Evolution of near vertical incidence skywave communications and the Battle of Arnhem

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Abstract: The use of near vertical incidence skywaves (NVIS) in battlefield communications is now commonplace. Though not referred to as such until recently, the propagation of HF radio waves over short distances without the intervention of the skip zone is a natural consequence of the use of appropriate frequencies plus transmitting and receiving antennas that favour high angles of radiation. It has occasionally been suggested that the first dedicated use of NVIS techniques took place during conflicts in the 1960s, whereas evidence exists of its use during the D-Day landings of June 1944. However, wartime documents have recently come to light which show that the British Army Operational Research Group carried out dedicated research into this method of short-range HF communication at least a year earlier and released its reports containing operational recommendations in 1943, prior to the Battle of Arnhem.

1 Introduction

Much has been written ([1–3] are a representative sample) about the 'Battle of Arnhem', Operation Market Garden, fought during the Second World War between 17 and 26 September 1944. Although, characteristically, the commander-in-chief, Field Marshal Sir Bernard Montgomery regarded the outcome as '90% successful [4] it never achieved its major objective, that of opening up the route of advance of his 21 Army Group towards the Ruhr and Germany's industrial heart and, by so doing, ending the war before the end of that year. Montgomery's plan for a massive 'single punch' or thrust, focussing on Berlin, depended crucially on getting his army across three rivers, the Maas (or Meuse), the Waal and the Neder Rijn (Fig. 1). To achieve this required the capture of the bridges that spanned them and none proved more elusive than that at Arnhem (Fig. 2). The battle that raged there and in its immediate environs is one of the great feats of arms of the British Army. That it ultimately saw the destruction of the British 1st Airborne Division is one of the undoubted disasters of the Second World War.

Various reasons for the failure of Market Garden have been given over the years. What is important from the point of view of role of technology in modern warfare is the part played by radio communications in this fiasco and, especially, the underlying reasons for its perceived lack of success. In his official report after the battle, Major General R.E. Urquhart, commanding the 1st Airborne Division, is quoted as saying: 'Signals need drastic revision and improvement. The sets are unsatisfactory. The range attributed was always grossly exaggerated' [1]. Thus perceived shortcomings in the radio equipment, and especially its claimed performance, have been cited frequently as being responsible for what was, undoubtedly, a major weakness throughout the battle: an almost total breakdown of communications. Although this was indeed a serious shortcoming, Arnhem was not lost for reasons of poor communications alone. Poor military strategy was much the major culprit. However, since good communications are vital in military operations the reasons for any such deficiencies must be found and in the case of this battle, probably more than for any other, they have been the subject of much investigation [5]. It is now apparent, with the benefit of some hindsight, that the real reasons for the communications failure are more complex than often thought, particularly as they reveal shortcomings of both a technical nature and within the Signals echelons of the War Office.

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2 Background

For much of the time during the battle there was no radio contact between the Corps commander (Lieutenant General F.A.M. Browning) his headquarters and the units under his command, while such communications as did exist were often plagued by interference or were marginal when they most mattered. The Battle of Arnhem was thus fought in near radio silence. Only occasionally was it punctuated by brief periods of reliable communications, and then these were so often fortuitous. Some radio contact between units on the battlefield and higher-level formations did indeed take place throughout the duration of the battle. Almost without exception, though, it was provided not by the regular signallers attached to the fighting formations but by unconventional elements within the British Army, most notably a liaison regiment known as 'Phantom'. Naturally this caused some pique within the Royal Corps of Signals who were primarily responsible for providing the Army's communications but it is a fact and the reason for Phantom's success requires an explanation. It is to be found amongst the annals of the Army Operational Research Group (AORG) with its headquarters at Roehampton.

