In 1916 Captain A. V. Hill was transferred from the infantry to the Ministry of Munitions to work on anti-aircraft gunnery. He determined the three-dimensional coordinates of flying objects by placing two mirrors far apart. The mirrors were viewed from a fixed distance above them and observers simultaneously marked the position of the object. He gathered brilliant men, most too old or too young for conscription, who became known as Hill’s Brigands. They determined the coordinates of the explosions of shots fired with different fuse settings and fitted them with the ballistic equations to construct accurate gunnery tables. They solved the puzzle of erratic fuse timing at high altitudes. They developed apparatus to locate aircraft by sound. Travelling groups of Brigands worked with anti-aircraft gunners, which Hill regarded as the dawn of operations research. Hill was as adept at leading scientists as he was at doing science.

Keywords: A. V. Hill; H. Darwin; D. R. Hartree; E. A. Milne; anti-aircraft; World War I
on leave, recovering from influenza. At their meeting, Darwin, an expert on aviation, spoke of the battle with enemy aircraft. In the past year German dirigibles had dropped 34 tons of bombs on targets in England, killing 181 people and wounding 455.

Darwin’s elder brother, Leonard (1850–1943), had served as a Royal Engineer. In the 1880s he used a camera obscura in a setup to determine the $X$, $Y$ and $Z$ coordinates of balloons. Now Horace wanted to use the camera obscura to train anti-aircraft (AA) gunners without expending scarce ammunition. The gunners would track the target until the order ‘fire’ was given, after which the target’s position would be marked on the projection at 1-second intervals. At the point of explosion of the imaginary shell, its location would be calculated from the gun table and the settings of the gun, and compared with that of the target. Hill was asked to inspect the gear and suggest improvements.

They met a few days later at the Central Flying School at Upavon, Wiltshire. The camera obscura was a large, immobile dome, resembling a yurt, with a lens at the top to focus an image of the sky on the floor. Only a small area of sky was seen on the floor, and the image was dim. Next Hill was shown another apparatus they were working on, a horizontal mirror viewed through an eyehole placed above it. The reflection of a bombing plane was observed and the points of bomb release and impact were marked on the mirror.

Hill had the hoped-for brainwave. They needed two identical, absolutely flat, horizontal mirrors, each engraved with a calibration grid. They should be placed at the ends of a long, measured baseline. Observers would look at the mirrors through peepholes, keeping the distance between eye and mirror fixed. On a telephoned command, they would mark the position of a reflected aeroplane on the mirror with a dot of coloured glycerine ink. From the coordinates of the ink marks, the elevation of the eyehole above the mirror, and the length of the base line it was easy to calculate the $X$, $Y$ and $Z$ coordinates of the target (figure 2a). He attributed his proficiency in writing the equations on the spot to

Figure 1. The inventors of the mirror method. (a) A. V. Hill in 1914. (Churchill Archives, Cambridge.) (b) Horace Darwin. (Royal Society.)
over-studying for the Cambridge Mathematical Tripos—he was third Wrangler. His exposition was gripping. His handsome face sparkled when he talked science. His prematurely greying hair added an air of authority, which was coupled with compelling, boyish enthusiasm—science is such grand fun.

Darwin ordered the mirrors, the heavy tables for bases to hold them precisely level, and the viewing eyeholes from the Cambridge Scientific Company, at a cost of £70. He requisitioned telephone wire and telephones. The MID obtained a short extension of Hill’s leave and applied for his transfer. Now they needed more clever hands and minds. The Military Service Act of January 1916 made all single men aged 18–41 years liable to call-up. A few occupations, such as clergymen, were exempt—mathematicians and scientists were not. (Four months later the exemption for marriage was eliminated.)

Hill started recruiting in Cambridge. He began at the top, sounding out the renowned mathematician G. H. Hardy (1877–1947). He was always an odd fish and I remember

![Figure 2. The Darwin–Hill mirror method and a major application.](image-url)

(a) Two mirrors are placed far apart. On a signal the observers look through their eyeholes and mark where a target in the sky appears on their mirror, indicated by the asterisks in the drawings. Its coordinates on the mirrors are used to calculate the three-dimensional coordinates of the target from the mirror on the left. (b) The calculated trajectory of a shell (+ + +) fired from an AA gun and the position at which three smoke shells with different fuse setting would explode (asterisk). The Brigands measured the locations of the shell bursts and then by trial and error determined the parameters for the trajectory that fits the points.

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Hill started recruiting in Cambridge. He began at the top, sounding out the renowned mathematician G. H. Hardy (1877–1947). He was always an odd fish and I remember
him expressing great indignation and saying that although he was ready to go off and have his body shot at he was not prepared to prostitute his brains for purposes of war'.

Hardy did suggest an outstanding student Edward Arthur Milne (1896–1950)—‘Apparently he was ready to have Milne’s Brains prostituted’.

Milne was a slight, pale, 20-year-old mathematics scholarship student at Trinity. He had tried to enlist but had been rejected because of his abysmal eyesight; his thick spectacles gave him a pop-eyed, slightly bewildered expression. He listened quietly to Hill’s proposal. He started to reply hesitatingly, in low tones, but when warmed up his quick comprehension and keenness showed that he was a good catch. Milne went on the MID payroll at 25 shillings per week.

Hill heard that his contemporary, Ralph Howard Fowler (1889–1944), was in Cambridge. A fellow Wrangler (after numerical ranking was eliminated), he was convalescing from a nasty shoulder wound suffered on Gallipoli. Fowler had been commissioned in the Royal Marine Artillery at the outbreak of the war, just before becoming a Fellow of Trinity, possibly winning such a coveted military appointment for his prowess on cricket pitch and golf links rather than his standing in the Tripos. Now he was a first lieutenant. He was delighted to do something useful.

