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Radio communications through rock strata – South African mining experience over 50 years

Significance:

The pioneering work done in South Africa in developing radio communications technology for use underground in mines is summarised. Propagation took place, in the main, directly through the rock strata with incidental coupling into power cables, pipes, rails and other conductors. The research established the optimum frequencies for communications as well as the most appropriate antennas. Specialised radio equipment was developed for this task as constrained by the technology of the time. Size and weight were major constraints; ultimately, handheld equipment, using single-sideband modulation, was produced that functioned exceptionally well in numerous situations underground.

Introduction

It was early in 1938 that the medical superintendent of Rand Mines, Dr A.J. Orenstein, asked Professor Basil Schonland, the Director of the Bernard Price Institute of Geophysical Research (the BPI) at the University of the Witwatersrand, about the feasibility of radio communications underground in mines. Orenstein had long been concerned that firefighting and rescue teams were severely hampered by a lack of communication between those personnel and anyone else when they ventured into the most hazardous of situations. Schonland was sceptical that radio signals would propagate over useful distances through rock strata, but agreed to investigate.[1,2]

The war, radar and the Special Signals Services

International events soon intervened as war with Nazi Germany loomed. South Africa declared war on 6 September 1939, just three days after Britain. From then, the research focus of the BPI shifted inexorably. Henceforth, all its resources, as limited as they were, would be given over to the investigation of RDF, or radar as it was known in those earliest days (see Figure 1). What followed, was the formation of the Special Signals Services (SSS), as part of the South African Army's Corps of Signals with Lt Col Schonland as its commanding officer.[2,3] And immediately, the SSS co-opted the services of engineers and physicists from South Africa's major universities – one of whom was a young engineering graduate from Durban by the name of Trevor Wadley.

The development of South Africa's own radar equipment and its deployment, along with subsequent British radars, around the country's coastline as well as in East Africa, the Middle East and in Italy, has been reported extensively elsewhere.[2-4] It was that massive wartime effort at the BPI that was the spur to the formation of the Council for Scientific and Industrial Research (CSIR), which was formally established in October 1945 with Schonland as its President. And the CSIR's first specialist laboratory to come into existence was the Telecommunications Research Laboratory, with Wadley among its first members of staff.[5]

Wadley and radio underground

Wadley's genius was soon evident. He designed a revolutionary type of radio receiver that became the mainstay of British naval communication when the equipment was produced by a British company. Subsequently, he developed

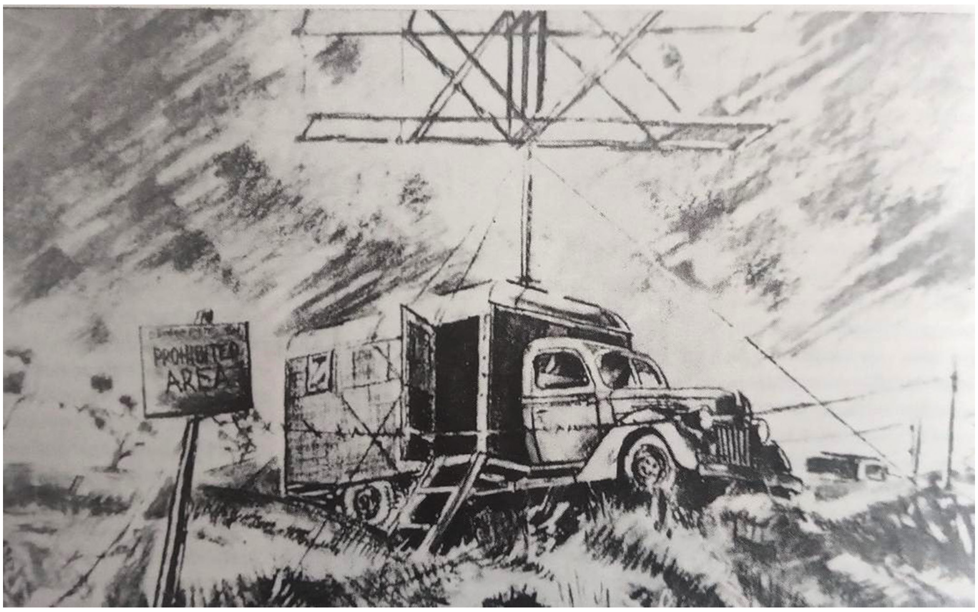

Figure 1: The mobile radar system designed and constructed by the Special Signals Services at the Bernard Price Institute of Geophysical Research, University of the Witwatersrand, in 1942.

a distance-measuring device of quite unparalleled accuracy called the Tellurometer which revolutionised the field of surveying.[5,6] Remarkably, he also turned his attention to the problem of radio communications in mines that had first been raised almost a decade before.

