outstation" set) and Wireless Set SR HQ (the recording site set) – see Figure 4.5. A striking similarity to the Wireless Set 22 will be noticed and it appears that both sets are built into a WS22 case, with many components being common with the WS18, WS19 and WS22. However, the electronic design is novel.

Each set had a tunable master oscillator covering the 9 – 10.5Mhz frequency range and they could be netted together with the HQ set on R/T in the normal way. However, the OS sets could be switched between five channels, differing from the nominal frequency by -20Khz, -10Khz, 0, +10Khz and +20Khz for the transmission of gun sounds from the SR microphone when the "SR" button was pressed. The HQ set contained five separate IF and detector units, tuned to the five channel offsets of the OS sets. Note that the offsets were not operator variable, all that was necessary was for the R/T netting (on the nominal, centre frequency) to be carried out. Further detail may be found in Colin Guy's excellent article, originally published by VMARS, but available on the internet [40].

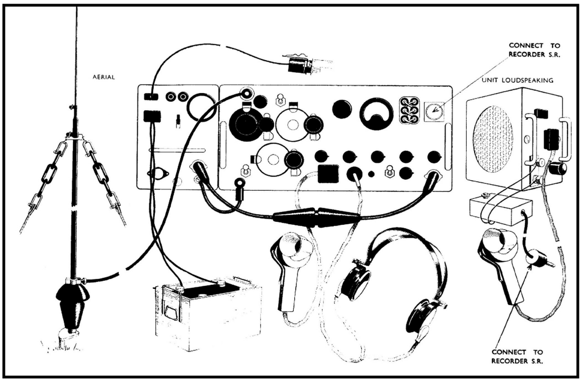
(a) Outstation

(b) H.Q.

Figure 4.5: Radio Link, SR Mk II



(a) Outstation



(b) HQ Station

Figure 4.6: Station layouts

Deployment of the Radio Link, SR Mk II (see Figure 4.6) was very similar to that of the Mk I version in that up to five microphone sites could be set up and equipped with OS sets, as were one or two APs. In this case, of course, normal R/T intercommunication and gun sound transmission were combined into one set. The HQ set was connected to the Recorder, SR via a multicore cable and connector.

The Mk II link was in use up to the early 1950s, and until recently it appeared likely that is was also used in the Korean War. However, an article in the Journal of the Royal Artillery[41] has recently come to light which makes it clear that this was not so. It seems that the 15th Locating Battery, RA was ordered to Korea from Hong Kong at the end of 1952, becoming fully operational on 9th January 1953. They were originally equipped with the WS62 for use at APs but these HF sets were found to have excessive range and were replaced by the WS31, which performed satisfactorily for the remainder of the campaign, other than frequent whip aerial replacement due to shrapnel damage! It is clear from this article that microphones were only line connected and there was no alternative wireless system.

It remains to be proved how successful the Radio Link, SR Mk II was in operational use and there are indications that there was a period from the early 1950s when no SR radio link was available.

Chapter 5

Location in the U.S. Army

Much has been written on the events which led up to the declaration of war on the German Empire by the United States Congress on 6th April 1917 and it is not proposed to rehearse the issues again here. The significant factor for the purposes of this book are that the US Army was essentially unprepared to wage the "war to end wars" as President Woodrow Wilson put it at the time. In early 1917, the strength of the US Army was some 160,000 and it is a testament to the energy and focus of the American people that by the end of the war some 2 million men had volunteered and 2.8 million had been drafted, with 10,000 fresh troops being sent to Europe *per day* by summer 1918!

By mid-June 1917 General John Pershing had been placed in command of the American Expeditionary Force and led an advance party to France. There was debate about how the AEF should be deployed, with Britain and France arguing that:

1. The US Army should be used as reinforcements for active units.
2. Scarce shipping resources should not be used for ferrying US supplies across the Atlantic.

Gen. Pershing was adamant that the AEF should not be broken up[1] and he carried the day on that point. However, it was agreed that the use of shipping for supply of materiel should be limited and the net result of this was that specialised units used existing French and British equipment, particularly of course, where no US equivalent existed.

One area in which the US Army may be said to have been deficient in 1917 was Artillery Location but Gen. Pershing despatched Engineer members of his team to study the methods and equipment in use which, as we have seen were the systems developed by Hemming, Bull, Bragg, Tucker and others. A fascinating article from the July to September issue of the Field Artillery Journal by an unknown author[42] lays down a framework for an "Artillery Information Service" to be charged with identifying targets for US artillery under the prevailing conditions of indirect fire from well camouflaged sites, of which they had little experience.

Following investigations, which recommended the use of the existing British and French equipment, the US staff were able to establish a Flash and Sound Ranging school at Fort de St. Menge near Langres by the first week of January 1918. For eight months, up to the cessation of hostilities on 11th November 1918, the US Army had four Flash and four Sound Ranging Sections successfully operating in the field. For a comprehensive review of the work of the US Flash

[1] There were, however, some exceptions made – for example, the use of the "Harlem Hellfighters" with the French 16th Division.

and Sound Rangers, see Hinman's excellent book[43] which is available on the internet.

5.1 Between the Wars

It seems that, as in Britain, Artillery Location languished somewhat in the US Army once the Great War ended, mainly from the effects of financial constraints imposed by Congress and, it may be supposed, a reluctance to do anything other than breathe a sigh of relief that the war to end wars had been successfully ended. The doctrines for the employment of observation units did not change significantly from the British/French pattern and a good summary is available in an article in the Field Artillery Journal by Maj. H Crampton Jones from 1929[44].

5.2 Sound Ranging Set, GR-3

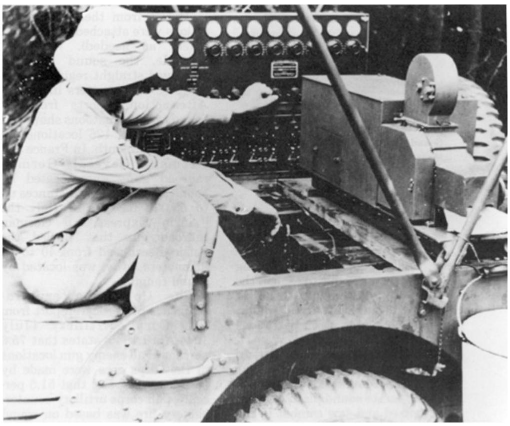


Figure 5.1: A GR-3-C Truck Installation

Also developed in the inter-war period was the American sound ranging system, the Sound Ranging Set, GR-3[45] which operated on somewhat similar principles to the British SR Recorder No 1, having the following components:

- Six condenser microphones (T-21) with shelters, although up to eight could be used. The microphones were designed to be dug into the ground and protected by the shelter and hanging from it. (The arrangement was similar to that shown for the GR-8 in Figure 5.16 below).
- An eight-channel galvanometer of different design to the harp type. In this case all eight "strings" (known by the Americans as Oscillograph Units) were separately mounted within the galvanometer's magnetic field.
- A complex optical path with timing components and automatic developer system. This unit was known as the Oscillograph Equipment IE-14.
- A control and testing board for the microphone circuits (BD-85).
- Equipment for two Outposts (the British APs) which consisted of an Outpost Unit BE-51 used with the standard EE-8 field telephone. The function of the BE-51, like its British equivalent, was to start the recording equipment when the gun sound was heard.

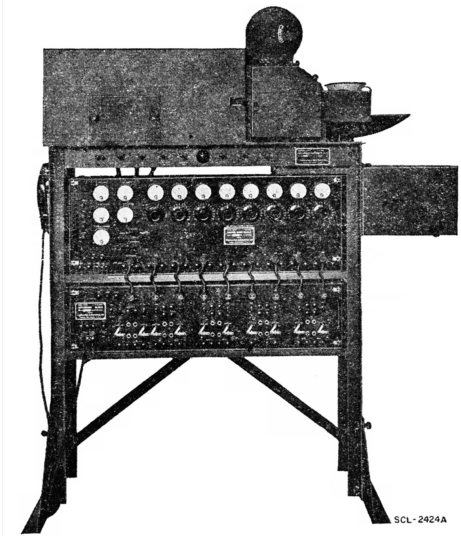


Figure 5.2: GR-3-C Sound Ranging Set

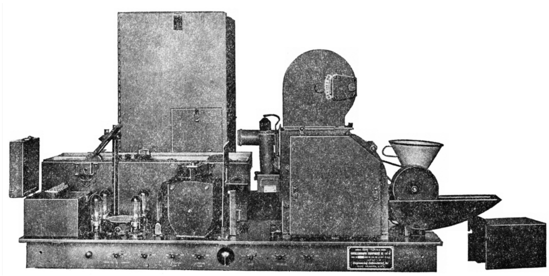


Figure 5.3: GR-3-C Oscillograph Equipment

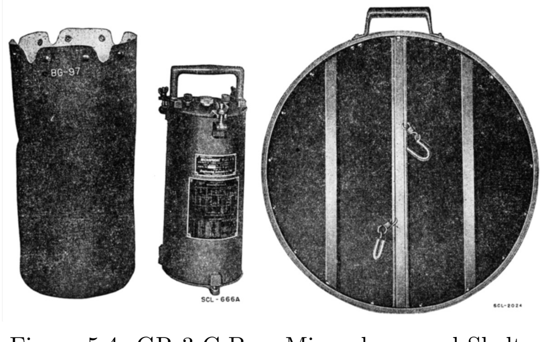
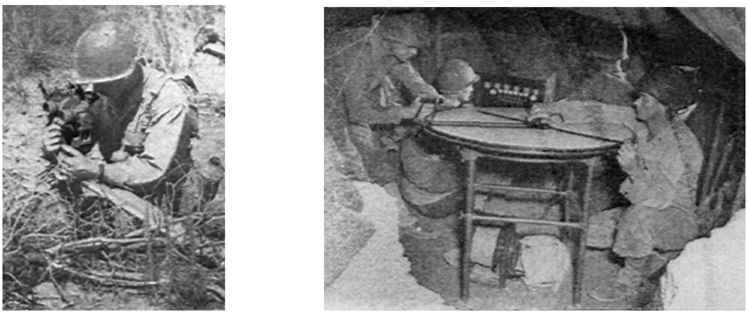


Figure 5.4: GR-3-C Bag, Microphone and Shelter

- A switchboard BD-62 was provided for intercommunication and a wide variety of patching operations between telephone, microphone and outpost lines.