Hill’s transfer to the MID was approved. His military servant, Freeman, a former plumber, was also reassigned. When the mirrors were ready, each 2 feet (ft) square and ruled in both directions with a 1 cm grid, Hill, Fowler and Milne tested them with a tall radio wireless mast on the Huntington Road in Cambridge whose height was also measured with theodolite and measuring chain. The two estimates agreed nicely. The definitive test was at Northolt Aerodrome. The MID obtained 2 miles of scarce telephone wire, partly used but ‘in good order’, which they threaded along a hedge at the side of the aerodrome. The first test with an aeroplane was done less than a month after Darwin and Hill had met in London. The base between the two mirrors was 4000 ft. The height of the first aeroplane they followed was not known; they marked points at intervals of 3–5 seconds. Their results were 1810 ft, 1800 ft, 1845 ft, . . . , 1905 ft, 1935 ft, 1965 ft; obviously the aeroplane was climbing. The next flight was laid on for them. The pilot was to fly at a constant altitude and to measure height with his aneroid barometer. On the first run, the determinations were 3840 ft, 3820 ft and 3800 ft. The flyer’s measurement was 4000 ft. They must have been elated. We know that they had fun because Hill teased Fowler about profligate abuse of physical strength, claiming that he repeatedly heard on the telephone line from the observer on the second mirror, ‘I have broke my pen’. It was an impressive first step, as Hill liked to say: ‘A thing never becomes so real as when one measures it . . .’.

Hill wrote to the comptroller of the MID, Colonel Goold-Adams, listing needed supplies. Some of the results of the first trials were crossed out on the back of the paper he used for the letter. The results of the tests were sent also to Lieutenant W. L. Bragg (1890–1971), who was working in France on a method for locating enemy guns by recording their boom with a widely spread array of six microphones. On Thursday, 10 March 1916, Colonel Goold-Adams and two other MID bigwigs came to see the Darwin–Hill mirrors in action. The base was extended to 6650 ft. The results were excellent, and Hill enthusiastically reeled off a list of what the team could do: ‘training AA crews, speed tests and measuring wind velocity, checking aneroid readings, used in field to observe target and burst and hence used for spotting’. Hill and Fowler wrote a secret pamphlet (M.I.D. 2) describing the apparatus.

Why did they not use standard optical rangefinders? They were lent a Barr & Stroud instrument for testing, modified so that it could be pivoted to point at aerial targets and
with an added scale showing the angle of tilt. A proficient, agile operator who could keep focused on a rapidly moving aeroplane obtained good results, but the instruments were so expensive and in such short supply that for the time being AA needed to find simpler options.

MORE RECRUITS

Hill was still short-handed. Following a lead from the director of the National Physical Laboratory (NPL), he wrote to William Hartree (1870–1943) (18th Wrangler in 1892) in Guildford, asking him to come, ‘on ridiculously short notice’, to Northolt Aerodrome the following day. Hartree was a 45-year-old engineer, with ample income from a family marine engineering business on the Thames. He had retired from lecturing at Cambridge to experiment with wireless. Hartree was unable to oblige because he was now a war worker, employed by the Post Office as a ‘skilled workman’ testing local lines. After some back and forth he agreed to resign and to find lodging near Northolt so he could be there in the early morning when aeroplanes flew. Hill was not impressed when he first saw this ‘shabby, middle-aged linesman’.

A few weeks later Hill met Hartree’s eldest son, Douglas Rayner (1897–1958), who had just started mathematics at St John’s College, Cambridge. He was a quiet, self-effacing, brainy youth also interested in railways and music—as an amateur conductor and percussionist. Hill invited him to join. A wag in the group dubbed him Hartree II. Later, Hartree’s second son, Colin, also joined—Hartree III.

Hill was elected to a fellowship at King’s College, Cambridge, which protected his academic future. A dinner in hall was followed by a letter from a distinguished King’s mathematician, William Herbert Richmond (1863–1948) (third Wrangler in 1885), who offered to help. Richmond worked on algebraic geometry and was a notable musician, naturalist and raconteur. Perhaps his greatest attribute was ‘his genius for friendships with men of all academic generations’.

Another elderly recruit was Geoffrey Thomas Bennett (1868–1943). He was Senior Wrangler in 1890. Now he was a fellow of Emmanuel College, Cambridge. His competitive spirit is displayed by his standings for the three times he entered the University Bicycle Club 50 Mile Race: third, second and first. He was also an accomplished pianist—he would improvise by the hour. (Later in the war he transferred to the gyrocompass division of the Admiralty—they required his mastery of dynamics.)

HEIGHT FINDERS

Horace Darwin had consulted Bennett earlier about AA gunnery. Bennett grasped that gunners needed a simple way to measure their target’s height. An aeroplane’s range was constantly changing, but usually it kept at the same altitude. For height determination he set up two stations separated by a substantial distance. It is difficult to keep a swiftly moving aeroplane in the restricted field of a theodolite. Instead each observer was provided with an adjustable rectangular panel the size of a small table. The panel was held high enough above the ground so that the observer could sight along its top face. He rotated it toward the target, and adjusted its angle so that the face of the panel lined up with the target. The angles measured by the two panels and the distance between them
gave the height of the target. Once the target’s height was known, its range could be calculated from the angle of elevation provided by the scale on an aimed gun, which gunners called the quadrant elevation. Bennett joined the group, now based at the NPL. The height finder did well when tested by mirrors, but the panels were heavy, cumbersome and difficult to move about.