In seeking an explanation for the failure of communications at Arnhem the radio equipment in use has been severely criticised. There is no doubt that, with some

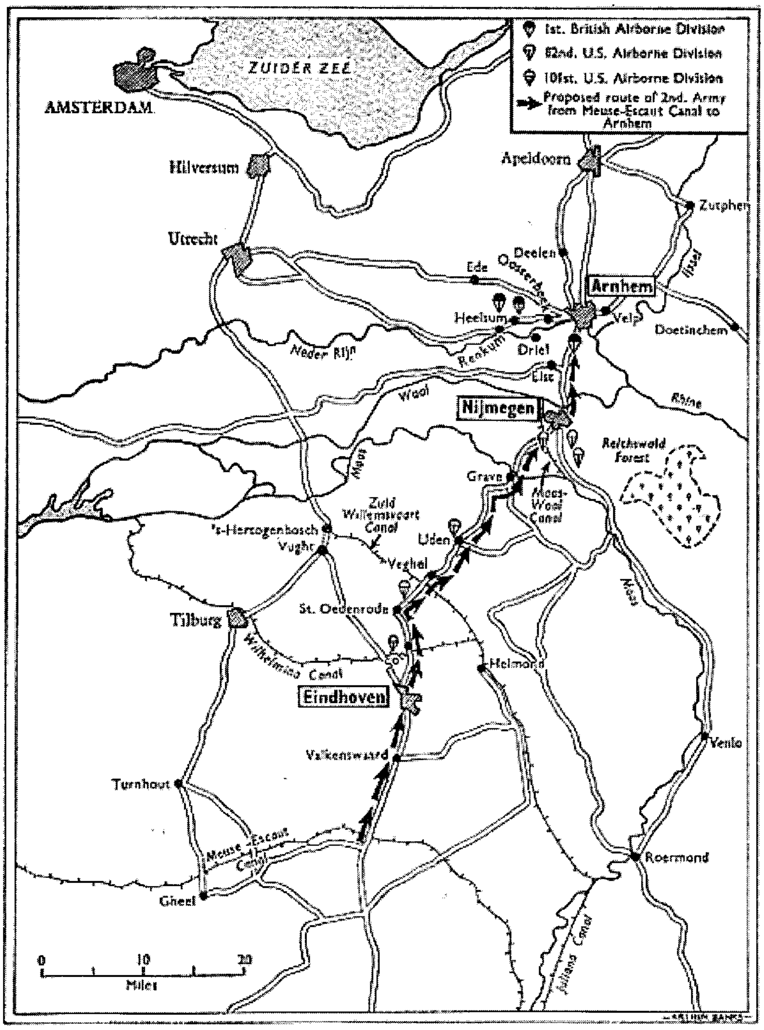

Fig. 1 *Map showing area in which Operation Market Garden was fought in September 1944*
Acknowledgment to Pen and Sword Books, Col. John Waddy and Michael White

notable exceptions, the wireless sets used by the British Army during the Second World War were crude in comparison with those of the Germans. Not only were they far less rugged in their construction but the electronics concepts on which they were based were often dated. Certainly, little or no consideration had been given to the development of sets suitable for rapid deployment or for use in those theatres of warfare where speed and flexibility were paramount. But for all these defects a much more fundamental problem was the almost total reliance that was placed on groundwave propagation in compliance with the Signals doctrine adhered to by the Army at the time [6]. This meant that the radio sets, almost without exception, operated at HF (typically between about 2 and 12 MHz) with vertically polarised, short monopole antennas that would naturally favour the groundwave. Furthermore, low transmitter power was typical of such portable equipment. Thus the vehicle-mounted sets, such as the No. 22 (Fig. 3) produced a maximum of 1.5 W on CW (Morse code) and even less on RT (amplitude modulated voice), while the manpack No. 68P (Fig. 4), with which Urquhart's paratroopers were equipped, was rated at just 250 mW output. The details of these wireless sets, plus those of the larger and considerably more powerful No. 19, of which only two were deployed at Arnhem, and the No. 76 used only at headquarters, are shown in Table 1. The standard antennas in use were self-supporting rods never exceeding 12 feet (3.6 m) in length with which, it was claimed somewhat optimistically, the sets could achieve a range of up to 10 miles on CW [6]. In reality the extremely poor radiation efficiency of such short antennas, compounded by propagation losses, made this most unlikely.