Figure 5.2 shows the complete system with the Oscillograph Equipment at the top, then the BD-85 control board and the the BD-62 switchboard at the bottom. Figure 5.3 shows a view of the Oscillograph Equipments and Figure 5.4 shows the microphone kit.

5.3 Flash Ranging Set, GR-4



(a) M-2 Instrument (b) Flash Ranging Central

Figure 5.5: World War 2 Flash Ranging

The instrument used for Flash Ranging appears to have been developed at this time and is known to have remained in service for many decades. Reference to the rather poor illustration from the Second World War, Figure 5.5(a), will show that it bears a remarkable resemblance to the British Instrument, Flash Spotting described above. There are clear differences however, and it must be assumed that the M-2 is of American design and manufacture, whilst being based on similar principles to the British instrument. Figure 5.5(b) (again of low quality), shows a Flash Ranging "Central"[2] and includes an M-5 Plotter Board in the centre, with a BD-70 partially visible behind it.

Figure 5.6: The BD-70 Switchboard

[2] Command Post.

The BD-70 was the core component of the Flash Ranging Set, GR-4 which remained in use until the early 1950s, when it was replaced by a different switchboard, the AN/GTC-1. Little is known about the BD-70 and the only available picture, Figure 5.6, is again of low quality. However, it is known that the GTC-1 switchboard (discussed in detail in Chapter 7 below) performed a similar function to the British Flash and Buzzer Switchboard in that indicator lights, operated by OP switches, were used to ensure that all OPs were observing the same flash.

5.4 Sound Locating Set, GR-6

At the beginning of 1945, a new type of locating device was issued to the US Army. It could logically be said that this system, the GR-6 Sound Locating Set[46], has no place in an article on artillery location because its purpose was the location of small arms firing positions. However, the method used was completely different from that used in all previous systems and embodies a concept which is the basis of current artillery location systems and is therefore worth considering in some detail. See Appendix G for a discussion of the theory of this system, the 3-microphone array.

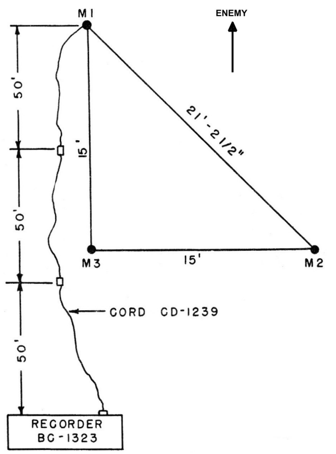


Figure 5.7: Layout of GR-6 Locating Unit

In the case of small arms fire, there is no shell wave and burst, simply the blast wave from the muzzle of the weapon, which travels at the speed of sound towards the observer. This gun sound, unlike that from an artillery piece, is composed of relatively high frequency components and so no special microphones are required. However, this nullifies any ability to discriminate between gun sounds and locally interfering sounds (traffic, conversation, etc.) on the basis of their frequencies.

In operation, the system consisted of two sets of three matched locating microphones, laid out as right isosceles triangles with sides of 15′, 15′ and 21′ 21.5″. Each microphone set was connected to a Recorder unit via a cable of up to 150′ in length and the recorder allowed the relative times of arrival at the microphones to be measured. Note that microphone number 3 (M3) was the reference and was located at the right angle apex of the triangle, with M2

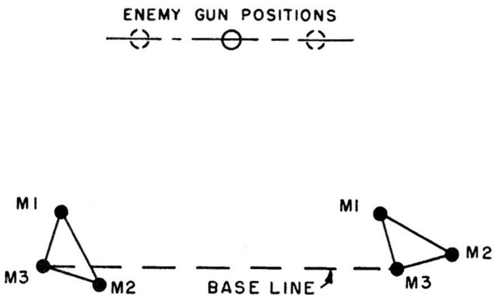


Figure 5.8: Layout of Full GR-6 System

facing the enemy. The arrangement of a locating unit is shown in Figure 5.7 and the general layout of the complete system with two locating units is shown in Figure 5.8.

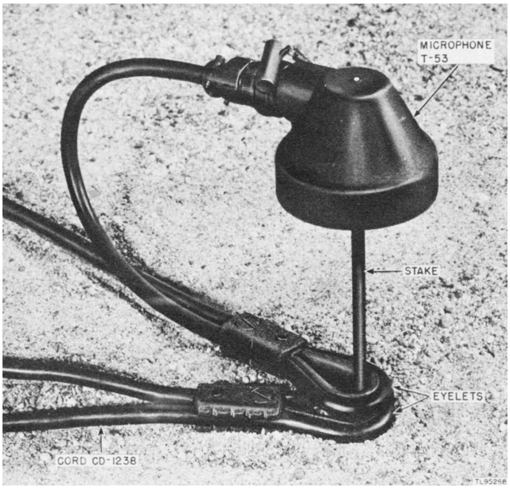


Figure 5.9: Microphone Position

The T-53 magnetic microphones came as a matched set, connected to a three-cable cord (CD-1238). Each microphone was provided with a stake, to be driven into the ground, and the cables had eyelets at each microphone through which the microphone stakes were driven. When the cables were stretched tight, the right isosceles triangle was automatically formed. Figure 5.9 shows a microphone being driven into the ground with its stake through the two eyelets at its apex and Figure 5.10 shows a microphone in position (the shelter has been omitted). The operating instructions state that each microphone array was to be installed on level ground of less that 6″ slope in 15′ and avoiding roads, buildings and electrical installations. Once the array was in position, it was necessary to take the bearing from M3 of the side M3-M1 using a magnetic compass and aiming circle[3].

[3]Since the microphones contained permanent magnets, using a compass near them was

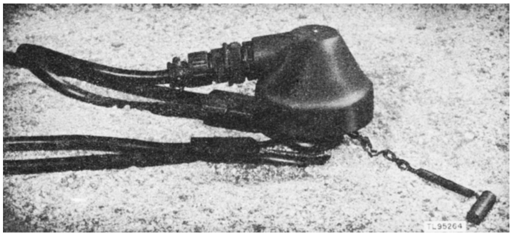


Figure 5.10: Microphone Fully Positioned

Because of the sensitivity of the microphone arrays to interfering noise, particularly from wind, a shelter was provided for each microphone – basically a bag with a thick wall filled with wool or fibre. Once the two microphone arrays had been put in place, cables of up to 150′ [4] were led back from each array to its recorder, positioned within friendly lines. A diagram of the complete arrangement of an array and its recorder is shown at Figure 5.11. Note that there is a connection between the two recorders which permits the operator at the one of the recorders to start and stop recording on both the local and remote recorders. The recorders are started when observation begins and stopped once the shot has been heard in the headphones. The operators can also communicate using the handsets provided.

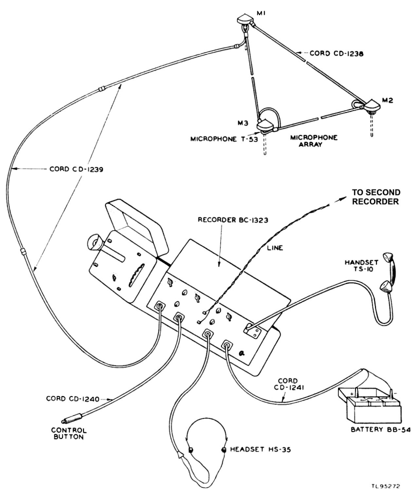


Figure 5.11: Location Array Setup (Left or Right)

The heart of the GR-6 system was the recorder unit, which is shown in Figure 5.12. Within this unit was a tape recorder which used an endless loop of steel

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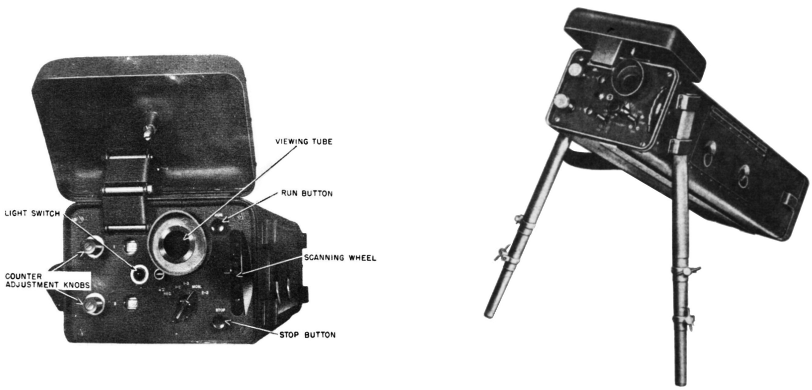
difficult. The instructions advise locating the aiming circle at least four feet above the microphone, but this must have been hazardous, as the manual advises that the microphone could be carefully removed and its position noted before the bearing was taken nearer the ground!

[4]It was possible to reconfigure the array cables to increase this distance by up to 15'.

tape 48″ long, 0.05″ wide and .002″ thick. The tape ran around two rollers, one driven from the unit's dynamotor via a magnetic clutch and the other an idler roller. The rollers were mechanically connected to the "Scanning" wheel on the front panel and when the motor was stopped, this calibrated wheel could be used to move the tape backward and forward.