In 1949, Wadley wrote a report for the Transvaal and Orange Free State Chamber of Mines describing the outcome of his research and his recommendations for suitable equipment.[7] The important question he answered was what the optimum frequency was in order to achieve maximum communication range directly through the rock. Reliance could not be placed on signals propagating via the underground tunnels because of their irregular shapes, their curvature and roughness, which ruled out line-of-sight communications.

Electrical properties of rocks

In order to determine how electromagnetic energy might propagate through the lossy dielectric medium of rock, one requires a knowledge of its propagation constant γ where:

$$\gamma = \alpha + j\beta = \sqrt{j\omega\mu(\sigma + j\omega\epsilon)}\ .$$

Here α is the attenuation constant, β is the phase constant and $\omega = 2\pi f$ is the angular frequency. The other terms are the fundamental electrical parameters of rock: its conductivity (σ), dielectric constant (ε) and magnetic permeability (μ). Of these, only the permeability remains constant with changes in frequency, while most geological materials are also non-magnetic.[8] By contrast, both rock conductivity and dielectric constant are frequency dependent.[8,9]

Wadley measured both the resistivity (the reciprocal of conductivity) and the dielectric constant of quartzite and some shales typical of the gold mining region of the Witwatersrand. He used borehole samples with apparatus specially designed for the task. In his report he showed how the resistivity of quartzite varied from about 9×10^4 to 5×10^3 ohm-metres over a frequency range from 100 kHz to 3 MHz. By contrast, the dielectric constant hardly changed and had a value of about 6. Using these data, he calculated the attenuation of a radio signal propagating through 300 m of quartzite and showed how it increased rapidly with frequency, implying that the lower the radio frequency, the better for communicating through rock.

Antennas in lossy media

The fact that the antennas would be surrounded by rock complicated the situation considerably. Wadley considered that a long centre-fed dipole antenna laid along the tunnel floor, or footwall, would be an appropriate antenna for a fixed station underground. For the portable equipment he chose a frame aerial which is essentially a loop of wire (perhaps of many turns) that would be wound around a miner's helmet or 'hardhat'. He measured the impedance of the dipole at a particular frequency and attributed the results to the electrical characteristics of the surrounding rock. From those measurements he deduced the antenna's loss from 10 kHz to 10 MHz. As expected, there was a trade-off, between the rock-induced loss and the improved performance of the antenna as its apparent length, relative to the wavelength, increased with frequency.[7]

By contrast, the small loop antenna was difficult to treat theoretically because the interchange of energy between the air-space and rock was not well understood. This was undoubtedly true and it was to be many years before the underlying electromagnetics principles affecting such electrically small antennas, when immersed in lossy dielectric media, were fully explained.[10,11]

The optimum frequency

Wadley produced a graph of the total loss in decibels (dB) suffered by a radiating signal over a distance of 900 m for frequencies between 30 kHz and 3000 kHz. The graph went through a distinct minimum at about 300 kHz, which, therefore, is the optimum transmitting frequency for that particular distance. The graph also showed that for communications over greater distances a lower frequency would be required, while a higher frequency could be used over shorter distances.[7]

As in all radio communication systems, it is not just the strength of the signal that determines optimum performance but rather the signal-to-noise ratio. A deep-level mine presents an almost unique environment from a noise point of view. The great thickness of the overburden removes, almost completely, any electrical noise generated above ground (including by lightning) and therefore the only noise will be that caused by nearby electrical equipment and within the radio receiver itself. In the case of mining emergencies, all electrical power is usually switched off in the affected area, leaving just the receiver-generated noise which can be reduced substantially by careful design.[7]

The radio equipment

Wadley recommended that two types of transmitters be developed: a static set, producing about 4W of power to be used at a fixed point underground where it could make use of a fairly long antenna; and a portable set, generating only a tenth of the power and using a considerably smaller antenna. Naturally, each transmitter had its companion receiver, with each being of a modern superheterodyne configuration for optimum performance. Based on those specifications, he predicted that the normal operating radius would be about 600 m. A workable signal should still be received at a distance of around 750 m, while the absolute limit would be about 900 m. An appropriate transmitting frequency should be about 350 kHz.[7]

Because the radio technology of those days was all based on thermionic valves, the equipment would naturally be rather bulky. Wadley estimated that the larger unit would weigh no more than 14 kg, while its portable counterpart might be about a third of that.