3 Terrain

Arnhem lies on the northern bank of the Neder Rijn: see Fig. 1. In September 1944 it also lay 100 km behind the German lines. A town of varied architecture (Fig. 2), Arnhem was heavily built up and provided few unobstructed sites for antennas, while those that could be deployed were likely to be temporary anyway. On the 17th of September it became the site of a paratroop invasion by troops of the 1st (British) Airborne Division, to be followed some days later by those of the 1st Polish Independent Parachute Brigade Group. Their objective would be the bridge across the Neder Rijn at Arnhem and this they were to hold until the arrival within four days, so it was planned, of XXX Corps of the British 2nd Army advancing some 100 km from the south through the area being held by the American 82nd and 101st Airborne Divisions. Ideally, the British parachute troops should have landed immediately to the south of Arnhem, and close to the bridge, but the unsuitability of the ground for accommodating the troop- and equipment-carrying gliders, and the perceived threat from antiaircraft defences led, at the insistence of the RAF,

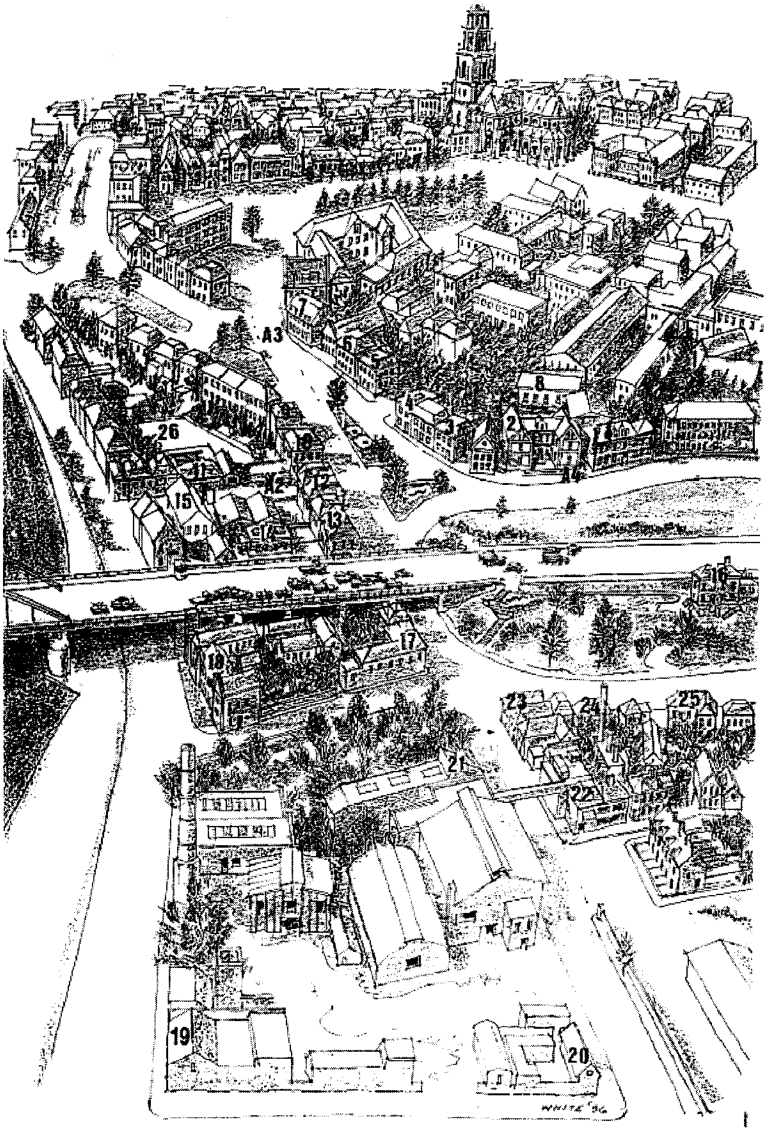

Fig. 2 *Town of Arnhem and its bridge at height of battle*
Acknowledgment to Batsford Press and Salamander Books