William Hartree suggested replacing the panels by a pair of cables mounted on poles at right angles to one another, the lower cable just above man height and the upper several feet higher. The observer would slide a simple sight along the lower cable until the target was in line with the sight and the upper cable. Height was calculated from the distances between the two stations and the measured angles. Hill purloined a few old gas pipes, added some wire and tape, and they assembled a prototype. It worked nicely. Their second instrument was made honestly at a cost of £2 6s. In May 1916, 20 Hartree instruments were sent to the army in France, where they gave good service.

A few months later the MID work on range and height finders was moved to Farnborough, Hampshire, manned by a lieutenant and 15 ‘light-duty’ men. Later they relocated to Rochford, Essex, where they improved the instrument by bracing the cables to keep them from sagging. Later, Hartree I and II added a second scale to the lower wire. When the angle was telephoned from the apparatus at the other end of the base, the operator set this value on the second scale and then could read off the height of the target directly.

The mirrors, placed a mile apart, were used to determine the path taken by bombs released from aircraft. The aviator fired a Very pistol when the bomb was released, and its position was marked on the two mirrors at set intervals.

TRAJECTORIES

They used the mirrors to locate a few shell bursts during a test firing of a 4-inch gun. But ammunition was in such short supply that no further test shots were scheduled by the army. However, Commander ‘Barmy’ Gilbert of the Royal Navy had devised a new AA gun sight; a prototype was mounted on a 6-inch gun on a monitor stationed at Great Yarmouth. It was to fire a series of test shots with different fuse settings; Darwin arranged for Hill’s group to be present. They set up the mirrors. On the first day they located three bursts and lost one in a cloud. Then the weather turned foul, in subsequent days there were only brief clearings, during which they pinpointed 20 more bursts. At long last there was a glorious clear day, but it was Sunday and the monitor’s captain refused to violate the Sabbath. The gray pall returned. Hartree passed the tedious days by composing a heroic poem about AA gunnery. To keep up morale, Hill responded with verses ‘in the style of W Hartree’. It was three weeks before the test firings were completed.

Hill was sent to show their results to an ordnance expert in Portsmouth. He was invited to dinner, where another guest was the experimental officer from the Royal Naval Gunnery School. One of Hill’s precepts was ‘The secret of science is to ask the right question ...’. He told his dinner companions that the weeks at Great Yarmouth had taught him that the gun table for the 6-inch gun was hopeless for AA: its numbers for firing at high quadrant elevations were crude guesses. For AA gunnery the only trustworthy information in the table was the velocity at which the shell left the muzzle and the resistance to the passage of the shell close to ground level; variables such as the reduced resistance expected at high altitudes were ignored.
This uncertainty could be resolved by firing a series of shells with different fuse settings from a gun at a fixed quadrant elevation and determining where the shells burst. They knew the position of the gun and its muzzle velocity. Then they must fit the calculated trajectory through the points (figure 2b). The parameters obtained would enable them to calculate accurate range tables for AA guns.33

Fitting curves was second nature to Hill. He had begun with the contraction of a frog muscle exposed to various concentrations of nicotine.34 He fitted the points with an equation that assumed that the strength of contraction was proportional to the fraction of receptors in the muscle that had bound nicotine molecules.35 Next he fitted data obtained by Joseph Barcroft (1872–1947) on the disassociation of bound oxygen from haemoglobin with an equation describing several oxygen molecules successively unbinding from sites on the haemoglobin molecule.36 He assured his fellow diners that fitting the points on a shell’s trajectory would be difficult but possible. But how could they obtain enough measurements to do the job?

His chance dinner companion was certain that Hill would be welcome at the Royal Naval Gunnery School; they were about to test an experimental AA mounting for the 3-inch gun for use on submarines. Thanks to this opportune encounter, Hill’s team came to HMS Excellent, the Royal Navy Gunnery School in Portsmouth harbour. The school had started aboard ship, but when the short-range broadside became obsolete she transferred onto Whale Island.

The ship’s captain was Commander Vincent Lewin Bowring, a merry chap who maintained that he detested the roar of gunfire because it inhibited the growth of his flowers and vegetables. According to Hill, Bowring’s duties were ‘To look after pigs, fowls, old horse and dogs, grow oats and vegetables, produce chickens and eggs, look after the welfare of some 2000 officers and men, and several gardens; and weekly inspect some 65 women W.R.N.S. to see that their clothes were properly worn’.37 Without waiting for approval from his superiors, on the first clear day after the mirrors were surveyed into position Bowring had a 3-inch gun fire shells at a high quadrant elevation—testing the gun’s mounting. As Hill put it, ‘it was my luck my party was standing about in the neighbourhood during this trial—with their instruments’.38 On the first day, 19 shells were fired. Fourteen of them were, in gunner’s jargon, blind: that is, they did not explode. This problem will be dealt with later. The five shells that exploded were far from the points predicted by the range table.

Naturally, there were queries in the officer’s mess about the identity of this incongruous team. A captain of infantry who looked born for a uniform—even in old age Hill’s martial bearing was noteworthy—and a captain of marines with a wound stripe were not too odd, but what to make of six civilians, youths and greybeards? Some inspired wag—my guess is Bowring—decided that they were indubitably a band of brigands. Henceforth, they cheerily identified themselves as ‘Hill’s Brigands’.