Wadley never published his results in the open literature. This was an unfortunate omission because there was a real dearth of such quantitative data at that time.[10]

An industrial hiatus and a mining catastrophe

It was not until the late 1950s, on the formation of what was to become the research laboratories of the Chamber of Mines, that Wadley's recommendations received serious attention from the South African mining industry. The problems foreseen by Dr Orenstein all those years before had by no means gone away: if anything, the expansion of the post-war gold and coal mining industries, and the stepped-up production then taking place, had exacerbated the problem of underground fires, accidents and, of course, the ever-present risk of rock falls at the increasing depths at which gold was being mined. On 21 January 1960, a disaster occurred at Coalbrook Colliery in the northern Free State when the mine workings collapsed, entombing 435 men, all of whom perished. Immediate attempts to rescue them were set in train with the Mines' Rescue Brigade of 250 men leading the effort. These highly trained personnel were all experienced miners who had volunteered for the dangerous task of firefighting and rescue work underground. They were trained at the Chamber's Rescue Training Station in Johannesburg.[12] However, once they went underground, those rescue teams were without any form of communication.

Designing the equipment

The underground radio project had been resurrected by the Electronics Division of the Chamber's laboratories during the late 1950s. Wadley's findings and recommendations underpinned their work. Their own calculations had confirmed that a system loss of 150 dB between transmitter and receiver was tolerable and the family of curves in Figure 2 indicated the optimum frequencies for particular distances between them.[13]

Despite the decade or so that had elapsed since the invention of the transistor, and its rapid embrace by many sectors of the electronics engineering industry, the germanium transistors of that era were still limited to low-frequency and relatively low-power applications. They were also thermally sensitive devices, which was an important consideration to be born in mind given the very high temperatures experienced in deep mines.

The radio equipment would be used by members of the Mines Rescue Brigade, known as 'Proto teams' because of the Proto breathing apparatus they used. It required its user to clench a snorkel-type breathing tube between their teeth and to wear a nose clip. Both made speech impossible. This restriction had a great bearing on the design of the radio equipment.

Standard practice during mine emergencies was to establish a so-called fresh-air base, as close as possible to the disaster area, where breathing apparatus was not required. The Proto team, carrying the portable radio equipment, would then go forward from there to carry out its task.

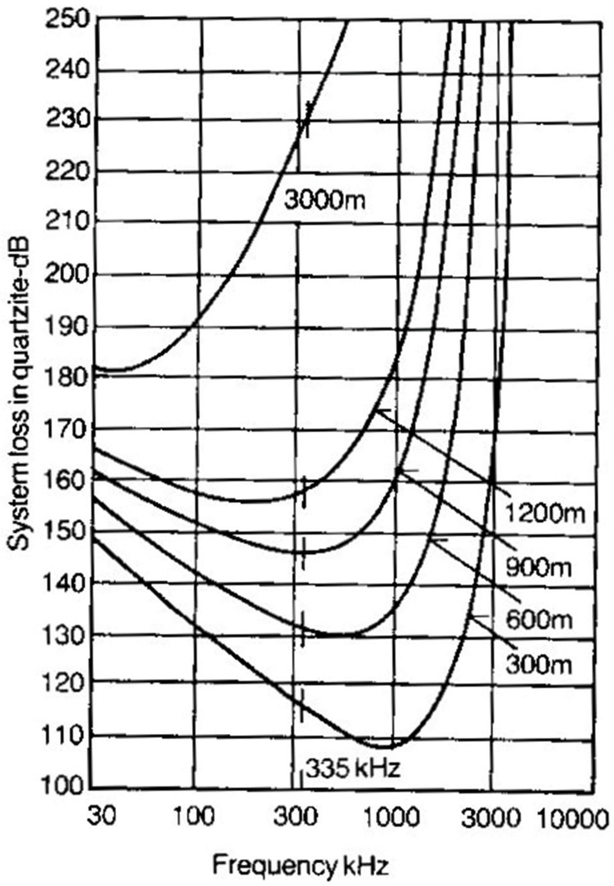

Figure 2: Calculated system loss with frequency for various distances through quartzite rock.