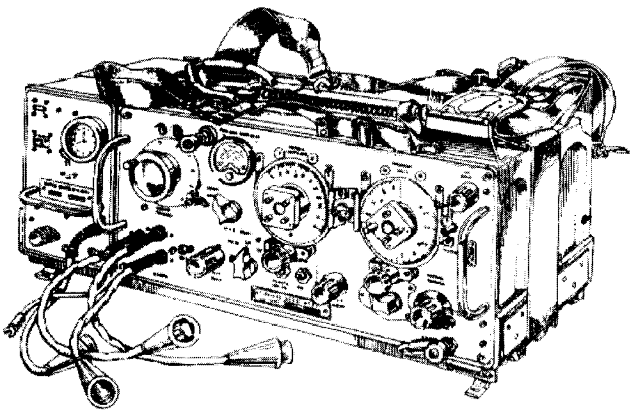

Fig. 3 *Wireless set No. 22 as deployed at Arnhem*
Acknowledgment to The Royal Corps of Signals Museum, Blandford

to the drop-zone being some 6 to 8 miles (10 to 13 km) to the west. Good radio communications between the disparate elements of this major enterprise were surely vital for its success.

Effective radio propagation by means of the ground-wave requires the ground to be of reasonable electrical conductivity. Typically, propagation at 3 MHz over 10 km within the Netherlands, where the conductivity varies from about 3 to 30 mS/m at HF would result in about 16 dB additional loss in signal strength compared with propagation over the sea, the ideal case [7]. To further compound the problem the headquarters of General Browning's 1st Airborne Corps, from which Operation Market Garden was to be co-ordinated, was at Groesbeek, all of 20 miles (32 km) south-east of Arnhem. None of the low-powered wireless sets were expected to be capable of achieving much more than 5 km under the prevailing conditions.

In view of the inadequacies of the equipment, the distances involved and the various geographical factors, it was apparent to some of the signals planning staff in the weeks prior to the landings that communications would be seriously compromised. They duly voiced their concerns but these went unheeded; Operation Market Garden would go ahead regardless [8].

4 Battle

The Battle of Arnhem was fought over a period of nine days and after an heroic struggle it resulted in a British

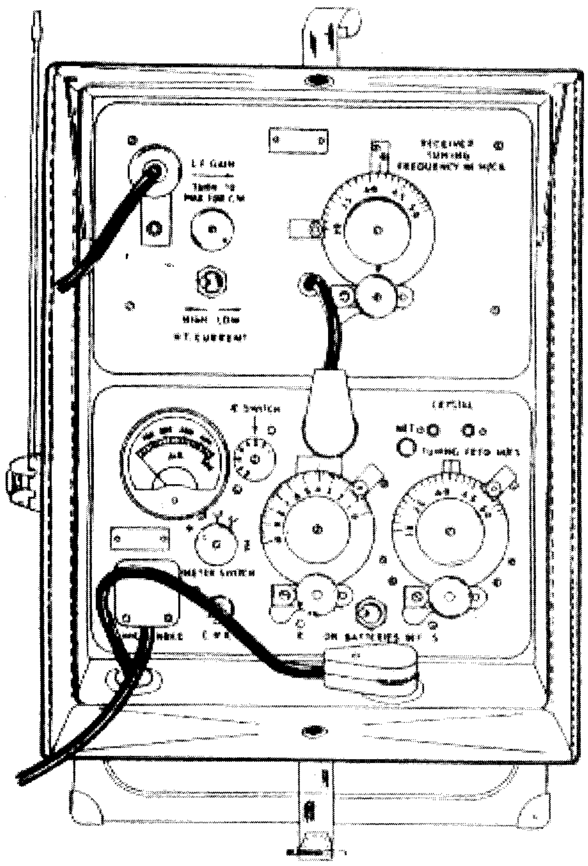

Fig. 4 *Wireless set No. 68P used by paratroopers of 1st British Airborne Division at Arnhem*
Acknowledgment to The Royal Corps of Signals Museum, Blandford

Table 1: Characteristics of radio equipment in service with British Army at Arnhem [6]

Type of set	Transmission	Frequency range (MHz)	Power output (W)
22	CW/RT	2 to 8	1.5 CW; 1 RT
68P	CW/RT	1.75 to 2.9	0.25
19	CW/RT	2 to 8	12
19 (HP)	CW/RT	2 to 8	30 to 70
76	CW only	2 to 12	9

surrender and retreat. In the operation as a whole there were over 17000 Allied casualties, considerably more than occurred during the biggest invasion in history when their massed armies landed in Normandy on D-Day, 6 June 1944. Urquhart's Division was almost completely destroyed, while Montgomery's northward thrust was temporarily thwarted and the war went into its sixth year.

