Radio Underground

South African experience of radio communications in mines

by Brian Austin

The use of radio communications underground in mines has a history almost as old as radio itself. As early as 1910 German researchers used radio telegraphy apparatus in underground mines as part of a geological investigation. Though their purpose was not primarily to communicate they showed that such signals did indeed propagate underground. A decade later, when thoughts had certainly turned to telecommunications, dedicated research was under way on both sides of the Atlantic.

In the United States, the US Bureau of Mines published the results of experiments carried out in 1922, while a year later in England an enthusiastic group of wireless experimenters, who included some professionals within their ranks, conducted a series of tests at Desford Colliery near Leicester. Investigations continued throughout the decade, especially in the USA and Canada, to establish the best frequencies to use and the effects of the geology on signal propagation. The results, though promising, highlighted many problems. Most apparent was the fact that equipment, suitable for use on a day-to-day basis in the rugged and inhospitable mining environment, just did not exist, while the technology of the time held out little hope for portable apparatus. In many ways the problem was very similar to that being faced by the military – valves and their power supplies were just too bulky. Real progress would require a new technology altogether.

In South Africa, a country virtually built on the fruits of mining, the idea of using wireless communication in the gold mines was first mooted in 1938. The immediate need was to assist the rescue teams who were called upon all too frequently to battle underground fires and to rescue men trapped by "falls of ground". Once they ventured forward of their "fresh air base", set up as close as possible to the scene of the disaster, these men of the Mines Rescue Brigade were incommunicado. They were then entirely on their own with no means of contact with anyone. Thus, reports in the technical press suggesting that a British company had developed radio apparatus capable of working in mines created much interest and an investigation was immediately called for in Johannesburg. That was the beginning of a programme of research and development that went through a number of peaks and troughs over the next fifty years. This article traces some of its history and describes the radio sets that were designed to communicate directly through the rock.

The Mining of Gold

South African gold mines boast some of the most formidable mining conditions in the world. The deepest vertical shaft descends more than 3.6km into the earth. The gold itself is found in the 'reef', a narrow band of carboniferous material in places no more than a sliver encased in very hard, quartzite rock. The rock temperature at such depths can exceed 50°C while the humidity, due to the circulated cooling water, can be close to saturation. Drilling and blasting produce abrasive dust with the texture of grinding paste while the water corrodes fiercely. Such conditions are severe for the miners themselves; they are equally so for any electronic equipment.

All mining is an industrially intensive activity which relies on heavy machinery and equipment powered by a network of high voltage cables. Electrical noise therefore proliferates wherever these cables exist. And then there is the rock itself.

Fig.1. Dr Trevor Wadley demonstrating the Tellurometer to the British Prime Minister, Mr Harold Macmillan, on a visit to South Africa in 1960

Though obviouslyly an electrical insulator when compared with copper, rocks of all types actually behave as quasi-conductors because of the water that is naturally entrapped within their interstices. They therefore absorb electromagnetic energy and so attenuate radio signals. Communication ranges are therefore limited to distances much less than those encountered above ground. So, any radio system intended to function in such conditions has to be especially designed to cope not only with an exceedingly harsh environment but also with one that hinders the propagation of electromagnetic waves.

Soon after that first query about using radio underground in 1938 the Second World War broke out and South Africa's industrial resources were all directed in support of the Allied cause. The engineers and scientists in Johannesburg who had initially given some sceptical attention to the mining communications problem now found themselves diverted to the highly secret subject of RDF, as Britain's wartime radar technology was known at that time. All work in the Bernard Price Institute of Geophysical Research at the University of the Witwatersrand was focused on developing South Africa's own radar, based on the disclosures made to the Dominions by Robert Watson Watt at Bawdsey just a few months before. For the foreseeable future the gold mines, whose output was vital to sustain South Africa's economy, would have to cope with just their telephones for communications.