(a) Front Panel (b) General View

Figure 5.12: GR-6 Recorder Unit

Three sets of magnetic heads were mounted around the tape loop as shown in Figure 5.13. In each set, R was Record, P was Playback and E was Erase and the numbers corresponded to the three microphones in the location array. The operating procedure was to start the tape in Record mode and stop it immediately the shot was heard on the headphones. The shot sound from the three microphones would be recorded at three locations of the tape, any previously recorded sounds having been erased.

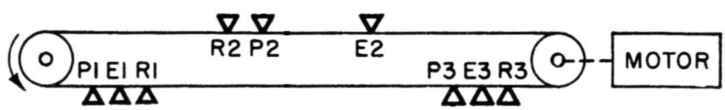


Figure 5.13: Arrangement of the Magnetic Heads

In addition to the Scanning wheel, the Recorder unit had two "Counter" knobs marked "1" and "2" which allowed the head sets for microphones 1 and 2 to be mechanically adjusted forwards and backwards along the tape. These knobs were calibrated and, with the Scanning wheel, were used to obtain the bearing.

Once a recording was made, the Scanning wheel was used to locate the sound on M_3 and then the sounds from either M_1 or M_2 could be compared with it in time by feeding the signals to the X and Y plates of the oscilloscope. As the tape was moved back and forth across the sound, a trace was seen and it could be adjusted by means of the appropriate Counter knob until it became a straight line, at which point the signals were synchronised and the time difference could be read from the Counter knob.

By means of a circular slide rule called the Computer M-414, the bearing of the $M_1 - M_3$ sub-base and the two time difference readings were used to produce the desired bearing. The M-414 was also be used to check the speed of sound at the time, which allowed a correction of the moment to be applied.

Finally, the Recorder had a distance measuring facility which allowed a telephone to be connected to the line which normally connected the two recorders and used instead of a microphone. With the telephone at the point at which the distance to the microphone array was to be measured, a shot was fired and once the shot was heard at the Recorder, the tape was stopped. The Scanning wheel was rotated to find the position of the sound as recorded from the telephone and as recorded from the array. The distance was found, with the aid of the M-414, from the difference between Scanning wheel readings and in this way, the distance between the two arrays and the position of the observers could be surveyed.

The foregoing description of the operation of the GR-6 makes it appear that it was fairly simple to use but it can be inferred from the number of arithmetic calculations needed before the M-414 could be used, that this may not have been entirely true.

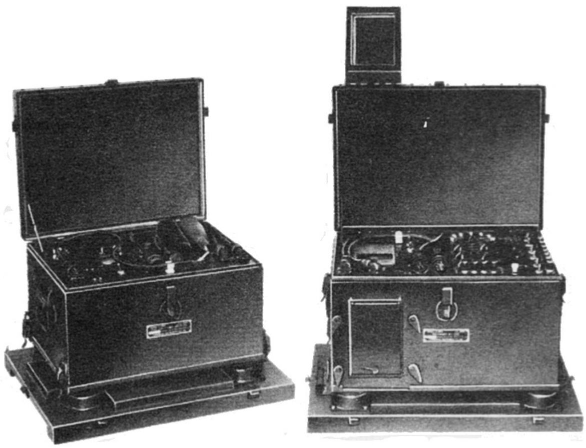


Figure 5.14: Sound Ranging Set, GR-8

5.5 Sound Ranging Set, GR-8

In 1945 a new SR system was issued which, like the British No 2 Recorder of 1944, used a multi-channel pen recorder rather than the harp galvanometer and optical recorder, although the American device, the GR-8[47], had solved the design problems of a six-pen system. The GR-8 was similar in function to the GR-3, but much more compact and simple to operate. However, there were some major design changes:

- As mentioned above, the recording device was a six-channel pen recorder using a "Teledeltos" paper roll[5].

[5] Teledeltos paper is sensitised to voltage. The back of the paper roll rests on an earthed plate and the pens (actually metal styli) are held at a voltage derived from the anode supply.

- Only six microphones could be connected.
- The T-23 microphone, despite looking very similar to the T-21, was in fact a hot wire microphone. The design incorporated a single valve amplifier and an accoustic filter which had cut-offs of 25 and 60Hz, presumably for selecting whether field guns or lighter weapons were being detected.

The US Army fielded SR platoons in all theatres of World War II, with two platoons to each observation battalion; overall, 23 observation battalions on active service and 5 separate platoons, a total of 51 SR platoons. One observation battalion was attached to each Corps Artillery and one to each Army.

Up to 1945, the standard SR set was the GR-3 but this was replaced in 1945 by the GR-8. As will be seen, the GR-8 was to prove a most successful system, which provided excellent service for several decades.

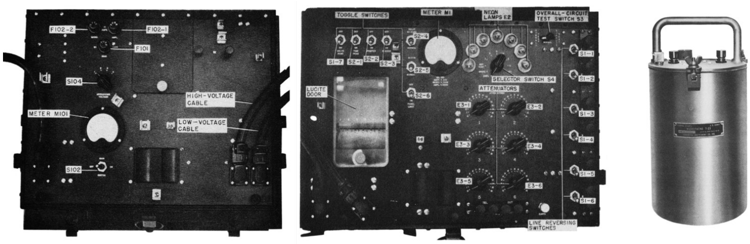


Figure 5.15: GR-8 : Plate Supply/Timer (left), Recorder, Microphone

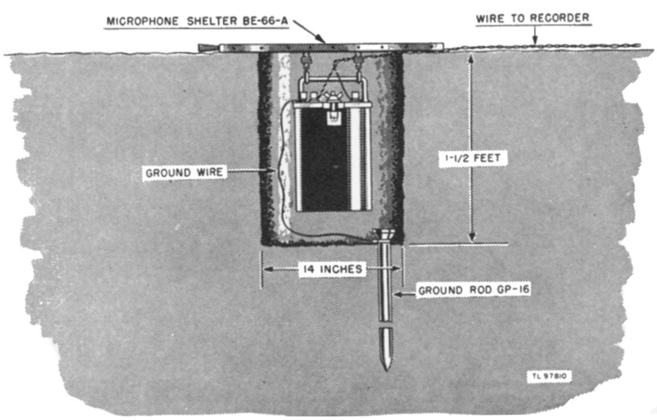


Figure 5.16: GR-8 : Installation of the Microphone T-23

Chapter 6

Post-war Developments - UK

Unlike Flash Spotting, location and ranging of artillery by sound did not disappear in the 1950s and several interesting systems were produced, as will be seen below. By the late 40s and early 50s two different arrangements for setting up a sound ranging operation were defined:

"Long Base" working: For locating distant guns, five to seven microphones were laid out from 1000 to 2000 metres apart. Two APs were normally positioned around one sub-base in front of the base on the right bisector of the flank sub-bases.

"Short Base" working: To locate mortars or relatively close guns, a base of four microphones could be deployed. In this case, the sub-bases were from 300 to 700 metres with one AP, 600 to 1000 metres in front of the centre of the base.

It should also be remembered that at the end of the war, bases of up to six microphones could be connected to the Recorder, SR No 1, while only up to four microphones could be used with the No 2 recorder. This was about to change, with the introduction of seven-pen recorders in the 1950s.

6.1 Carrier Link, SR

The first major advance concerned the line connection of microphones to the command post, and its recorder. There had been many developments in "voice frequency telegraphy"[1] during the war and it is likely that the Carrier Link, SR (also known as the Carrier Link, Base) was a spin-off from this work. It first appeared in early 1945 and was used to carry up to six microphone connections to the command post via a single cable.

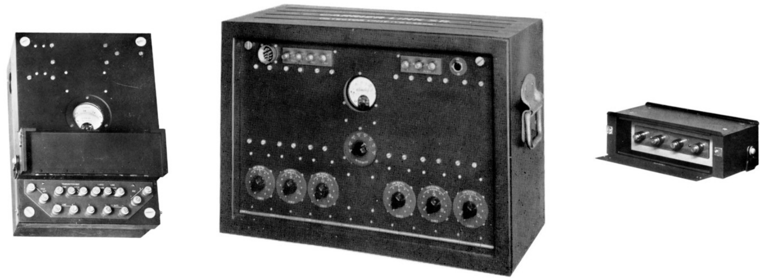
The complete equipment consisted of six transmitter units for use at the microphone positions, a detector unit installed at the SR command post and a number of low pass filter units. These can be seen in Figure 6.1.

Channel	Frequency
A	5,850c/s
B	6,750c/s
C	7,650c/s
D	8,550c/s
E	9,450c/s
F	10,350c/s

Table 6.1: Carrier Frequencies

The transmitters each operated on a different VF channel as shown in Table 6.1 and used two valves, an oscillator and a screen-grid modulated amplifier, while each of the six channels in the

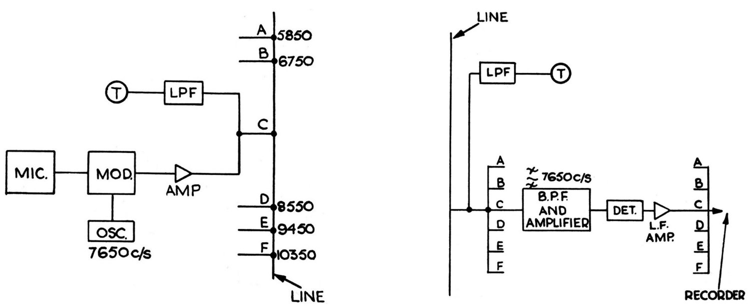
[1] The use of audio frequencies to transmit telegraph signals over a telephone circuit.



(a) Transmitter (b) Detector (c) Filter

Figure 6.1: Carrier Link, S.R.

detector again used two valves, a VF amplifier and an output amplifier which drove a channel of the SR Recorder directly. Both units were powered by a six volt secondary battery and had a vibrator HT supply circuit. The circuits of all the transmitters were identical as were the detector circuits, except for the frequency determining and filtering components.