Some have claimed that the failure of radio communications was a major reason for the defeat but this is too simplistic given the multitude of other factors that played a part. Prime amongst these was Montgomery's own flawed strategy. The expectation that XXX Corps could reach the bridge at Arnhem within the four days that the lightly armed paratroopers could be expected to hold it was misguided and constitutes, arguably, the greatest mistake in his military career [9]. In addition, flawed intelligence reports drastically underestimated the strength of the German II Panzer Korps busy refitting close to Arnhem, and they precipitated a false sense of security amongst all concerned. The ensuring reaction of those battle-hardened German troops then far exceeded Allied expectations and XXX Corps' progress northwards along an elevated isthmus toward Arnhem became perilously slow. In addition, the element of surprise so vital in operations behind enemy lines, was soon lost because of the protracted period of three days needed to fly in the British, American and Polish troops, and all their equipment. These clear lapses in strategic thinking cost Montgomery and his planners dearly. By contrast, the inadequacy of the radio communications at all levels of command, though extremely serious, is just one element of many that led ultimately to a débâcle. However, such Signals shortcomings might so easily have been avoided had the recommendations of the AORG, based on their research of 1943 and given wide circulation at the highest level, been implemented in the Army as a whole and not just within selected elements of it, such as Phantom.

5 Army Operational Research Group

The AORG was formed in January 1943 under the command of Brigadier B F J Schonland FRS, a scientist of great flair who found himself in uniform for the duration of the war. The AORG's purpose in broad terms was to assist the Army with the evaluation and operational deployment of new systems and equipment, and to advise the War Office and the various military Commands accordingly. One of its specialist sections (AORS3) concentrated on 'Signals in the Field' [10]. The problem of effective radio communications between units operating in a variety of geographical locations, from desert to jungle, formed an important part of its work.

In August 1943, the AORG issued a report entitled 'The relative merits of HF (3–30 Mc/s) and VHF (30–300 Mc/s) for short distance communications' [11]. It was written by Major E W B Gill, another occasional soldier of considerable scientific ability. The report's conclusion, based on extensive measurements made in various parts of England and Wales, was that the Army could benefit greatly by using VHF from 30 to 50 MHz instead of the HF systems presently deployed for communications over distances from 6 to 10 miles, regardless of the topography of the land or its electrical features. This was heresy to some who believed that VHF was usable only within line-of-sight but it was borne out by American experience where VHF sets were now very much part of the US Army Signal Corps inventory. The AORG's crucial finding was that the space wave radiated predominantly at VHF not only propagated very well over line-of-sight paths, as was well known, but it was also readily diffracted around obstacles such as mountains and buildings, a fact already appreciated by the police who had made extensive use of VHF, as Gill observed in his report. In addition, the virtual absence of electrical noise and interfering radio transmissions, plus the great increase in available channels, gave VHF considerable signal-to-noise and operating advantages over comparable HF systems.

However, no revolution in British Army doctrine followed the publication of this AORG report. The fact that the first name on the list of its recipients was Sir Edward Appleton's probably accounts for this. Appleton, of course, was a pioneer in the study of the ionosphere and its role in HF communications and he was no protagonist for VHF with its perceived optical-like limitations. As a senior War Office adviser, his word carried considerable weight [12]. The AORG, given its wide-ranging brief, had also applied itself to the problem of improving the performance of HF communications over short distances and their recommendations were published in late 1943, well before the Battle of Arnhem [13]. They warned that '... wireless communication by means of groundwaves in the HF band is a particularly difficult problem for Army mobile sets. In some theatres of war the ranges are bound to dwindle to insignificance'. They went even further: 'Army field stations not only have to use frequencies suitable to the prevailing ionospheric conditions but ... have to adjust their frequencies to conform with the frequency allotments of their formations. These allotments ... have constantly to be varied to meet tactical moves. ... Frequency changes have therefore to be made quickly and often. Aerials must be compact and simple'. Telling caveats indeed in the light of what was to come.