**SOLVING THE BALLISTIC EQUATIONS**

Trajectories are relatively unimportant for terrestrial gunnery. What counts is where the projectile lands and how long it takes to get there. Most trajectories were calculated by solving a set of approximate equations derived by the Italian mathematician Francesco Siacci (1839–1907). His method is only applicable to quadrant elevations less than 15°, and assumes that the density of the air is uniform throughout the trajectory. The
alternative, far more laborious, method to calculate a trajectory is by solving the simultaneous
equations describing the path taken by a fired shell, how gravity alters its path and how
resistance to the passage of the shell affects its progress. Resistance is a function of shell
size and velocity, altitude and temperature. It seemed that AA trajectories would have to be
calculated by solving the equations numerically, taking very small time steps and recording
each result to many significant figures. This method was called ‘small arcs’.

Hill learned that Lieutenant J. E. Littlewood (1885–1977; bracketed Senior Wrangler
1905) had a new method for calculating AA trajectories. Hill knew Littlewood as a
Fellow of Trinity, and every Brigand knew him as a leading mathematician. At the
outbreak of the war he had been called for active service in the Royal Garrison Artillery.
He was at a large camp where he trained gun crews and enjoyed horseback rides. Off
duty he did mathematics: in 1915 he and his co-worker G. H. Hardy published three
papers, and from 1914 to 1918 Littlewood published 12 papers, 11 with Hardy as co-
author. Distance did not matter; even when both were at Trinity they exchanged ideas
largely by letters carried by the college servants.

In the autumn of 1915 Littlewood was orderly officer, idling away his watch in the early
hours of the morning. On an office table he saw a sketch of a trajectory fired at a relatively
high quadrant elevation; someone had been thinking about AA gunnery. He gave it a
moment’s thought. The next day his colonel stumbled across the sketch and asked about
it. Littlewood provided a brief, lucid exposition of the problems of calculating AA
trajectories. This started him thinking about how to bypass wearisome small arcs. He
devised an indirect method, using small arcs to calculate the time–height points for
vertical (90°) fire—far easier with only two dimensions—and the Siacci equations to
calculate time–height points for horizontal fire (0°). Then he devised an ingenious
procedure to interpolate between these two extremes to find the trajectory at any desired
quadrant elevation. There were still many tedious steps, but fewer than with small arcs,
and fewer significant figures had to be carried forward.

Littlewood was seconded to the Ordnance Committee at Woolwich, which changed his
lifestyle agreeably: he lodged with friends in London and was not reprimanded when he
appeared in uniform carrying his umbrella. Littlewood’s interpolation scheme did not
impress Hardy: ‘Even Littlewood could not make ballistics respectable’. And there were
few data with which to test whether his calculated trajectories matched reality.

**Testing the Interpolation**

The Brigands used Littlewood’s interpolation to fit trajectories to their measurements of shell
bursts and found reasonably good agreement. He visited occasionally to consult and to
demonstrate his latest tweaks. They began with the customary assumptions about how
resistance is altered by velocity (v), altitude and temperature. If they saw they were not
going to fit the points, they made a guess at better parameters and started again—tedious,
to say the least. A major presumption was that resistance is proportional to \( v^2 \). With \( v^2 \)
the curve strayed from the points. The fit was much better with \( v^3 \), but the calculated
resistance was in senseless units. Even Hill did not see a way out. Milne was a quiet lad
who kept silent until an idea came, which then spilled out excitedly and lucidly. He
suggested that the third v must be a ratio to another velocity, so the units would cancel
out properly, and suggested trying the ratio of v to the speed of sound. It fitted nicely.
Hill was often away seeing to other Brigand units that you will read about below and at meetings in London and in France, presumably often travelling on his beloved motorbike. The credentials of his deputy, Fowler, as a group leader at a naval establishment were admirable: exuberant good humour, infectious laugh, sporting fame and frame—scarcely the stereotypical reclusive scientist. But he was not on Excellent for long. Despite pleas from the MID, the navy relocated him to inspect steel at a shipyard. Undaunted, Horace Darwin went directly to the top: writing to First Lord Arthur Balfour, a contemporary of his at Trinity. It worked: ‘Fowler turned up for duty with my gang in two or three days’. Fowler occasionally ruffled the feathers of fellow Brigands by rough and autocratic ways, as Milne wrote to his mother: ‘Fowler comes fussing around, ordering everybody about without considering whether it is the best thing they can do. He always means astonishingly well, but I think he would get rather a shock if he knew how he annoys us sometimes’. Hill would restore good feelings on his next visit. Blow-ups should not shroud the intellectual pleasures that Fowler provided. As Milne later wrote:

> It was always tremendous ‘fun’ collaborating with Fowler. Usually it was not he (to be quite just) who produced the first original idea; but he tossed it back with lightning speed; and you had to be very agile to field it properly. There was a thrill about the investigation—it was as though one were physically in love with a particular problem, when Fowler was present.

By the end of the war, Fowler commanded 15 Brigands on Excellent: 8 officers and 7 civilians. He enhanced their popularity in the officer’s mess by obtaining vintage port from the cellars of Cambridge colleges, for example, 1887 at a thrifty 2s. 6d. a bottle. Richmond was the oldest Brigand, but he was always willing to bike out to make measurements—which was disagreeable when coastal winds raged. He also took his share in the prolonged, tedious calculations that followed each successful trial. Despite his shyness, he fitted in easily. He and Milne, one of the youngest, were roommates. By mid November they had located with mirrors the smoke puffs from the detonations of 150 rounds of shell fired from a 4-inch gun at different quadrant elevations and had made a good start on a series of 630 rounds fired by 3-inch guns with the No. 80 fuse. The 3-inch 20-hundredweight (cwt) gun was the backbone of British AA, and was so good that it was used in World War II. A 16 lb shell left with a muzzle velocity of 2500 ft s\(^{-1}\), which could send it up to 11 000 yards—well above the ceiling of aeroplanes of that time. Shooting had to be precise because the shrapnel from an exploding shell would only hit a target within a sphere 18 yards in diameter.