An amplitude-modulated (AM) transmitter was designed for use at the fresh-air base. The frequency allocated by the Postmaster General for mining applications was 335 kHz. The transmitter's output power was approximately 5 W. To exploit the very low noise conditions expected during a disaster, the receiver was designed to have the lowest possible noise figure. The base station weighed 13 kg. However, the motor car battery needed to power it weighed rather more at 15 kg.[13]

The portable equipment to be carried by a Proto team brigadesman was as small and light as possible within the constraints imposed by the valve technology of the time. It was intended to transmit a simple on-off code by means of a push-button because of the radio operator's inability to speak. It was believed, quite rightly, that teaching everyone the Morse code was neither feasible nor necessary as long as a simple question and answer protocol was developed between the fresh-air base radio operator and his counterpart using the portable equipment. The portable transmitter, which resulted, produced about 2 W and its receiver also had the lowest possible noise figure. The portable set weighed just over 6 kg, including batteries.[13]

Loop antennas were used at both the fresh-air base and with the portable equipment. The base station antenna, shown in Figure 3, was a 1-m diameter multi-turn loop encapsulated in fibreglass and intended to be positioned horizontally on the ground. This orientation would ensure that it had all-round coverage, unlike the long length of wire intended by Wadley, which was markedly directional. The portable set, with its multi-turn loop antenna contained within the rigid carrying harness, is shown in Figure 4. The receiver's loudspeaker was mounted within the harness and positioned close to the operator's ear.

Underground trials

Numerous underground trials were conducted by the Chamber's engineers. It soon became apparent that the communication ranges achieved were often considerably greater than those predicted by Wadley. The reason was that the signals were being conducted (and then re-radiated) by any cables, pipes and even the rails used by the electric and diesel-powered locomotives that transported men, materials and, of course, the gold-bearing rock throughout the mine.[13]

By contrast, in areas completely devoid of all conductors, communication range varied considerably, not only from mine to mine but also within a single mine. The reason, of course, was the complexity of the geology.

Figure 3: The fresh-air base radio equipment, its battery and multi-turn loop antenna.

Figure 4: A brigadesman, using Proto breathing apparatus, with the portable radio equipment slung across his chest.

Extensive investigations carried out in subsequent years provided considerable insight into the propagation mechanisms involved through what was an inhomogeneous lossy dielectric medium, usually stratified and intersected by intrusions such as dykes. A most important theoretical analysis, carried out by J.R. Wait in the USA, provided the first detailed explanation of the phenomena.[14] He showed that rock stratification can actually guide radio signals to greater distances than would be possible through a homogeneous medium. This would later be confirmed both in US coal mines and in South African gold mines.[15]

But, despite the progress made, it was clear that the equipment was too bulky and heavy.

A solid-state solution

In the late 1960s, the Chamber contracted a company in Cape Town to produce a compact, fully transistorised transceiver modelled on the packsets then coming into service with the armies around the world.

Instead of a separate base station and a portable unit, a single piece of equipment could function in both roles, with the option to use a much bigger loop antenna when the equipment was set up at the fresh-air base. Single-sideband modulation instead of the AM would be used. For the same amount of transmitted power, single-sideband yields a 9 dB signal-to-noise ratio advantage at the receiver. The equipment, as produced, operated at 335 kHz and is shown in Figure 5 along with its elliptical loop antenna. Being completely solid-state, it was considerably smaller and lighter than the previous valve-based hardware and contained its own rechargeable battery supply. The transmitter power output was increased to 10 W and the receiver, again, was as sensitive as possible. Once again, small multi-turn loops were used with the portable equipment with a larger, single-turn, flexible loop at the base station. Attention was also paid to ensuring that the equipment was 'intrinsically safe' so that it could be used in the flammable atmospheres typical of some mines.[16]

Figure 5: The single-sideband 335 kHz solid-state transceiver with its elliptical loop antenna.

Once the prototypes had been evaluated and accepted by the Chamber's Electronics Division, a company in Braamfontein, Johannesburg, was commissioned, in 1972, to manufacture a small quantity for further testing by the Rescue Training Station personnel. Word had by now reached the United States Bureau of Mines (USBM) about these South African developments and they purchased six transceivers for evaluation in US coal mines.[15] Soon applications other than mining emergencies suggested themselves and the Chamber laboratories demonstrated the equipment's usefulness for complex underground activities such as raise-boring and tramming as well as within the stopes adjacent to the reef being mined. One of those special projects was the Chamber's Mining Technology Laboratory's mechanised mining programme at Doornfontein Goldmine near Carletonville. There, more than 3000 m below the surface, multiple rock-cutting machines were undergoing evaluation and assessment. It was believed that good communication between the machine operators and the maintenance personnel would improve the efficiency of the process significantly. But the extremely cramped confines of a gold mine stope made even that packset-size equipment too unwieldy and so the need arose for something even smaller.