(a) Transmitter (b) Detector

Figure 6.2: Carrier Link, SR Block Diagrams

The really clever feature of this system was not so much the use of VF telephony technologies, but the fact that it used an "omnibus" line connection, as can be seen in Figure 6.2. A single line circuit (which would normally be twisted pair, but could be earth return if necessary) was laid past all the microphone points and the command post and each unit was "tee-ed" onto it. The order of the units and where the detector was positioned were both immaterial, providing an extremely flexible system. The transmitter and detector units were all equipped to allow the line to be properly terminated, used when the unit was at either end of the line. It is noted in [48] that the time to deploy was around 8 hours, dependent upon conditions. According to the EMER on the system[49]:

> The power handling capacity of the system is adequate for use with any length of transmission line likely to be used but, in presence of induction currents or adverse weather conditions, operation of the

system may be impaired if the distance between the detector unit and the furthest transmitter unit exceeds six or seven miles.

It will have been noticed that the transmission of gun sounds by the Carrier Link, SR does not occupy baseband frequencies and this was to allow the use of normal telephones on the line. Each transmitter unit and the detector unit contains a low pass filter designed to permit the connection of a standard field telephone to the line without interference from (or to) the VF channels. In addition, a number of the separate low pass filters shown in Figure 6.1(c) were provided to allow the connection of field telephones at other points on the line.

When issued in 1945, the Carrier link, SR was meant to be used with the six channel photographic recorder described above. However, a modification instruction dated 1959 [50] described how the detector unit could be modified to drive the Recorder, SR No 5. This device was a pen recorder, and the modification connected the output of each channel demodulator via a capacitor directly to the recorder, bypassing the output amplifier valve. Note that the system described in the next section is undoubtedly the Recorder, S.R. No 5 – it was not unknown for the same system to be known by slightly different names.

6.2 Equipment, Recording, Sound Ranging, Long and Short Base, No 5

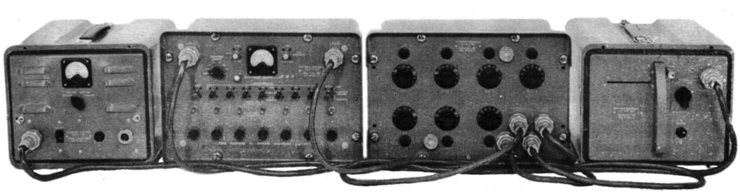


Figure 6.3: Equipment, Recording, Sound Ranging, Long and Short Base, No.5

By the late 1950s, the technology of the Radio Link, SR Mk II was becoming outdated and, as mentioned above, it seems that it went out of use well before 1960. The next radio link system would not appear for more than another decade and when it did arrive, it was utterly different from anything which had gone before (see below). It has been suggested that there may have been a failed project in the 1950s to design a replacement for the Radio Link, SR, Mk II, but this has yet to be proved either way. The replacement which did emerge in the mid-1950s was a line-only system, the Equipment, Recording, Sound Ranging, Long and Short Base, No.5 [51][52]. This equipment had six main elements:

1. Supply Unit Vibratory, 12 volt, SR No.1.
2. Test Unit, Lines, SR Mk.2.
3. Amplifier, SR, Mk.I. This unit had eight amplifiers (one was a spare).
4. Recorder, 7 Pen, Mk.I (used a “Teledeltos” paper roll).
5. AP Control Units, No.1 and No.2 (not shown).
6. Microphones,hot wire or moving coil (not shown).

Interestingly, the deployment diagram in the User Handbook[51] and the EMER[53] (see Figure 6.4) shows one microphone connected by what appears

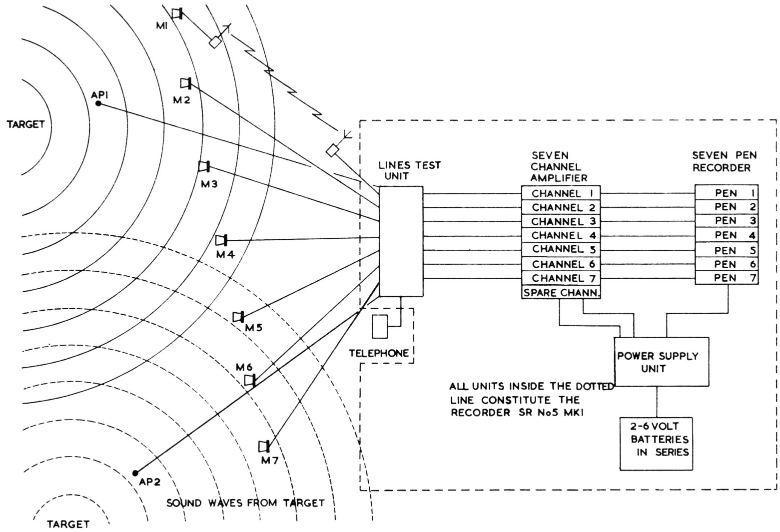


Figure 6.4: Deployment of Recorder, SR No.5

to be a radio circuit. However, there is no mention of radio in the text. This could be seen as further evidence that by 1955, radio was no longer in use. It is likely however, that up to six channels could be connected to the Carrier Link, SR described above.

Figure 6.5: Recorder, Sound Ranging, Mk III

That the No.5 Recorder had a long operational life is proved by the replacement, in 1981, of the amplifier and pen recorder units by a combined set known as the Recorder, Sound Ranging, Mk III (see Figure 6.5)[54].

6.3 Sound Ranging Set, Radio Link No 2

In the 1960s, a new sound ranging radio link system was designed and it was taken into service in 1967[55][56]. Like earlier radio link systems, the No.2 Link could be used in a mixed environment of radio and line connections – however that was really the only similarity, full advantage having been taken of solid state logic to produce a system completely unlike anything which had gone before.

The major items of equipment were externally similar to the "Larkspur" range of wireless sets current at the time, built in hermetically sealed cast aluminium cases. A complete set of equipment allowed the setting up of one or two APs, up to seven MPs and one Command Post – Figures 6.6 to 6.8 give a general idea of what the system looked like.

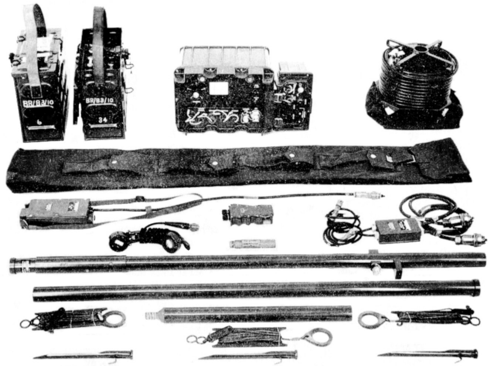


Figure 6.6: SR Radio Link No 2 – Advanced Post equipment

Advanced post (Figure 6.6) The AP system was the simplest and contained a Transmitter, a Control Unit, a Remote Switch Unit and an Aerial (plus cabling and supply components).

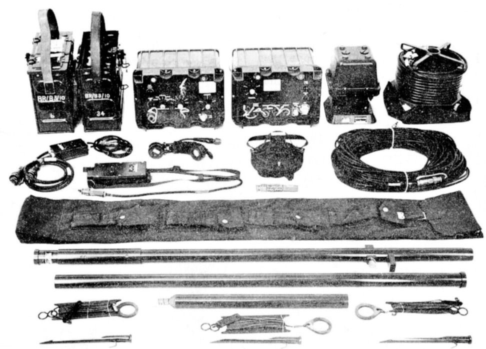


Figure 6.7: SR Radio Link No 2 – Microphone Point equipment

Microphone Point (Figure 6.7) Each MP was equipped with a Microphone (second item from the right in the top row - standing upside down in the picture!), a Transmitter, an MP Receiver and an Aerial. The microphone was no longer based on the hot wire principle but was built around an RF Capacitor unit, the Sennheiser MKH/110P. See Appendix D for a description of the RF Capacitor Microphone.

Sound Ranging Command Post (Figure 6.8) The SR Command Post was equipped with the most complex system comprising a Transmitter, a Control Receiver, a Data Receiver, a Power Supply and System Selector, a Recorder Amplifier, a Recorder and two Aerials. Note that the

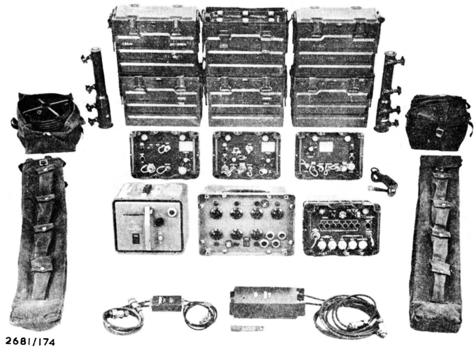


Figure 6.8: SR Radio Link No 2 – Command Post equipment

recorder and amplifier units are the same units as are used in the Equipment, Recorder, Sound Ranging (Long and Short Base) No 5. Because Figure 6.8 dates from 1968, it is impossible to tell if the Recorder, Sound Ranging, Mk III replaced the amplifier and recorder units in 1981, but it seems likely.

In addition, if line connections were to be used for some microphones, a Lines Test Unit was added (not in the picture). No picture of this unit is currently available, but it is a reasonable assumption that it was the unit from the No.5 Recorder kit.

The system operated on 57 channels spaced at 250Khz in the frequency range 70 – 84 Mhz, crystals for five channels at a time being fitted. Each transmitter and receiver unit had a five position channel selector on the front panel. In operation, three of the channels were used as described below, and two channels were spare, presumably in case of interference. There was only one type of transmitter, despite the three roles (which in fact differed only in the signal transmitted) but there were three types of receiver (MP, Data and Control). However, the RF and IF stages of the receivers were common.

Refer to the System Diagram, Figure 6.9 when reading the following description.

When a gun sound was heard at an AP, the remote switching unit (also known as the remote "trigger") was pressed, or the Start switch on the control unit was operated. This caused a half second Start tone to be sent to the control receiver at the command post. Once sufficient time had elapsed for a recording to be made, the trigger was released or the Stop switch operated. This in turn caused a half second Stop tone to be sent to the CP – see Table 6.2 for the tone frequencies. If required, a handset could be used to allow the AP to send speech to the CP via the control receiver.