Squatting beside Darwin–Hill mirrors was uncomfortable, so when possible they were replaced with vertical glass windows, etched with calibration lines and viewed through eyeholes set at known distances. Of course they were frustrated by the glut of cloudy days on the English south coast and the tedious trial and error needed to find parameters that fitted. Hartree I was invaluable because: ‘Nobody could see shell-bursts so nearly into the sun...’. And Hartree II relished numerical calculations and devised clever shortcuts that made them easier.

Hill convinced the Ministry of Munitions that AA guns should fire heavier shells, containing more shrapnel bullets, although the added weight decreased the muzzle velocity. (For instance, a 3-inch 20-cwt gun with 12.5 lb shell had a muzzle velocity of 2500 ft s\(^{-1}\). A 16 lb shell decreased the muzzle velocity to 2100 ft s\(^{-1}\).) Lower muzzle velocity was a benefit, because the higher the velocity the faster the rifling in the gun
barrel erodes, and wear was a serious concern for guns firing 30 rounds per minute. The MID also recommended that all of the 3-inch guns in the UK should be in a single pool, whether manned by army or navy, so to even out rifling wear, guns were rotated between very active and less active batteries.

The conscription authorities relentlessly pursued the young Brigands, even if physical deficiencies would keep them behind the firing line. Hill put them forward for temporary commissions. While his nominations worked their way through the bureaucracy, Captain Bowring claimed that he ordered Excellent’s watch to arrest any recruiting sergeant who set foot on the bridge to the island. In 1917 Milne, Hartree II and another young Brigand were commissioned as lieutenants in the Royal Naval Volunteer Reserve, pleased with the ‘pair of curly gold bands, surmounted by a loop’ on their sleeves. The down side was that their pay decreased by £30 annually.

**WIND AND FUSES**

While Brigands waited for scheduled aeroplanes to fly over or for a gun to fire, they measured the speed and heights of clouds. They were flabbergasted by their speed. Hill checked with meteorologists to make sure their values were not preposterous. He purchased balloons manufactured to display advertising slogans above cities and they tracked them as they rose to the heights while buffeted by the winds. Wind forces and directions vary with altitude. From these data they calculated how the shell’s path was altered by the winds it encountered at different altitudes. This calculation was complicated, so Richmond and Milne devised an integral yielding an ‘equivalent constant wind’ that gave gunners a single correction for wind velocity and direction. Brigands were sent to the nearby aerodrome at Gosport to fly up to the highest altitude the aeroplane could attain with a passenger aboard, who recorded altitude and temperature. On the way down the pilots enjoyed disconcerting passengers by demonstrating acrobatics. Unperturbed, Milne loved to fly and became fascinated by the atmosphere.

The Brigands wondered why so many shells fired at high quadrant elevations were blind and why those that did explode burst later than stipulated by the fuse setting. Hill realized that ‘much of the “bad-shooting” by AA guns was really due to unanticipated variations in the fuse burning times’. They began to gather the data needed to write an equation describing how altitude alters burning time.

Fuses were screwed into the shell’s prow. A time fuse was an arc machined into the steel that was filled with gunpowder. When the shell was fired, its acceleration drove a firing pin onto a percussion cap, which ignited the gunpowder at one end of the arc. The powder burned its way along the arc until it reached a channel leading to the shell’s magazine, which then detonated. A gunner set the fuse time by rotating the gunpowder-filled arc with a spanner to alter its position relative to the channel leading to the magazine. The gases generated by the burning powder left the arc via a narrow passageway to the outside: the fuse hole. An obvious hypothesis was that at high altitude low temperature decreased the powder burning rate. The NPL had a low-temperature room. Three Brigands stationed there found that temperature had little effect. However, fuses burned more slowly when barometric pressure was decreased. External pressure is complicated for a flying shell, because the pressure at the fuse hole depends both on the external air pressure and on the shell’s velocity: the higher the velocity, the higher the pressure at the
fuse hole. It also depended on the position of the fuse hole, which varied in different models of fuse. As the data came in, the Brigands realized that there is no global theory; they gave up trying for an equation and instead measured the detonation times of each type of shell fired with different fuse settings and at different quadrant elevations.

Then they hit another stumbling block. Fuses burned more slowly when the shells were fired from guns with a higher muzzle velocity. As a result of the rifling of the barrel, a higher muzzle velocity increases the rate at which a shell spins when it leaves the muzzle. (It spins throughout flight because air offers little resistance to spin.) Hill requisitioned two custom-built 3-inch guns with altered rifling. One had more twist than usual. Shells fired from it at a high quadrant elevation were often blind. Some of the shells fired from a gun with usual twist also failed. All those fired from a gun with decreased twist exploded. Trajectory was almost unaltered by changes in spin. Consequently the rifling in the 3-inch gun was changed to lower spinning rates.

Further work on the effects of spin on the burning of gunpowder was done at University College London (UCL) in the laboratory of Professor Goudie, who had a turbine that could spin fuses at speeds up to 30,000 r.p.m. The rate of fuse burning decreased as the rate of spinning increased, as a result of centrifugal effects on the burning slag. Three Brigands were at the UCL laboratory. Arguably, the work on fuses was the Brigands’ most important contribution to AA gunnery.