Handheld communications

Examination of Figure 2 shows that a frequency close to 1 MHz could be used very effectively to communicate over a distance of 300 m through quartzite, with a considerable saving in transmitter power compared with 335 kHz. In addition, those experimental mechanised stopes were well served by armoured power cables and hydraulic lines. Tests had shown that this higher frequency propagated very effectively in and around the stopes, so an immediate design effort was mounted to produce a handheld transceiver.

The outcome was a single-sideband transceiver which weighed much less than a kilogram.[16] It was called the TXR-1 and operated at 903 kHz for reasons of the novel technology used (Figure 6). The transmitter output power was 1 W. The antenna was a flexible multi-turn loop that fitted, bandolier style, around the miner's body. The TXR-1 provided excellent two-way voice communications with a base station (using the same transceiver technology but with the addition of a 10-W power amplifier), plus a large loop antenna, erected in the storeroom close to the stope from where the whole operation was coordinated. More than a hundred TXR-1s in their canvas carrying pouches were produced over the following years to serve the rock-cutter stope.

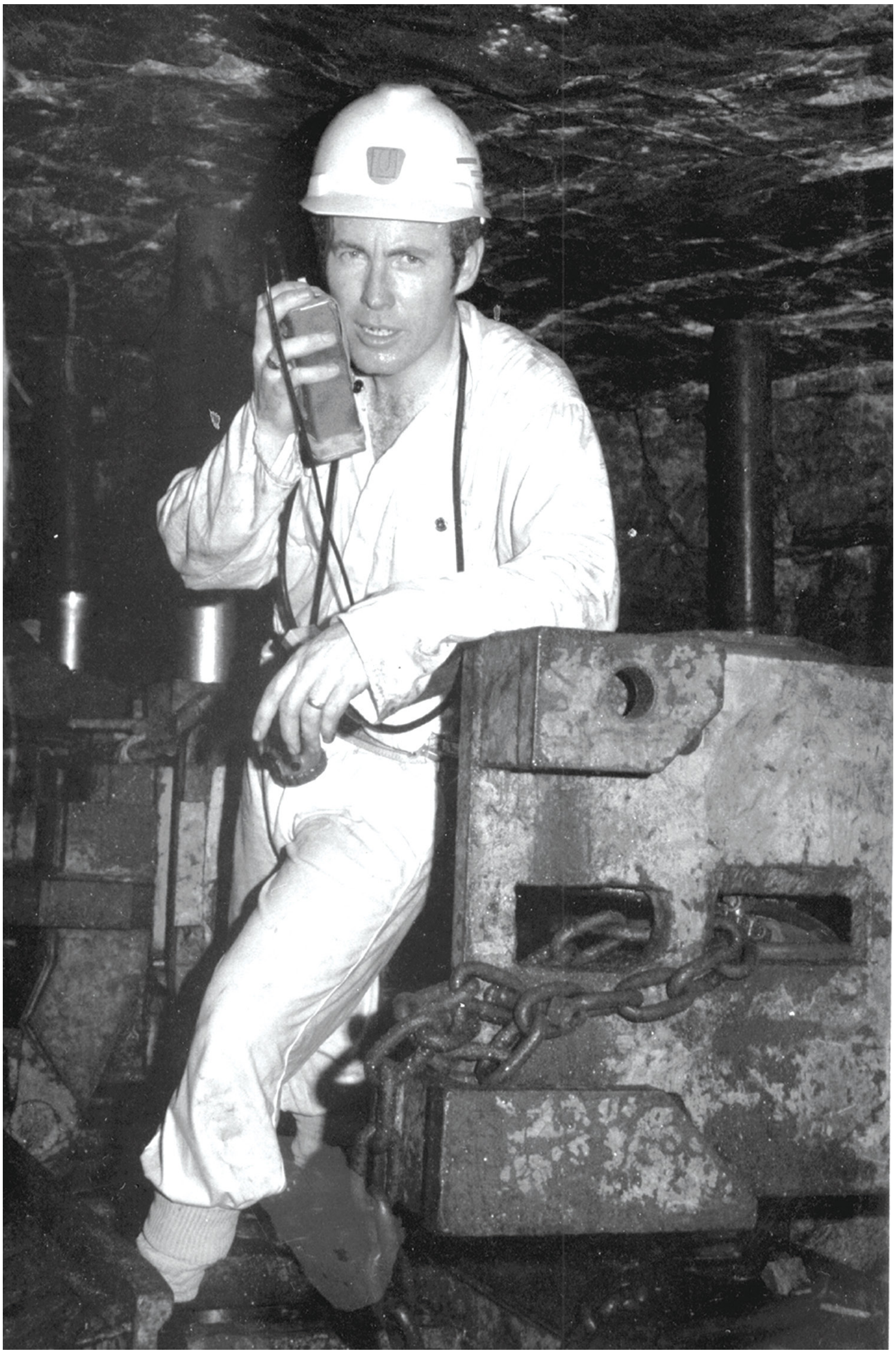

Figure 6: TXR-1 903 kHz handheld transceiver in a mechanised gold-mine stope.

Commercial opportunities