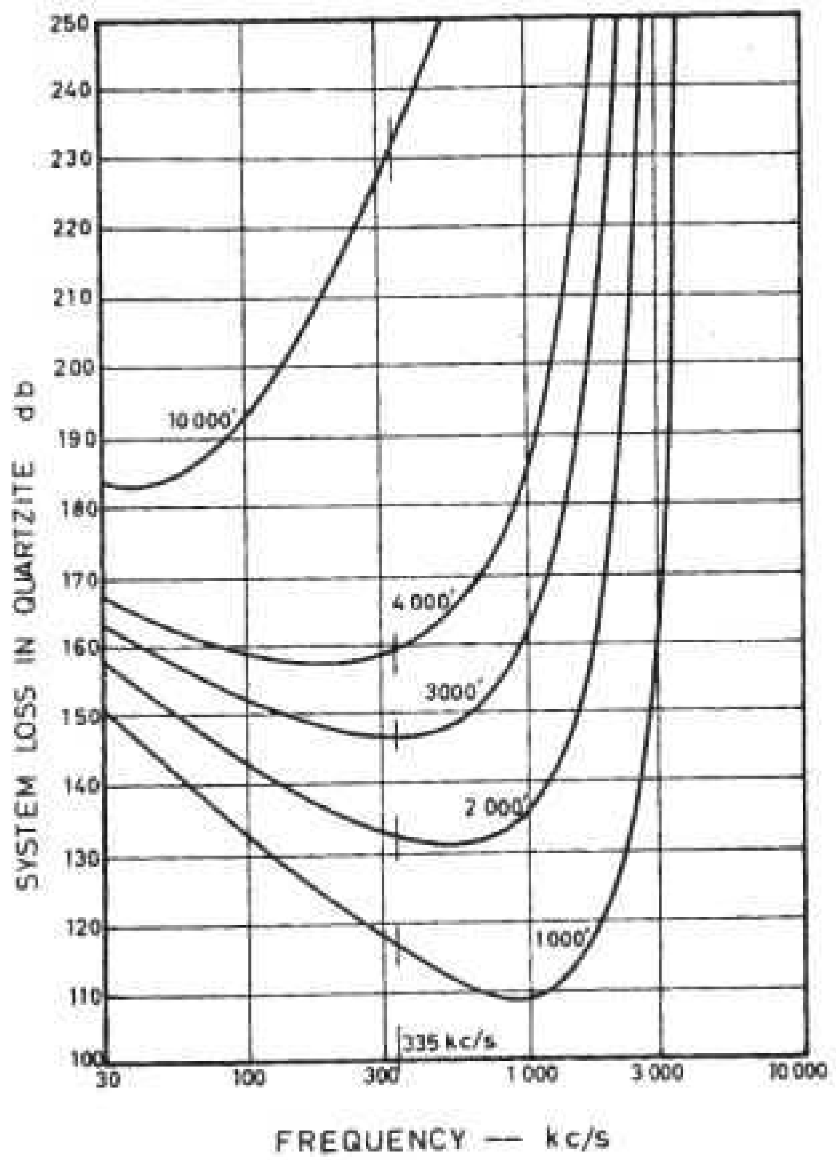


Fig. 2. Wadley's calculated curves of system loss with frequency in quartzite rock over various distances

The Wadley Connection

Undoubtedly the most brilliant electronics engineer that South Africa has produced was Trevor Lloyd Wadley (1920 – 1981), see **Figure 1**. Probably best known for the 'Tellurometer', the microwave distance-measuring instrument used for surveying, his fame was first established when the Racal Company in England turned his revolutionary triple-loop HF receiver into the famous RA17 in 1954. Immediately after the war, during which he had made significant contributions to the development of South Africa's own radar system, Wadley conceived and produced the prototype of that receiver which now bears his name. What was arguably one of the greatest advances in receiver technology took place when he was on the staff of the Telecommunications Research Laboratory (TRL) of the CSIR in Johannesburg.

The similarity of the letters TRL with TRE, the Telecommunications Research Establishment in England, has led some erroneously to conclude that Wadley designed his receiver at TRE when, in reality, he never spent any time there at all. It was all done in South Africa. Fascinating too, in the context of this article, is the fact that while heavily engaged on the design of his receiver Wadley also turned his mind to the problem that had lain dormant throughout the war – the problem of communicating by radio underground.

In 1949 he wrote a report entitled "Radio communication through rock on the Witwatersrand mines". It had been commissioned by South Africa's Chamber of Mines and was based on Wadley's measurements in the laboratory of the electrical characteristics of rock samples typical of the gold mining areas of the country. From those results, and his ready appreciation of the problem of designing rather special radio equipment well before the availability of transistors, he produced a document that defined in detail the underground radio communication problem. The graphs it contained indicated how the rate of signal attenuation by the rock increased rapidly with frequency. By contrast, the efficiency of small antennas that were necessary with portable equipment decreased markedly as the frequency was lowered. Taken together the two yielded the total system loss that had to be overcome for a given distance between transmitter and receiver. For any particular distance, therefore, there was clearly an optimum frequency that should be used. See **Figure 2**.