6 AORG's recommendations

The AORG recognised that effective short-range communications at HF meant that the groundwave must be avoided. To propagate a signal over the appropriate path would therefore require its reflection from the ionosphere, but for the short ranges of interest in many military applications this would entail nearly vertical angles of incidence. An antenna capable of launching such high-angle signals, while also being effectively matched to the Army transmitters of the day, was therefore required. In addition, careful selection of the operating frequency was necessary to ensure that it was close to the optimum frequency for the particular geographical location and state of the ionosphere at the time in question (the sunspot count, its controlling agency, actually reached its minimum between February and April 1944). It is well worthy of note that in producing these reports the AORG had essentially laid down the necessary conditions for what is known today as near-vertical-incidence skywave or NVIS operation. This was an important scientific milestone.

In essence, an antenna, of an appropriate length, must be predominantly horizontal to radiate skywards, while the operating frequency f_{op} must be chosen with care. For minimum propagation loss at nearly vertical incidence, it should approach the critical frequency f_0 of the appropriate ionospheric layer. However, to allow for the day-to-day variation of the ionosphere, it is usually made slightly less than the critical frequency to prevent penetration of the ionosphere. This requirement can be expressed in terms of the so-called 'secant law' where $f_{op} \simeq 0.85 f_o \sec i$, with i being the angle of incidence on the ionosphere. For communication paths that are short relative to the height of the ionospheric F-region (typically 300 km), $\sec i \simeq 1$ therefore $f_{op} \simeq 0.85 f_o$. Ionospheric data suitable for planning such links had long been produced by the Inter Services Ionsopheric Bureau and was supplied to the Army's various theatres of operation by the AORG [14].

The AORG antenna designed by Gill, though nothing more than a length of wire in an 'inverted-L' configuration, Fig. 5, had to be of the correct dimensions to radiate towards the zenith and to present the appropriate load impedance to the transmitter. The former depended on the antenna's orientation and on the distribution of current along it while the latter was a requirement of the British Army's wireless sets of the time. These, almost without exception, were intended to operate with antenna impedances that were essentially capacitive, i.e. the antennas were end-fed rods or wires of length $l < \lambda/4$, where λ is the operating wavelength, and direct connection was made with the end of the antenna without the use of any transmission line, coaxial or otherwise. A suitably oriented longer antenna would not only be more efficient than the rod

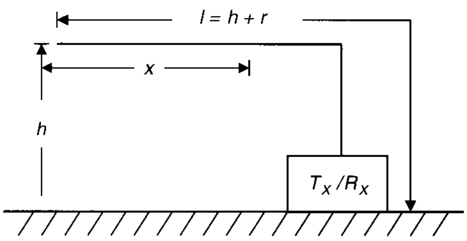

Fig. 5 *NVIS antenna proposed by Army Operational Research Group*

but its input impedance could easily be changed by the simple addition of a series capacitor. Based on practical considerations, and on the need to maintain a current maximum or antinode on the horizontal wire, Gill therefore assumed that at all frequencies $l \leq 3\lambda/2$. If mounted at an appropriate height h, the antenna plus its image in the ground would behave as an array radiating toward the zenith. His report (see Appendix, Section 10) showed that the optimum height should be $h = l/3$, with the vertical 'downlead' being half the length of the horizontal top r. Although based on some simplifying approximations that took no account of the mutual impedance between the antenna and its image, or of the radiation from the downlead itself, this result is found to be in very good agreement with a modern method of moments [15] analysis which makes no such assumptions.

An antenna's performance is often compared with that of a resonant halfwave dipole so Gill calculated the loss that would occur when using an inverted-L of smaller dimensions. He had shown previously that the field strength at the receiver for current I at an antinode is proportional to $I \sin^2(\pi r/\lambda) \sin(2\pi h/\lambda)$ which reduces simply to I for an antenna with $r = \lambda/2$ and $h = \lambda/4$. Therefore for the same assumed current on the shortened antenna the field strength produced would be modified by the sinusoidal terms to yield a loss in decibels given by $(40 \log \sin(\pi r/\lambda) + 20 \log \sin(2\pi h/\lambda))$. This was amenable to simple graphical representation and it appeared in the AORG report as in Fig. 6. Its use in practice was illustrated by a number of examples, one of which read:

'In a certain theatre, signals from the lower-powered sets are hardly strong enough to overcome atmospheric noise in the daytime frequency band which (for the theatre and the season concerned) is about 7 to 8 Mc/s. Signals at night, however, have 'plenty in hand' on all the night frequencies. The standard aerials at present in use have a 'top' 30 m long at a height of 5 m above ground. Can anything be done?'