The undoubted success of the TXR-1 had indicated that a more sophisticated small radio transceiver might well find applications throughout the mining industry. With this in mind, the Electronics Division set about developing a prototype which would embody state-of-the art electronic techniques. The intention was that it should operate from 100 kHz to 1 MHz in 10-kHz steps.[17] Multiple mining activities all within the same relatively small area, if required, could then be accommodated on adjacent frequencies. Trials underground showed the hardware to be very acceptable, and so an approach was made to a commercial manufacturer of military-grade electronics equipment in Pretoria to customise it. The outcome was that, by 1978, the SCR-100 portable and SC-200 packset transceivers were available for sale to the mining industry. They immediately went into service with the Rescue Training Station (Figure 7) and in the rock-cutter stope. An energetic marketing exercise was then mounted by the manufacturer which resulted in many mines in South Africa, elsewhere in Africa and abroad, purchasing the equipment.[17]

An underground laboratory

The part played by power cables, water pipes and even rails in enhancing signal propagation was an undoubted fact, but the mechanisms involved were poorly understood. However, research in the USA and Europe had identified two possible modes of propagation known as the

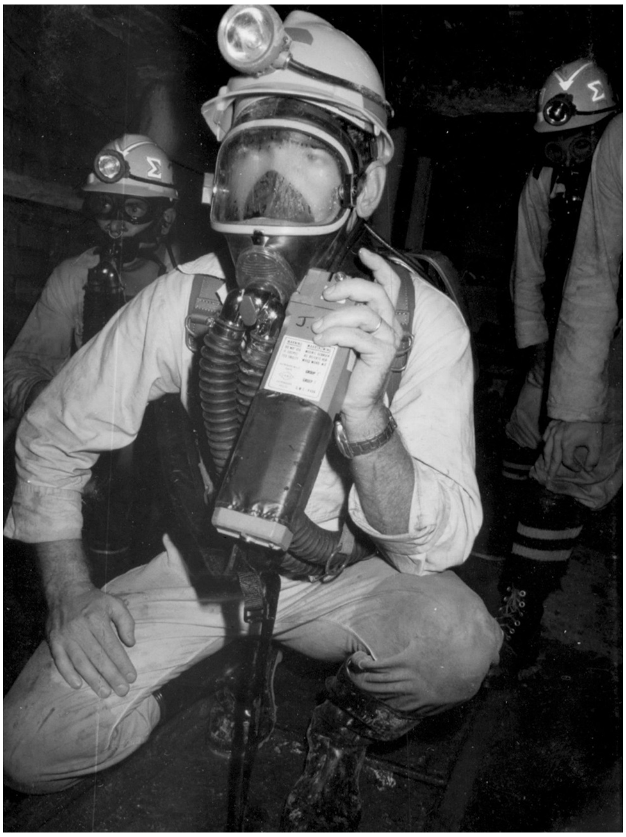

Figure 7: SC-100 portable transceiver used by a Rescue Training Station brigadesman wearing a full facemask.