	Start	Stop
AP1	4Khz	6.5Khz
AP2	10Khz	15Khz

Table 6.2: Control Tone Frequencies

Reception of the Start tone triggered two events; the starting of the recorder (which would subsequently be stopped by a Stop tone, or manual operation) and the initiation of a series of actions at the data receiver:

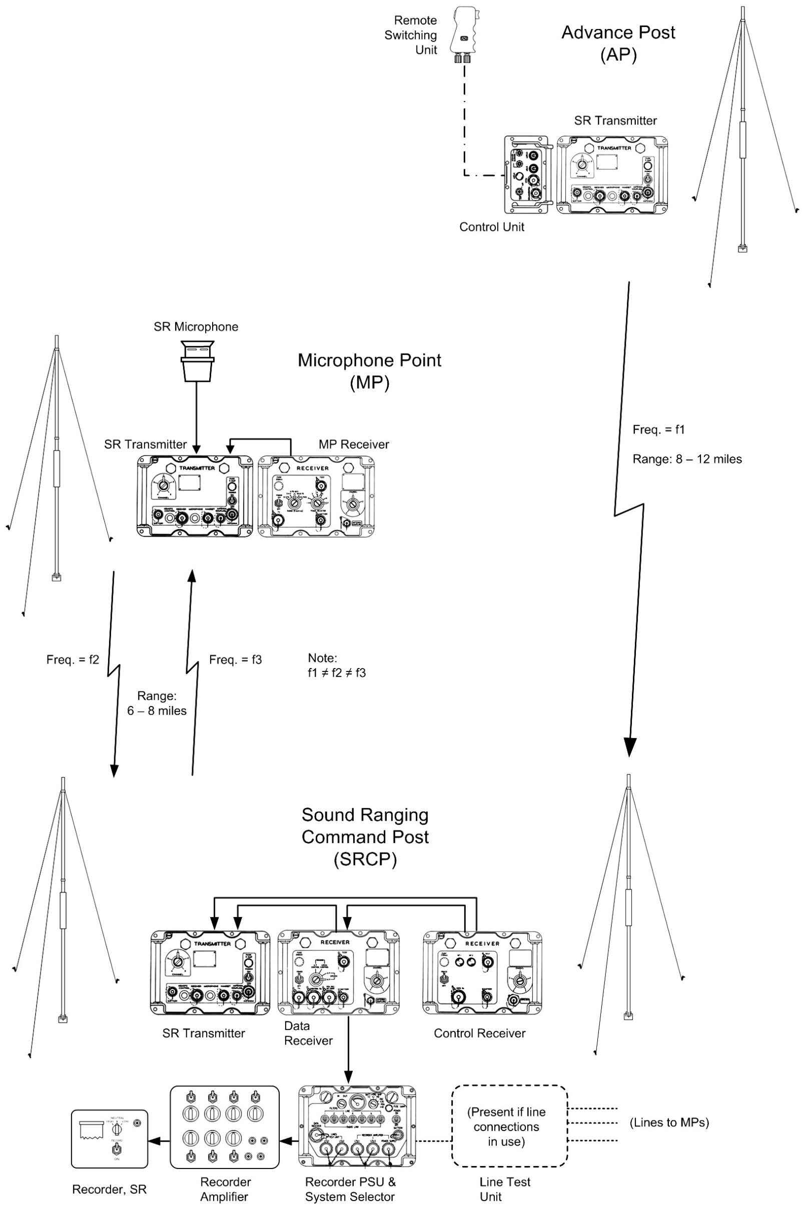


Figure 6.9: SR Radio Link No 2 – System Diagram

1. The CP transmitter switched on for 292.5μS and sent a synchronising pulse to the MP receivers. The off period of the transmitter was 607.5μS, giving a total frame period of 900μS (a pulse repetition rate of 1.1Khz). The sequence repeated for as long as the recorder was running.
2. The synchronising pulse had a positive excursion of 126μS and it's positive to negative trailing edge was used to phase lock the control clocks in the MP receivers.
3. At each MP receiver, the synchronising pulse reset a counter chain and phase locked the crystal oscillator driving the chain.
4. The counter chain produced a train of seven gating pulses, each 90μS in duration. By means of a "Trace" switch (trace refers to the pen recorder channel), the gating pulse to be used at each MP was selected.
5. The selected gating pulse switched the MP transmitter to send, modulated by the microphone output.
6. An identically phase locked counter chain in the CP data receiver produced gating pulses synchronised to the MP transmissions and directed them to the appropriate integrating detector which formed representations of the microphone signals. Note that the repetition rate of the system was relatively high (1.1Khz) compared to the microphone output frequencies and the integrators could produce valid outputs.
7. When a Stop tone was received from the AP, or the recorder was manually stopped, the whole system was reset and returned to stand by.

Because the timings were critical, the MP receiver had a five position "Range" switch which allowed the gating pulses to be shifted in steps of 22.5μS relative to the equivalent pulse in the CP data receiver, to overcome propagation delays.

Finally, handsets could be connected at the MPs and the CP, allowing two-way speech communication. However, this would only have been used during setup as the MPs were normally unmanned in operation.

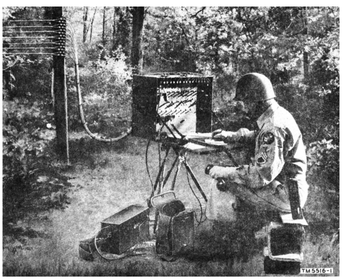
6.4 Current Systems

Introduced in the late 1960s, the Sound Ranging Radio Link No.2 remained in service for around thirty years. Over that time the recorders were replaced as technology developed, but the radio equipment remained essentially unchanged. It was eventually replaced by a system called HALO (Hostile Artillery LOcator) and then by ASP (Advanced Sound ranging Project) which is still current in 2012. Some information on ASP may be gleaned from the various Army web sites.

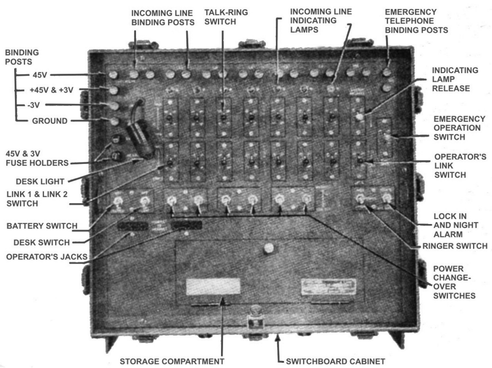
Chapter 7

Post-war Developments - USA

7.1 Flash Ranging Set, AN/GTC-1



(a) The GTC-1 in service



(b) Switchboard SB-4

Figure 7.1: Sound Ranging Set AN/GTC-1

At the beginning of the 1950s, the GR-4 was replaced by the AN/GTC-1 Flash Ranging Set[1] which, like the GR-3, was really a telephone switchboard system, in this case, the SB-4. The system in operation is shown in Figure 7.1(a) and the switchboard unit is shown in Figure 7.1(b).

The SB-4 switchboard was located at the Flash Ranging Central and was linked to up to six outposts and one "trunk" circuit to Battalion HQ. The connections are shown in Figure 7.2.

As with the original British Flash and Buzzer Switchboard, the SB-4 was designed to ensure that observers in the outposts could be sure they were measuring flashes from the same gun. Each outpost was equipped with a push button switch and a telephone, connected via a control box and two-wire line to the SB-4 switchboard. When the observer saw a flash, he would press the button and this would light the appropriate indicating lamp on the SB-4.

[1] By the end of the Second World War, the JETDS equipment designation system had been introduced but in this case, the GTC only tells us that this was a ground telephone communication system!

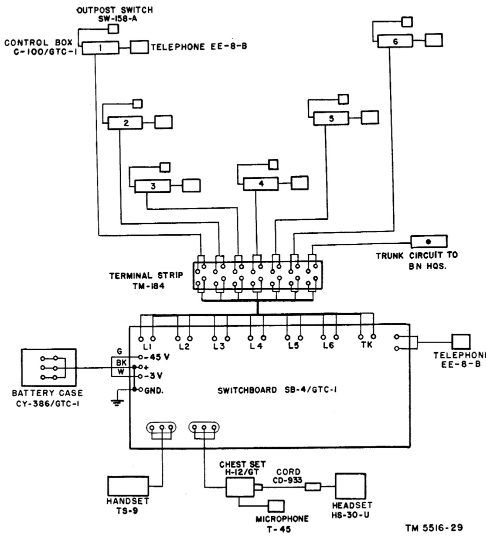


Figure 7.2: SB-4 Connections

It will be recalled that the British Sound Ranging Advance Posts and Flash Spotting OPs were equipped with specially designed or modified telephone sets incorporating a series capacitor and a switch to short it out and provide a DC loop at the switchboard, which was used to operate a sensitive relay and light a lamp. The US Army appears never to have used special outpost equipment (either for SR or FSp) and instead, each was equipped with the standard field telephone, the EE-8. The blocking capacitor was housed in a separate unit, along with connections to the switch. Figure 7.3 shows the outpost equipment supplied in the GTC-1.

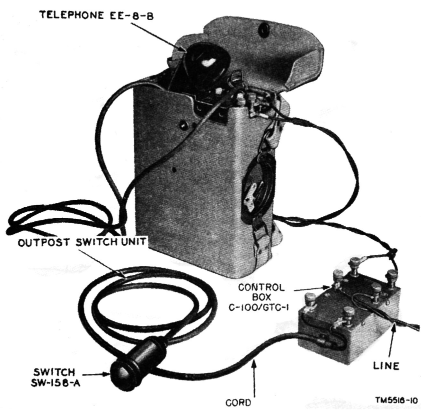


Figure 7.3: Outpost Equipment

The overall calling and indicating circuit of the SB-4 is shown in Figure

7.4. It would seem that there was no need for specially sensitive relays in the indicating circuit, possibly because a 45 volt battery was used to power the line circuit, rather than the 15 volt British equivalent. Also, the EE-8 was a magneto calling device capable of operating the indicating lamp relay directly, which meant that a flash had to be indicated by a push and release of the output switch whereas a ring would cause the lamp at the SB-4 to be lit for as long as the generator was turned.