Hill was always on the move, but kept in the lead. He came up with most of the brainwaves that the Brigands worked on. His self-control helped his men to keep on an even keel in emotional times, when friends and relations were being killed and wounded. For instance, Fowler’s brother was killed on the Somme in July 1916. Hill was ‘slightly humorous about the Germans. One might marvel at their misbegotten ideas, but hate was not helpful’.51 His restraint crumbled only when something was hilarious—tears would stream down his cheeks.52

The Germans dropped 116 tons of bombs on England in 1916, with the aim of cracking civilian morale.53 The attacks kept many guns and men away from the battlefronts. Total casualties in Britain for the year were 293 killed and 651 wounded, some by shrapnel balls and fragments of AA shells that splattered down during the raids. On 2 September, 16 dirigibles attacked London. One was shot down by a British night fighter with phosphorus-charged incendiary machine-gun bullets invented by the physicist Richard Threlfall (1861–1932),54 which detonated the hydrogen that made them buoyant. At the end of 1916 the German Army donated their surviving airships to the navy. The postwar German evaluation was that these assaults ‘yielded practically no results and entailed heavy loss of airships’.55

THE GALTON LABORATORY

The Brigands completed a ‘trajectory time & fuse chart (Graphical Range Table) for fuse 65A fired from a 3-inch 20-cwt gun for up to 30 seconds time of flight’. But they did not have time or hands to calculate the many tables needed for different guns and shells. To unearth more workers, Hill wrote to friends who might know talented youngsters too young for conscription. One of the friends wrote to Professor Karl Pearson (1857–1936), Director of the National Eugenics Laboratory at UCL, to ask whether his son might be interested. Pearson volunteered himself and his laboratory, so Hill reported in December
1916: ‘An offer of assistance in Computation has been made to me . . . he has 8 efficient computers [as they called the staff] & suitable calculating machines, which he has very kindly offered to utilize for our work’.56

Pearson (third Wrangler in 1879) was a true polymath with an idiosyncratic personality.57 He studied literature and practised law before becoming a full-time academic. He was too hot-tempered to attend scientific meetings; if he came there were violent shouting matches. He had collaborated with Charles Darwin’s half-cousin, Francis Galton (1822–1911),58 who left a bequest for a chair in eugenics and a laboratory at UCL with the provision that Pearson should be its first incumbent.59

Pearson’s group completed graphical range tables for the 3-inch gun and agreed to do the computations for the 4-inch QF Mark V gun, with a muzzle velocity of $2550 \text{ ft s}^{-1}$ for quadrant elevations in $\frac{5}{8}$ steps. But there was an eruption when Pearson saw that the printed tables for the 3-inch gun were initialled ‘K.P.’, rather than the ‘G.L.’ (Galton Laboratory) he had specified. After he was placated, Hill arranged for the three male and three female computers in the Galton Laboratory to be paid three months’ salary by the MID for work during the long vacation, based on their salaries of £100 to £150 annually.

Surprisingly, the next blow-up was triggered by the genial Richmond, who was standing in while Fowler was away. The Brigands always calculated the first, second, and often higher differences for the coordinates. He wrote to Pearson in October 1917 that in the latest table from the Galton the differences became impossibly irregular after 37 seconds. There had been a mistake. Pearson erupted. His honour and his laboratory’s honour had been besmirched. He would do no more. Richmond’s abject apology was rejected, as was Hill’s. Ultimately Colonel Goold-Adams paid a visit; he smoothed the water. Computations continued and the MID bought several new calculating machines for the Galton. The problem had come about because someone at the Galton had entered a point in the table taken from the graph rather than from the actual computation.

Even though shell trajectories and bursting times and the coordinates of the aeroplane were now known, they were still hard to hit. Even a slow-moving aeroplane making 60 miles per hour would move almost 30 yards in a second, and the shell might take tens of seconds to reach its target. To give the gunners a chance, they needed to know how fast the target was moving so that they could lead it by an appropriate distance. In October 1916 the Brigands were lectured about a French contrivance: the Brocq electromagnetic predicting apparatus. The British had purchased six of them. The instruments had eyepieces for two observers. Each observer kept the target fixed in his telescope’s crosshair, one following the target in the lateral dimension, the other in the horizontal dimension. Target height and fuse timing were dialled into the apparatus, the reading was corrected for wind velocity, and the results were passed along to men standing beside gun, who adjusted the pointer’s sights to lead the target. The apparatus evolved so that an electrical computing network output the corrections to dials viewed by the pointers. Still later, the Brocq instrument adjusted French gun sights directly by electromechanical coupling. The Germans used a similar apparatus.60 In practice, as we shall see, AA gunners customarily used a broader brush.

TRAVELLING CIRCUSES

To interact with AA gunners in the field, in 1917 Hill established a travelling detachment of three officers and four other ranks. They would set up mirrors near an AA battery. One gun
would fire a smoke shell. Then every gun in the battery would fire eight or ten rounds at the
smoke puff—the days of short ammunition supply were long past. The results enabled the
gunners to adjust their sights. Hill wrote to Pearson: ‘Fowler and Milne are now in
Scotland going around with our so-called travelling circus, recording high angle “battle
practices” with great success’.61

Then Fowler’s circus went to France, and he visited Brocq. Soon two Brigands circuses
were based there and Hill was searching for additional men to establish a third. The tactic
used was for batteries of AA guns to fire together to try to set up a wall of shrapnel
barring their target’s path. The best method, as Hill put it, was ‘to fire a very large
number of shots in a very short period of time distributed more or less evenly over a
large region through which it is known that the target must pass’.62