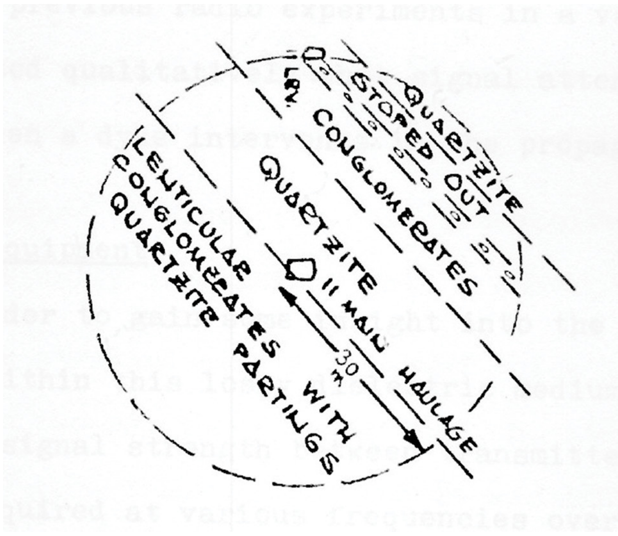

Figure 8: The geology of the rock surrounding the test area underground devoid of all conductors.

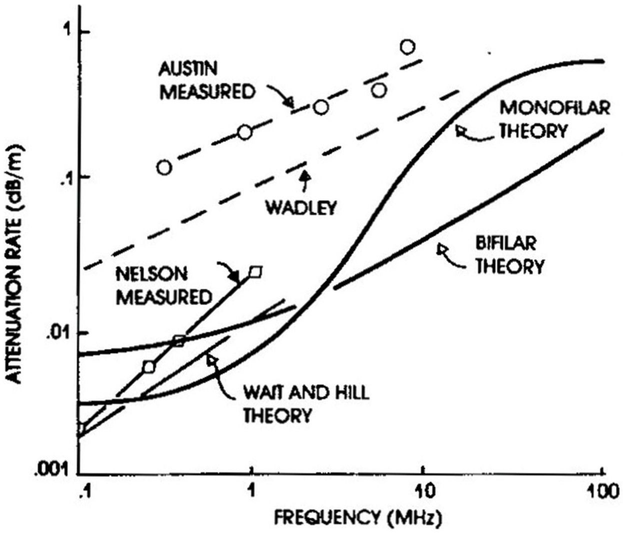

Figure 9: Comparison between theoretical and measured attenuation rates with frequency for various modes of propagation underground.

monofilar and bifilar modes.[18] The details are beyond the scope of this Commentary, but suffice it to say that one or other of those modes can be used very effectively if the radio antennas are in fairly close proximity to those conductors. It was found that positioning a base station within an electrical sub-station, either underground or even on the surface, could yield really long-distance (>3000 m) radio communications by one or other of those modes.[19]

To investigate all the modes of propagation, an underground laboratory was required and a convenient site was found in a completely worked-out area of a mine devoid of electrical conductors. The rock was predominantly quartzite but there was also considerable stratification both above and below the test area. It became apparent that the direction of the electric field polarisation affected the rate of signal attenuation. Maximum signal strength occurred when the antennas were tilted some 40 degrees to the horizontal. This implied that the strata of the surrounding rock were affecting propagation. Examination of a map (see Figure 8) showing the geology of the area confirmed that dip angle of the strata.[17,20]

To investigate conductor-assisted propagation, a single 1400-m length of copper wire was suspended from the hanging wall of the tunnel. As no other conductors were present, it was assumed that the monofilar mode might propagate with the current return path being through the surrounding rock.[18] However, measurements showed rates of attenuation that were significantly lower than were expected between 100 kHz and 1 MHz. There had to be another conducting path for the signal. It turned out that a water trough filled with mine run-off water some 500 times more conductive than tap water, and considerably more conductive than quartzite, provided the return path. An extensive set of experiments confirmed this to be the case[21], and again there was theoretical support in the literature.[22]

In summary, Figure 9 shows a composite set of curves representing all the various propagation modes discussed above. It is clear that there is general agreement between experimental and theoretical results, while the frequency dependence and complexity of all the various modes of radio propagation underground are evident.[23]

Conclusions

The work undertaken on radio communication underground in South African mines in the 50 years after the issue was first raised in 1938, has been reviewed. Significant progress was made, particularly in the design of radio equipment suited to this demanding task. Modes of propagation, both directly through the rock and indirectly via any suitable conducting paths that spanned the area between transmitter and receiver, were identified and numerical data obtained to substantiate their characteristics.

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Competing interests

I have no competing interests to declare.

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