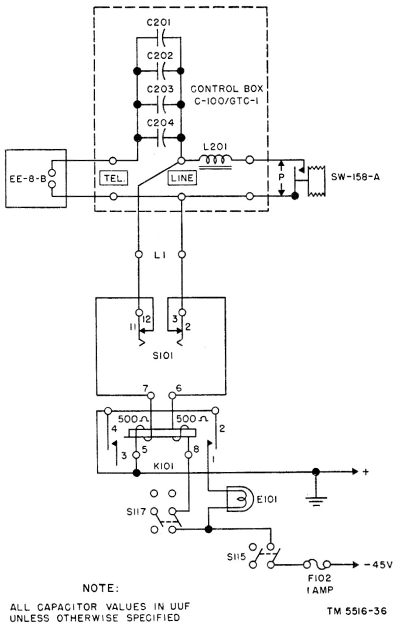


Figure 7.4: SB04 Calling Circuit

Using the SB-4, you might think that the operator at the Central controlled flash ranging activities in much the same way as his British counterpart would have done until the Flash and Buzzer board was taken out of service[2], but this was not the case. Starting with all the talk/ring and link switches in the centre position, the operator waited until he saw two or more indicator lamps flashing in unison. He then called those outposts simultaneously and asked for their bearings to the flashes.

At this point, the British operator would have directed the other OPs to observe on a bearing calculated for them from the intersection of the original bearings and in this way, the location of the observed gun would be refined. In the Technical Manual for the GTC-1[57], dated 1951, there is no mention of the refinement step. Why this should be is unknown.

[2] For a description, see Chapter 2 Section 2.6.

7.2 From Korea to Vietnam

For the period from 1946 onward for around thirty years, that was the end of the development of non-radar locating systems in the US Army! Major Glen Coffman comments in his 1973 article in The Field Artillery Journal[58] :

> ″...the war was over and target acquisition, just as in the post-World War I era, took a back seat to "move, shoot, and communicate". We were not so gullible as to believe wars would stop, but we were not so intelligent as to realize we must continue to train in all aspects of artillery. In 1950, we were designing new radios, new vehicles, and more powerful cannons but were still using World War II target acquisition equipment.
>
> The priority of target acquisition was so low that only one observation battalion was still active in the Army in 1950.″

But in 1950, they were committed to the Korean peninsular as the major force employed as part of the UN "police action", otherwise known as the Korean War. Targets were needed by the artillery and two observation battalions took part (the 1st committed in September 1950 at 60% strength and 235th at full strength in December 1952).

Because of the rough and mountainous terrain of Korea, SR was difficult so the platoons normally had to use irregular bases and were expected to cover wider fronts than in WW2 – all with no increase in establishment. Consequently, SR was not as successful as it had been in the earlier war but is estimated to have accounted for 60% of all locations found, the rest being credited to Flash Ranging, local observation and a new radar system, the AN/MPQ-10[59].

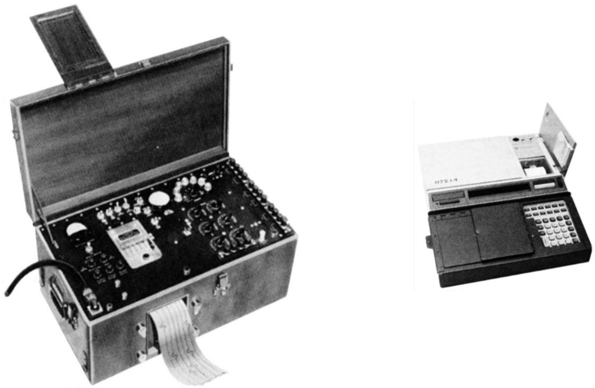
After Korea, interest in artillery location again failed (apart from the renaming of Observation Battalions to Target Acquisition Batteries in 1961). Yet in 1967 the US Army became committed to a limited war, this time in Vietnam, a very different conflict to Korea. This time just two SR troops were committed.

It will be noted that by 1967, the British army had been using the Carrier Link SR since 1945, simplifying the installation of the microphone line networks and the up to date Recorder No 5 had been the standard SR system from the late 1950s. Also, the need for microphone lines had been removed from 1943 to the time of the Korean war. Although there was a gap in the use of wireless until 1967, it would have been available in Vietnam (had we been involved), in the form of the Radio Link, No 2.

The US Army appears never to have attempted to move away from fully wired microphone bases and in Vietnam, due in large part to infiltration, the maintenance of line networks was extremely difficult as each wire crew had to be heavily defended. There were also several instances of the microphones being blown up by US troops as suspected enemy mines!

7.3 Later Developments

The first new SR kit since the GR-8 was the Sound Ranging Set, AN/TNS-10 issued in the early 1970s and was a transistorised version of the GR-8 system, 35 years after that set was originally developed. It was officially described as a "product improvement" to the GR-8 and originally was simply a repackaging, with replacement of the recording head and solid state conversion as separate phases of the improvement[60] – see Figure 7.5(a) for the TNS-10 and Figure 7.5(b) for a picture of the sort of calculator used with it to compute the results.



(a) TNS-10 Sound Ranging Set (b) OL-274 Computer

Figure 7.5: TNS-10 SR Set and OL-274 Computer

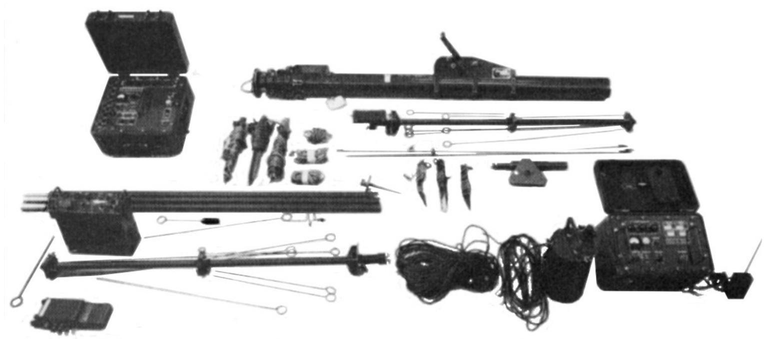


Figure 7.6: GRA-114 Digital Radio Link

And then in 1982 the US Army finally received the AN/GRA-114 SR Digital Radio Data Link!

The remit of this book includes the date range 1914 - 1970 and we have strayed slightly outside that with the US Army kit, as we did with the British systems. Obviously, details of the newer equipment, particularly that from America, are difficult to find and perhaps a later revision may contain further information.

Chapter 8

Afterword

Indirect fire as the standard means of artillery operation is a little over one hundred years old and only a few years younger is the science of artillery location. Long before the birth of radar, location was by means of the flash or the bang of the gun, both methods invented by brilliant men who also designed the supporting technology required.

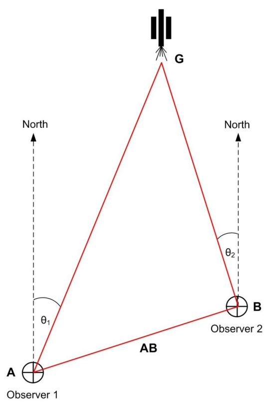
For those interested in military technology, the highly specialised equipment used over the last ninety three years in artillery location has its own fascination. The fact that so relatively few locating units have ever existed makes physical examples of the equipment exceedingly rare and even the documentation is difficult to find. Therefore there are still gaps in our knowledge which may, hopefully, be filled over time.

And finally, although (as far as is known) Flash Spotting ceased in the British Army in the 1950s, Sound Ranging is alive and well – and may be in a city near you (Google “gunshot detection”)!

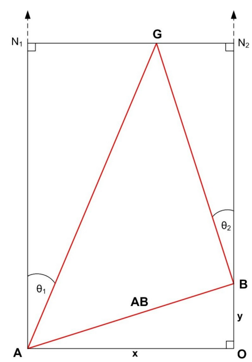
Appendix A

Solution of Triangles for Flash Spotting

The observations are shown in (a) below. [1]



(a) Observation



(b) Calculation

Figure A.1: The Geometry of Flash Spotting

In (b), two East–West lines (AO and N_1N_2) and two North–South lines (N_1A and N_2O) have been added, to construct three right angled triangles around the observation triangle, which is shown in red. The object of the calculation is to determine the grid position of point G, which can be in the form of Easting and Northing offsets from point A. Thus the required lengths are N_1A and N_1G.