The answer was as follows:

'Reference to Fig. 4 [Fig. 6 in this paper] shows an improvement in the band 7 to 8 Mc/s could be effected either (a) by reducing r from 30 to 25 m or even 20 m, or/and by (b) increasing h from 5 to 10 m or as near 10 m as possible. (a) will reduce night-time signals on the low frequencies, but (b) will increase them as well the daytime signals. (b), however, is more difficult mechanically than (a), and we can afford some reduction in night-time signals. (a) would therefore be worth trying first.'

Though seemingly unknown to the communications planners with 21 Army Group the AORG's proposals were indeed implemented is some quarters. The crucial success achieved by Phantom, the GHQ Liaison Regiment, in providing the only contact with the 1st Airborne Division at

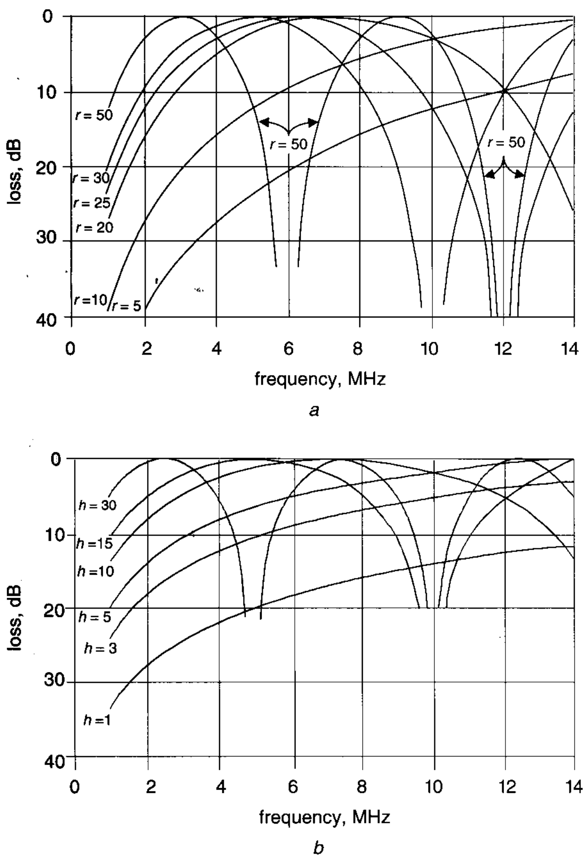

Fig. 6 *Loss against frequency compared with that of reference halfwave dipole with top = λ/2 at λ/4 above earth*
r is length (m) of horizontal top
a Various antenna lengths *r*; loss due to length factor = $40 \log \sin(3rf/5)$
b Various antenna heights *h*; loss due to height factor = $20 \log \sin(6hf/5)$
h is height above ground (m) of horizontal top

Arnhem at the height of the battle has been attributed by military historians to their use of 'a special kind of antenna' [16]. Described as a 'Wyndham' it is better known as the Windom, a horizontal halfwave wire dipole fed by a single conductor connected at a point 3/8th from one end of the horizontal portion. Its undoubted good performance at Arnhem was due entirely to its horizontal top section; any other claims made for it are just mystique. Intriguingly the Windom, along with a number of other suitable horizontal wire antennas, were described in detail in the Army's Signal Training Pamphlet, Part IX, of April 1943 but by implication they were all intended for oblique-incidence skywave applications over long distances, usually many tens to even thousands of kilometers. It was only the release of the AORG reports that drew attention to the significant short-range advantages accruing from the use of vertically incident skywaves, and the essentially simple antennas needed to radiate them. Official intransigence, hidebound bureaucracy and not a little personal prejudice may well have kept such knowledge from those most in need of it at Arnhem.