An intruder would usually be spotted at a distance of 7000 yards. Rangefinders provided
range and height measurements. The battery commander used a special slide rule to calculate
the fuse settings and quadrant elevations for his guns. They opened fire when the range fell to
6000 yards, each gun firing four rounds in quick succession. The commander observed the
shell bursts through binoculars equipped with a graticule, estimated the error, and issued new
settings for the next salvo of four rounds. If they got a firewall in place, the intruder would
usually avoid it by turning tail.63

**Sound Localization**

In 1917 the German air force struck at England with large, long-range bombing planes, starting
with two-engined ‘G-planes’, commonly known as Gothas after one manufacturer. They also
were building four-engined giant bombers, or ‘R-planes’. The Gothas bombed in daylight for
maximum psychological effect, targeting government buildings in Whitehall and press
buildings on Fleet Street.64 Their crews breathed O2 as they flew to London at 16 000 ft, but
bombed from lower altitudes. The top speed was 80 miles per hour, but in a strong headwind
they were lucky to reach 50 miles per hour—it was a long, exhausting journey.

On 25 May 1917, 23 Gothas struck, killing 95 people and wounding 195. On 13 June, 18
bombers killed 162 Londoners and wounded 432. Most poignantly, 46 of those who died
were children attending kindergarten. The next strike by 20 Gothas was on 7 July, killing
54 and wounding 196. Thereafter, to reduce their losses, the Germans shifted to night raids.

The British interceptors had to meet the bombers at high altitude. The Sopwith Camel, the
latest British fighter, took roughly 25 minutes to make the climb. Advance warning was
crucial. The attackers were often invisible above the clouds. Lieutenant William Tucker,
who with W. L. Bragg had invented the hot-wire microphone,65 now worked on long-
range sound detection. They built parabolic sound reflectors into the white chalk cliffs
along the coast or above ground from concrete.66 Tucker microphones were mounted at
the focus to respond to the sound of the approaching bombers. They also mounted
microphones in pits along the coastline, to catch the sound when the enemy passed
overhead. Hot-wire microphones were sensitive but had a poor frequency response for
aircraft noise, and sound warning only became effective in 1918 when they could amplify
the output of less sensitive magnetic microphones with vacuum-tube amplifiers.67

Work on devices to locate aircraft by sound had begun before Hill appeared on the scene,
but he took it on and the investigators became Brigands. Unaided humans are very good at
localizing a sound source in the lateral dimension, working primarily from the difference in
the arrival times of the sound waves at our ears. We are less successful in estimating the
elevation of a sound, trying to do so by cocking our heads up and down. Louder sounds
are localized better, so intensity was increased by listening through a wooden trumpet,
connected to the listener’s ear by a rubber tube and an earplug, like a physician’s
stethoscope. The trumpets used in aircraft detectors amplified sound intensity sevenfold to
tenfold. Localization is best with two trumpets 5 ft apart. For height estimates a second
pair of horns was added, mounted on a vertical axis, directing sound to a second listener.
Each listener adjusted his horns so that the sound seemed to be directly ahead, and the
bearing and height were read from dials. They were accurate to 0.5°, and Hill realized
that greater precision would not pay off. As he wrote years later:

Airplanes are moving at half of the speed of sound and air is never a clear medium,…
hearing through the open air is more like seeing through a pane of ribbed glass; the
inequalities of the density of the air bend the rays of sound out of their straight path.

These instruments were in action in 1917.

Milne was now occupied with sound and searchlights. At night the coordinates of an
intruder determined by the listeners were passed on to the searchlights. When one had an
aeroplane in its beam, the gunners stopped setting up the barrage and aimed at the target.

1918

Pearson finally gave up in disgust in early 1918, but the computers in the Galton Laboratory
continued as employees of the MID, supervised by a deputy responsible to Hill. Four more
calculating machines were bought at £25 each. On 23 April 1918 the team handed over its
100th graphical range table.

In May 1918 the Germans made their last air raids on England; they had lost 49 Gothas and
137 aviators, most of them when landing—the Gothas flew atrociously after they had dropped
their ballast. London was defended by 266 AA guns, 159 day fighters, 353 searchlights and
123 night fighters. Fragments of AA shells killed 167 British civilians and wounded 432.

AFTER THE WAR

A striking testimony to their intellectual enthralment was that Fowler, Richmond and two
others arranged to stay on at Excellent to finish the mathematics describing the motion of
a spinning shell ‘at velocities both greater than and less than the velocity of sound’. They
wanted to allow for the wobble of the shells, and Hill showed them how to measure
wobble by firing the shell through a series of 10–12 stiff pasteboard pistol targets. Deviations in the successive holes were caused by the yaw of the shell.

Hill was subpoenaed to testify at the trial of a lawsuit initiated by ex-Sergeant-Major Hanks,
who had invented a gun sight that was tested with the mirrors. He and his investors from the
City of London attended the test in formal morning wear, but the projectile missed the target by
0.8 mile. His lawsuit claiming scientific bias failed, but it gave Hill a chance to make a
splendid drawing (figure 3b). (He was also a skilled amateur photographer.)

Major Hill, Captain Fowler, and Hartree I were each awarded the OBE. Hill issued
certificates—he drew them and 100 were printed by the Ordnance Committee—licensing
the recipients to practise as a Brigand at a specified rank. Some of them are shown in
figure 3a. They were an intellectually distinguished group: four Brigands were Senior Wranglers. Hill also sat down with scientific Brigands to discuss postwar plans and to see how he might help. Milne was thorny. He insisted that at the age of 23 years he was too old to be an undergraduate (not mentioning that his father had died and family finances were stretched). Hill said he was ‘being silly’ and finally persuaded him to return under a special programme that allowed veterans to obtain a war degree without the usual examinations. Shortly after returning to Cambridge, Milne was elected a fellow of Trinity and given a paid post in the Solar Physics Laboratory. Fowler was adviser for one of the three theses he submitted. Milne became a leading astrophysicist. Hartree I so liked working with Hill that for years he was a volunteer collaborator working on muscle. Hartree II became a leader in numerical computation and was instrumental in introducing digital computation to Britain. Bowring was retired as a captain in 1921.