We will use the position of the first observer, point A, as the reference and since we know the position on the grid of both observers, we know the distances AO and OB (shown as x and y respectively, in Figure A.1b). So from Pythagoras' Theorem, we can find the distance between the observers, AB:

$$AB^2 = x^2 + y^2$$

[1] For those who feel the need of a refresher at this point, Stan Brown's excellent *Trig Without Tears* website is recommended [61].

thus

$$AB = \sqrt{x^2 + y^2}$$

We can now find the two unknown angles in $\triangle ABO$ using sines:

$$\begin{aligned} \sin \widehat{OAB} &= \frac{y}{AB} \\ \sin \widehat{ABO} &= \frac{x}{AB} \end{aligned}$$

thus

$$\begin{aligned} \widehat{OAB} &= \arcsin \frac{y}{AB} \\ \widehat{ABO} &= \arcsin \frac{x}{AB} \end{aligned}$$

Given these angles it can be seen by inspection that the angles θ_1, $\widehat{OAB}$ and $\widehat{GAB}$ sum to 90° while θ_2, $\widehat{ABO}$ and $\widehat{GBA}$ sum to 180°. Remember that we know θ_1 and θ_2 from the observed bearings. Thus

$$\begin{aligned} \widehat{GAB} &= 90 - (\theta_1 + \widehat{OAB}) \\ \widehat{GBA} &= 180 - (\theta_2 + \widehat{ABO}) \end{aligned}$$

From the sum of angles in any triangle, we can write the value of $\widehat{AGB}$:

$$\widehat{AGB} = 180 - (\widehat{GAB} + \widehat{GBA})$$

From the Sine Rule, we could now find the ranges to the hostile gun from each observer, but it is in fact only necessary to find one. We will find AG:

$$AG = AB \cdot \frac{\sin \widehat{GBA}}{\sin \widehat{AGB}}$$

Finally, we can find the required Easting and Northing offsets, N_1G and N_1A:

$$\sin \theta_1 = \frac{N_1G}{GA}$$

so

$$N_1G = GA \cdot \sin \theta_1$$

and similarly

$$N_1A = GA \cdot \cos \theta_2$$

Appendix B

The Asymptote

(This explanation of asymptote plotting is reproduced from The Manual of Sound Ranging [23].)

In order to draw the asymptote scale on a plotting board, it is necessary to know the angle between the right bisector of the sub-base and the asymptote, for a given time difference. In the diagram, if a circle is described with M_1 as centre and radius $(T_1 - T_2)$, the hyperbola (dashed) is the locus of the centre of the circle which touches the circle with centre M_1 and passes through M_2.

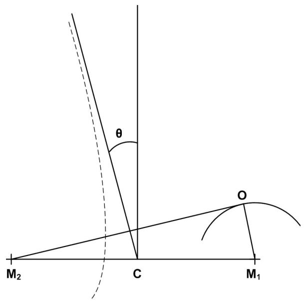


Figure B.1: The Asymptote.

Suppose the gun is at a very great distance. The arc OM_2 of the circle whose centre is the gun position is then almost a straight line and, in the limit, when its centre becomes infinitely distant, will be a straight line passing through M_2 and touching the circle whose centre is M_1 at O, while the gun will lie on the right bisector of the tangent M_2O. The right bisector of the tangent will pass through the midpoint of the line M_1M_2 and will touch the hyperbola at infinity. It is therefore the asymptote of the hyperbola.

Let l represent the distance between the microphones M_1 and M_2, for which $T_1 - T_2$ is the time difference and θ is the angle between the right bisector of the line M_1M_2 and the asymptote of the hyperbola corresponding to the time difference T_1T_2.
In the diagram, $\theta = O\widehat{M_2}M_1$.
Therefore

$$\sin\theta = \frac{OM_1}{M_1M_2} = \frac{(T_1 - T_2)}{l}$$

If

$$t = T_1 - T_2$$

Then

$$\sin\theta = \frac{t}{l}$$

From this, the angle θ can be calculated for a series of time differences t.

Appendix C

The Hot Wire Microphone

The "Tucker" microphone was, as mentioned above, invented by W. S. Tucker (who rose to the rank of Major by the end of the war), based on his earlier work at Imperial College. It was the subject of patent applications in 1916 (13123) and 1918 (8948), and Tucker continued to work on the design after the war, publishing his results in 1921 [62].

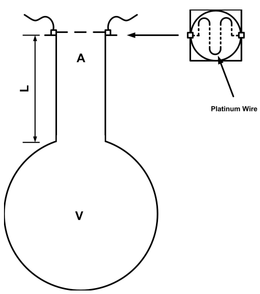


Figure C.1: Helmholtz Resonator

The hot wire microphone is unlike many other microphones in that it is not intended to reproduce sound as electrical variations. Rather it is a device for measuring the energy contained in a sound wave, specifically at very low frequencies, otherwise known as "infrasound". There is a similarity with the hot wire anemometer used to measure wind speed, but it differs from that device in having a degree of frequency selectivity achieved using a "Helmholtz Resonator" (see the figure above).

A thin platinum wire, typically 6μm in diameter, is fixed across one end of a tube, the other end of which connects to a closed cavity. When sound of a particular frequency arrives at the outer end of the tube, air rushes in and out of the tube, cooling the wire by forced convection and decreasing its resistance. The amplitude of the variations is greatest at or around the resonant frequency of the device, which is given by:

$$f = \frac{c}{2}\sqrt{\frac{A}{VL}}$$

where c = speed of sound
A = cross sectional area of the tube
L = length of the tube
V = volume of the cavity

The variations in the resistance of the platinum wire may be found by connecting it in a balanced bridge configuration. It should be noted that the signal thus produced gives one cycle of resistance change from nominal to a lower value and then back to nominal on both the rise and fall in pressure at the tube entrance. Thus the fundamental frequency of the microphone output is twice that of the gun sound.

Appendix D

The RF Capacitor Microphone

The "standard" condenser or capacitor microphone was invented by E.C. Wente at Bell Labs in 1916 and consists of a capacitor, one plate of which is the microphone's diaphragm. The principle is based on the equation which relates charge to capacitance and voltage:

$$Q = C \times V$$

where:

Q is charge (in Coulombs), C is capacitance (in Farads) and V is voltage (in Volts)

As the distance between the capacitor plates changes with the sound vibrations, the capacitance changes and assuming the voltage is roughly constant, the charge must vary. The applied or "bias" voltage across the capacitor is connected via a high value resistor (10MΩ or so) in order to keep the rate of change of charge slow. The result is that the voltage across the capacitor varies with the audio at the diaphragm.

However, the use of relatively high bias voltages in the field is somewhat unreliable and a variation on the capacitor microphone was used. The RF capacitor microphone uses an RF bias from a low-noise, high frequency oscillator (several Mhz.). In simple terms, this oscillator is fed to a bridge circuit which, under no-signal conditions, is balanced and produces no output. When the capacitance value of the microphone capsule changes, it unbalances the bridge and produces an audio signal. The importance of this system for Sound Ranging is that the microphone produces a very good response down to frequencies well below 1Hz.

The following description of the principle is reproduced from EMER Telecommunications B822 Part 1:

> Microphone Unit
>
> 335. The heart of the equipment is the Sennheiser microphone, MKH 110/P. This is a capacitor pressure transducer with a built-in amplifier employing an r.f. bridge technique, which gives a substantially flat response down to below 1c/s. The diagram below illustrates the basic principle of the microphone.
>
> 336. The output of the r.f. oscillator O is periodically switched at the r.f. frequency by the diodes S to the capacitor C via resistor R.

The switching phase is shifted 90° from that of the r.f. oscillator by means of loose coupling and aligning the resonance of the microphone circuit M under no-signal conditions. As a result, the voltage across the capacitor is zero. As soon as sound causes a deflection of the transducer element diaphragm, the switching phase changes in a manner proportional to the sound pressure and a corresponding audio voltage appears across capacitor C. A d.c. supply of 8V is required to energise the the capacitor microphone and operate the r.f. oscillator. A detailed circuit of the microphone is not given as it is not intended that this unit should be serviced. In the event of failure, the unit should be replaced.

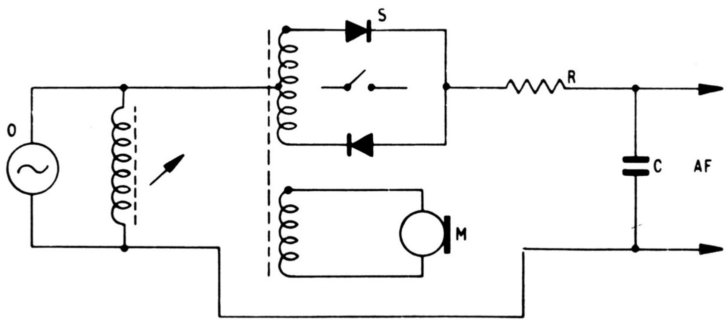


Figure D.1: RF Condenser Microphone, basic circuit

Appendix E

SR Correction for Temperature

Let V_θ be the velocity of sound at temperature θ and V_{10} the temperature at 10°C.
Since the velocity of sound is proportional to the square root of the absolute temperature.

$$\frac{V_\theta}{V_{10}} = \sqrt{\frac{273+\theta}{283}} = \sqrt{1+\frac{\theta-10}{283}}$$

If t_θ is the time difference at temperature θ and t_{10} the time difference at 10°C,

$$\frac{t_\theta}{t_{10}} = \frac{V_{10}}{V_\theta}$$

and

$$t_{10} = t_\theta \frac{V_\theta}{V_{10}}$$

Thus the measured time difference at temperature θ must be multiplied by the factor

$$\frac{V_\theta}{V_{10}} = \sqrt{1+\frac{\theta-10}{283}}$$

to reduce it to the time difference at 10°C.