7 Conclusions

The Battle of Arnhem was one of the epic encounters of the Second World War. Its outcome, due undeniably to a strategic blunder, delayed the end of the war in Europe by many months. Though inadequate radio communications are often cited as a contributory factor it is probably futile to speculate on the outcome had the recommendations of the Army Operational Research Group been implemented. However, what is certain is that this research of the AORG is probably the earliest rigorous treatment, in official documentation, of the peculiar mode of communication now used extensively by the military and others, and known as NVIS.

8 Acknowledgments

Acknowledgment is made to Michael White, the artist, and to Colonel John Waddy for permission to use two drawings from his publications on the Battle, and to the Royal Corps of Signals Museum for the illustrations of the radio equipment. In addition, the many comments and suggestions made by the reviewers of this paper were particularly helpful.

9 Appendix

E.W.B. Gill's determination, in AORG Report 126 of 27 September 1943, of the optimum dimensions of an end-fed skywave antenna for propagation nearly vertically; reported verbatim.

9.1 Field due to horizontal portion

If i is the instantaneous current at an antinode, the current at a distance x from the free end of an aerial of length l is $i \sin(2\pi x/\lambda)$ and the field strength at the ionosphere (vertically overhead) due to the element δx of the aerial is proportional to $(i/\lambda)\sin(2\pi x/\lambda)\delta x$. Therefore field strength due to whole horizontal portion (excluding image in ground) is proportional to

$$\frac{i}{\lambda}\int \sin\frac{2\pi x}{\lambda}\,dx, \text{ i.e. to } \quad i\sin^2\left(\frac{\pi r}{\lambda}\right) \tag{1}$$

where $r = l - h$.

9.2 Effect of Image

Let $i = I\sin\omega t$. Since reflection is assumed perfect, the ground image will produce an effect equal to that of the current in the horizontal portion but with change of phase $\pi + (2\pi/\lambda)2h$. Therefore for i in (1) we must write, in order to get total effect of aerial and image,

$$\begin{aligned} & I\sin\omega t - I\sin\left(\omega t - 2\pi\frac{2h}{\lambda}\right) \\ & \quad = 2I\cos\left(\omega t - \frac{2h}{\lambda}\right)\sin\pi\frac{2h}{\lambda} \end{aligned} \tag{2}$$

The factor $\cos(\omega t - \pi(2h/\lambda))$ merely shows the variation of the field strength with time, and we need not consider it further. Therefore instead of i in (1) we must write

$$I\sin\left(\frac{2\pi h}{\lambda}\right) \tag{3}$$

9.3 Best value for h

From (1) and (3) and the assumption that the current amplitude i is not a function of aerial height h, the field strength E at ionosphere is proportional to

$$I\sin^2\left(\frac{l-h}{\lambda}\pi\right)\sin\left(\frac{2\pi h}{\lambda}\right) \tag{4}$$

We have to find a value of h which makes this a maximum. From (4), dE/dh can be shown to be proportional to

$$\frac{l}{\lambda}\sin\left(\frac{l-h}{\lambda}\pi\right)\sin\left(\frac{2\pi h}{\lambda}\right) \tag{5}$$

and d^2E/dh^2 proportional to

$$\frac{-l}{\lambda^2} 2 \sin\left(\frac{l-2h}{\lambda} 2\pi\right) + \sin\left(\frac{2\pi h}{\lambda}\right) \qquad (6)$$

Therefore for a turning value either $(l-h)/\lambda = n$ or $(l-3h)/\lambda = n$. Now, n must be 0 if the total length of the aerial is $l < 3\lambda/2$ and therefore for a turning value,

$$h = l \text{ or } \frac{l}{3} \qquad (7)$$

From (4), $h = l$ gives $E = 0$, as is obvious from the fact that the horizontal portion of the aerial will be of zero length, while $h = l/3$ gives a substantial value for E and substituted in (6) gives a negative value for d^2E/dh^2 provided $l < 3/2\,\lambda$ which is true. It therefore gives a maximum for E and is the optimum value of h we are seeking.

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