The older mathematicians returned to their prewar themes, but Fowler had a new penchant for mathematical physics. Hill returned to physiology at Cambridge, even though before the war he had been about to become a lecturer in physical chemistry. Then he moved as professor to Manchester and finally to UCL. He was awarded the Nobel Prize in Physiology or Medicine in 1922 for measurements of heat production during muscle contraction and recovery. He went on measuring muscle heat with more and more sophisticated instruments for years. He established the Biophysics Department at UCL and his students helped to launch the field.

The list of offices he held as a scientific statesman is so long that only a few will be cited. He obtained positions for Jewish refugees from the Nazis, including his successor at UCL, Bernard Katz (1911–2003; Nobel laureate 1970). As Biological Secretary of
the Royal Society he was instrumental in assembling the Central Register of Scientific and Technical Personnel, which enabled the government to tap talent needed in World War II, and incidentally kept these men out of the firing line. With his high repute in the military, he was on the committee that oversaw the development of radar and its use in aiming AA guns. He recruited bright youngsters, including his son David Keynes Hill (1915–2002), to do the research. He even served as an MP. He continued to lead with intellectual brilliance and relaxed good humour—above all, science was jolly fun.

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NOTES

1 Much of the information in this article comes from Hill’s correspondence and his reports to the MID in the Churchill Archive Centre, Cambridge. The unattributed quotes that follow are taken from letters and reports in AVHL I 1. He wrote a history of their work: A. V. Hill, ‘Antiaircraft Experimental Section of the MID (1916–1918)’, AVHL I 1/37 (1918). The other primary source is A. V. Hill, Memories and reflections (3 volumes) (Royal Society, London, 1974). Hill annotated the manuscript in the Royal Society Library by hand.
4 He was in the Cambridgeshire Regiment, which during the war lost 864 dead. Great Britain, The roll of all ranks of the Cambridgeshire Regiment who died in the service of the country during the War against the German Empire 1914 to 1918 (Typographia S. Dominici, Ditchling, 1921).
6 The number of civilian casualties during the war is given in Public Record Office AIR 1/544/16/15/13.
8 The camera obscura was used for training bomber pilots during both world wars. Coordinates were obtained from the focal length of the lens and the altitude of the aeroplane determined by its altimeter. J. H. Hammond, The camera obscura, a chronicle (Adam Hilger, Bristol, 1981).
9 The mirror position finder. AVHL I 1/9.
10 There is no reliable single multiplier for converting the value of £1 in 1914 to that of today. I estimate roughly by using 200 as the conversion factor. W. Van der Kloot, World War I fact book (Amberley, Stroud, 2010).
13 Milne preferred to use Arthur as his Christian name.
Milne’s letters are at Oxford University in the Bodleian Library Special Collections and Western Manuscripts: CSAC 1026.84. Otherwise unattributed Milne quotes are from them. Extensive quotes from his wartime letters appear in M. W. Smith, ‘E. A. Milne and the creation of Air Defence: some letters from an unprincipled Brigand’, Notes Rec. R. Soc. Lond. 44, 241–255 (1990).


Milne, op. cit. (note 16).


Sir Richard Tetley Glazebrook (5th Wrangler 1876; 1854–1935), who was Hartree’s brother-in-law.


Miss Fawcett had a higher grade but women had no standing in the competition.

Notes on height finder, Public Record Office MUN 7/343.

Monitors were shallow-draft craft mounting very large guns, designed to provide firepower for amphibious landings along the Baltic coast, one of the favourite pipedreams of the prewar Admiralty. Some were used on D-Day in 1944.

Churchill Archives AVHL I 1/36.


Their work is summarized in A textbook of AA gunnery, Public Record Office WO 279/230.


Later workers showed that two nicotine molecules bind to each receptor.

Later workers established that there are four binding sites and that the binding constant changes according to the number bound.


Milne, op. cit. (note 15), states that this was first done at Great Yarmouth, but I have followed Hill (1974), op. cit. (note 1).

\[ R = \frac{\rho \pi^2 r^2 f_R(v/a)}{1 + f_R(v/a)} \]

where \( R \) is the total drag, \( \rho \) is the air density, \( v \) is shell velocity, \( r \) is the radius of the shell, \( f_R \) is the drag coefficient for the shell and \( a \) is the velocity of sound. R. H. Fowler, E. G. Gallop, C. N. H. Lock and H. W. Richmond, ‘The aerodynamics of a spinning shell’, Phil. Trans. R. Soc. Lond. A 221, 295–393 (1920).

This was not a new finding. ‘Fuzes also burn longer as the height above the sea level increases. For each 1\footnotesize{\textdegree} [1 foot] fall in barometer (\approx 1000\textquoteleft in height), the time of burning increases by about 1/30.’ War Office, \textit{Field Artillery Manual} (HMSO, London, 1914), p. 161.

Leonard Darwin was president of the Eugenics Society for many years.


Location of aircraft by sound, Public Record Office MUN 7/303.

The acoustic research section, Public Record Office MUN 7/308.


A newspaper clipping from 1935 in Hill’s scrapbook shows him and a group of army officers examining a mirror table. Churchill Archives AVHL 1/35.