Finally,

$$\sqrt{1+\frac{\theta-10}{283}} = 1+0.5\frac{\theta-10}{283}(approx.) = 1+0.0018(\theta-10^\circ)$$

Appendix F

Control Units, S.R. - Details

F.1 Control Unit, SR, Mk II

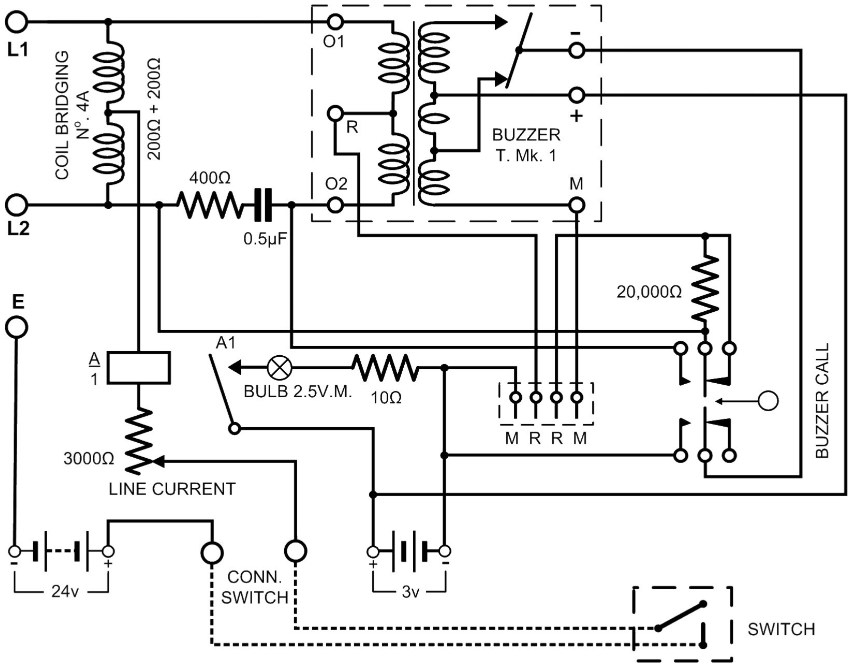


Figure F.1: Control Unit, SR, Mk II - Circuit

Instructions for use:

1. *Unscrew screws in hinged back and see that the 3 volt (two Cells, Dry X) and the 24 volt battery (two 12 volt units) are correctly connected.*
2. *Plug in 4 pin plug of handset.*
3. *Connect lines to terminals L1 and L2.*
4. *Remove earth pin from sling, push into ground and connect to terminal E.*

5. *See that connector switch is connected and metal slide in place.*
   NOTE This slide is pushed in from terminal side and prevents the wires being pulled off the terminals.
6. *To prove the instrument*
   a) *Short circuit terminals L1 and E.*
   b) *Turn increase line Current control anti-clockwise.*
   If the indicator lamp does not light press connector switch when lamp should light. Press connector switch to extinguish lamp.
7. *Remove short circuit from terminals L1 and E and give buzzer call by pressing Buzz Call key. Communications should now be possible with headquarters.*
8. *Press connector switch to light indicator lamp then by communication with headquarters adjust Increase Line Current control by stages until line current is sufficient to switch on recorder unfailingly.*
9. *To adjust buzzer*
   a) *Loosen collars marked lock then unscrew centre knobs to clear armature contacts.*
   b) *With Buzz Call switch pressed down, advance either knob until buzzer commences to operate irrespective of quality. Lock this knob then advance the other knob until a clear higher note is obtained. Lock this knob. Check adjustments by operating the Buzz Call key and readjusting if necessary. When adjusting buzzer do not force contact screws hard on to armature or buzzer will be put out of action.*

F.2 Control Unit, SR No 2, Mk I

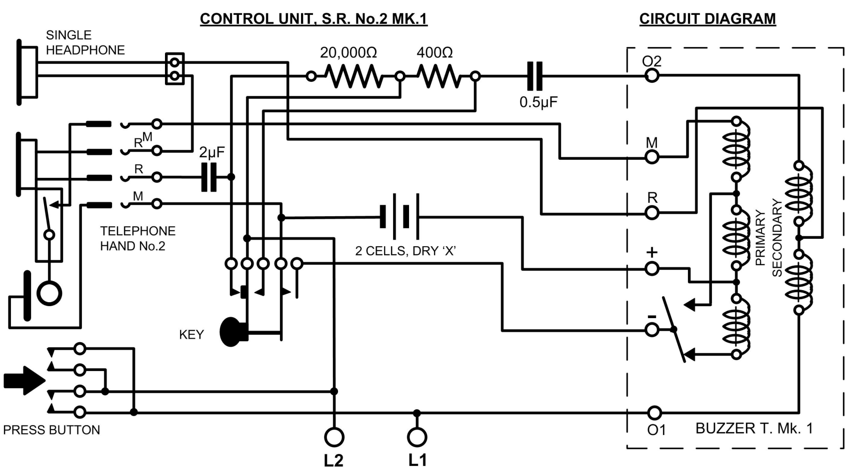


Figure F.2: Control Unit, SR No 2, Mk I - Circuit

Instruction for using Control Units S.R. No 2, Mk 1.

To use the unit.

1. *See that 2 'X' cells are connected up as shown in diagram in lid of cell case.*

2. *Connect lines to L1 and L2 respectively.*
3. *Plug handset into 4 way jack located below line terminals.*
4. *To call, press the key mounted on the unit.*
5. *To operate the Recorder S.R. No.2 Mk1 press the switch button at the end of the short cable. Releasing this button stops the recorder.*

To adjust the buzzer.

1. *Loosen the collars marked 'Lock' then unscrew centre knobs to clear armature contact.*
2. *With 'buzzer call' key down, advance either knob until the buzzer commences to operate irrespective of quality; lock the knob. Then advance the other knob until a clear, higher note is obtained; lock this knob. Check adjustments by operating the buzzer call key and readjust if necessary.*

To test instrument.

1. *Disconnect lines and operate handset (pressel) switch intermittently. Clicks should be heard in the receiver. Press the pressel switch and blow into the microphone. The blow should be heard in the receiver. When the instrument is connected to the line, the click and blow should be weaker and may be inaudible.*
2. *Press buzzer key and touch L1 and L2 with moistened fingers, when the current should be felt.*

Always remove handset plug when packing up.

Appendix G

The 3-Microphone Location Array

The 3-microphone location array appears to have first been used in 1945 by the US Army's GR-6 system, but is now the norm. Using three microphones on short sub-bases in a triangular arrangement, a bearing may be obtained by observing the differences in gun sound arrival times between the three microphones.

The GR-6 used a right isosceles triangle layout with sides of 15′, 15′ and 21′ 2.5″ whereas modern systems tend to use an equilateral triangle with sides of around 10m. Measuring times with such short sub-bases requires much greater accuracy than was possible in the days of Bragg and Tucker, for example the sound transit time over 10m is under 30mS.

The physical arrangement is in fact irrelevant, as will be seen below, but the orientation and length of each sub-base must be accurately known. The use of right isosceles or equilateral triangles simply allows the bearings and lengths of all the sides to be found from measurements of a single side.

Although the GR-6 arrays were designed to "face forward" to detect enemy firing positions in front of friendly lines, the 3-microphone method is not inherently directional and can detect sounds from any direction. However, the use of such short sub-bases means that there is insufficient accuracy to produce a range by intersection of the bearings calculated from the time differences across each microphone pair. Essentially the bearings calculated are so close to each other that an average produces an accurate bearing only, not range. Therefore, to determine the gun's range, two or more arrays must be set up with sufficient separation and used to produce bearings which can be intersected to provide range.

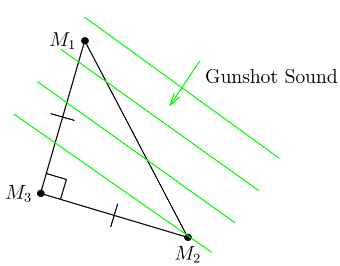


Figure G.1: The GR-6 Array

Figure G.1 shows a GR-6 style array with a gunshot sound passing over it.

Consider the instant when the leading edge of the sound wavefront has just arrived at microphone M_2, as shown in Figure G.2.

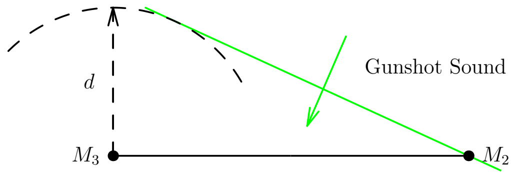


Figure G.2: Sound Wavefront Reaches M_2

Since the arrival time delay between M_2 and M_3 is measured, the distance d may be calculated as the distance the sound travels in that time. Thus we know that at the time the wavefront reaches M_2, it will still be distance d from M_3 and that the wavefront will be intersecting with a circle of radius d, centred on M_3.

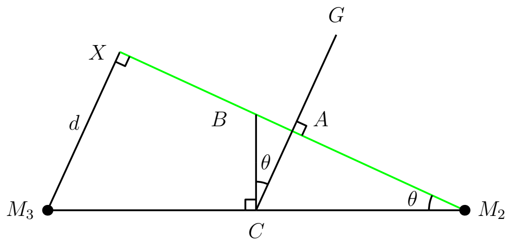


Figure G.3: Derivation of Bearing

(Figure G.3) Since the wavefront only intersects with the circle centred on M_3 at one point (it only arrives once!), it forms a tangent to that circle (at point X). Thus the triangle M_3DM_2 is right angled, with the lengths of sides M_2M_3 and M_3X known. Therefore the value of $\widehat{M_3M_2}X$ (labelled θ) may be found:

$$\sin\theta = \frac{M_3D}{M_2M_3}$$

$$\theta = \sin^{-1}(\frac{M_3D}{M_2M_3})$$

The line GC and is orthogonal to the wavefront M_2X and meets the M_2M_3 sub-base at point C. If a perpendicular is raised from C, it meets the wavefront at B.

Since

$$\widehat{BCM}_2 = 90^\circ$$

$$\theta + \widehat{CBM}_2 = 90^\circ$$

In $\triangle ABC$,

$$\widehat{BCA} + \widehat{ABC} = 90^\circ$$

$$\theta + \widehat{CBA} = \widehat{BCA} + \widehat{ABC}$$

$$\theta = \widehat{ABC}$$

Thus the bearing to the enemy gun may be calculated from θ and the bearing of the sub-base M_2X. Note that the same corrections derived from meteorological data which apply to long base sound location will also be applied to 3-microphone array systems.

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Colophon

This book was typeset using the LaTeXtypesetting system created by Leslie Lamport and the memoir class. The body text is in 9pt with Donald Knuth's Computer Modern font family. Image manipulation was carried out using Photo-Paint™, part of the Corel Graphics Suite, versions X3 and X6. The diagrams in Appendix G were prepared with the Asymptote diagramming system and document source preparation used the TeXWorks editor.