But there were other factors as well which mitigated against a simple solution. When fighting a fire the rescue brigadesmen would be using breathing apparatus which was bulky and uncomfortable. Additional equipment, such as a radio, might just prove to be an impediment rather than the aid intended. To make matters worse speech was impossible because all the brigadesmen wore mouth pieces and nose clips. Communication was therefore by signs rather than sound. Though the radio operator at the fresh air base might transmit speech, the brigadesman in action some distance away would only be able to reply by means of simple keyed messages, certainly not even in Morse code.

Operating Frequency

In arriving at the operating frequency for radio underground Wadley had dismissed any possibility of using the air-filled tunnels and stopes for communications purposes since they would only usefully convey signals whose wavelengths were considerably less than the tunnel dimensions and then only if they contained no bends or irregularities – ar

Fig. 3.The base station and its wagon-wheel antenna c.1960

unlikely situation in a mine. His research, therefore, concentrated on finding the optimum frequency for transmission through the rock. This, he concluded, was between about 100kHz and 1MHz for the geological conditions found in South African gold mines and practical communication ranges during rescue and fire-fighting operations. Using portable equipment with an input power of 1W and a fixed station of some 10dB greater at the fresh air base, he calculated that two-way communication over a maximum distance of some 900m through rock should be possible under ideal, noise-free conditions at a frequency of about 350kHz.

The antennas used would be severely compromised by the need for portability and ease of deployment. The portable station, Wadley suggested, might use a multi-turn loop accommodated within the brim of the radio operator's protective 'hard hat', while the fixed unit would, if at all possible, set up a dipole some 120m in length along a tunnel or haulage. In passing, he mentioned that the rails or pipes found within a typical mine might usefully serve as one terminal of the base station antenna but he made no mention of the possibilities of inductive coupling between the antennas and these conductors or the electric power lines that serve many parts of a mine. Such adventitious coupling would, indeed, play a major part in extending the range of the systems that followed from Wadley's pioneering work.

A Practical System

There was to be a lapse of some years before the first radio sets designed according to Wadley's research findings actually underwent trials underground. The development work was undertaken by the Electronics Division of the Chamber's Research Laboratories and it resulted in the design and construction of a base station and portable equipment believed to represent the state of the electronic art at that time. These units are shown in **Figures 3** and **4**. Except for three transistors in the audio stages of the base station receiver valve

Fig. 4. The portable equipment used by a rescue brigadesman wearing breathing apparatus, mouthpiece and nose clip

technology was used throughout. See **Figure 5**. Given the state of transistor development a mere ten years after their discovery this was not really surprising. Amplitude modulation was used in the base station while on-off keying had to suffice in the portable unit for the reasons given earlier.

Careful consideration of a typical mine layout had indicated that the dipole antenna suggested by Wadley for the base station would usually be incorrectly aligned relative to the direction in which the portable units would be operating. In addition, measurements made underground by the Chamber's engineers had shown that the rock-induced losses in the dipole antenna were excessive. On consulting Wadley about this he recommended that a wire loop antenna of large circumference be substituted at the base station, but the need for careful adjustment of transmitter tuning and matching to accommodate any changes in loop geometry suggested that a rigid, multi-turn loop of suitable intermediate size was a better option. The wagon-wheel configuration adopted can be seen in **Figure 3**.

The uncomfortable lot of the brigadesman wearing breathing apparatus and carrying a portable transceiver weighing some 6kg is shown graphically in **Figure 4**. The idea of placing the antenna in his hat had been abandoned; rather a loop antenna was encased within the pre-formed carrying strap that also housed a loudspeaker positioned close to the operator's ear. Though achieving reasonable performance, this portable apparatus soon proved to be unmanageable even for the most dedicated of brigadesmen and a valiant attempt to solve a very pressing problem was stillborn.

Solid-state and Single-Sideband

By the mid-1960s solid-state devices suitable for applications such as this were readily available, and there were many companies in South Africa that could design and manufacture this type of radio equipment. The Chamber duly awarded a contract to one of them to develop the next generation of what soon became known as the 'Underground Radio'.

Wadley's graphs still served as the basis for the system and a frequency of 335kHz was selected. Efficient use of battery power suggested that single-sideband (SSB) modulation at 10W PEP was much to be preferred over the earlier AM, while a tone-based keying system would still accommodate the voiceless brigadesman and serve as a general calling and alerting signal. Considerable reduction in equipment size was also possible without sacrificing any of its features and so the same type of apparatus, of the size of military man-pack radio, (see **Figure 6**), could now be used at the fresh air base and by the brigadesman on the move. The antennas, though, would differ because the fresh air base could deploy a much larger loop. Experiments had shown that a single turn of some 30m of wire could be set up easily by attaching it to any available supports within an underground tunnel. The

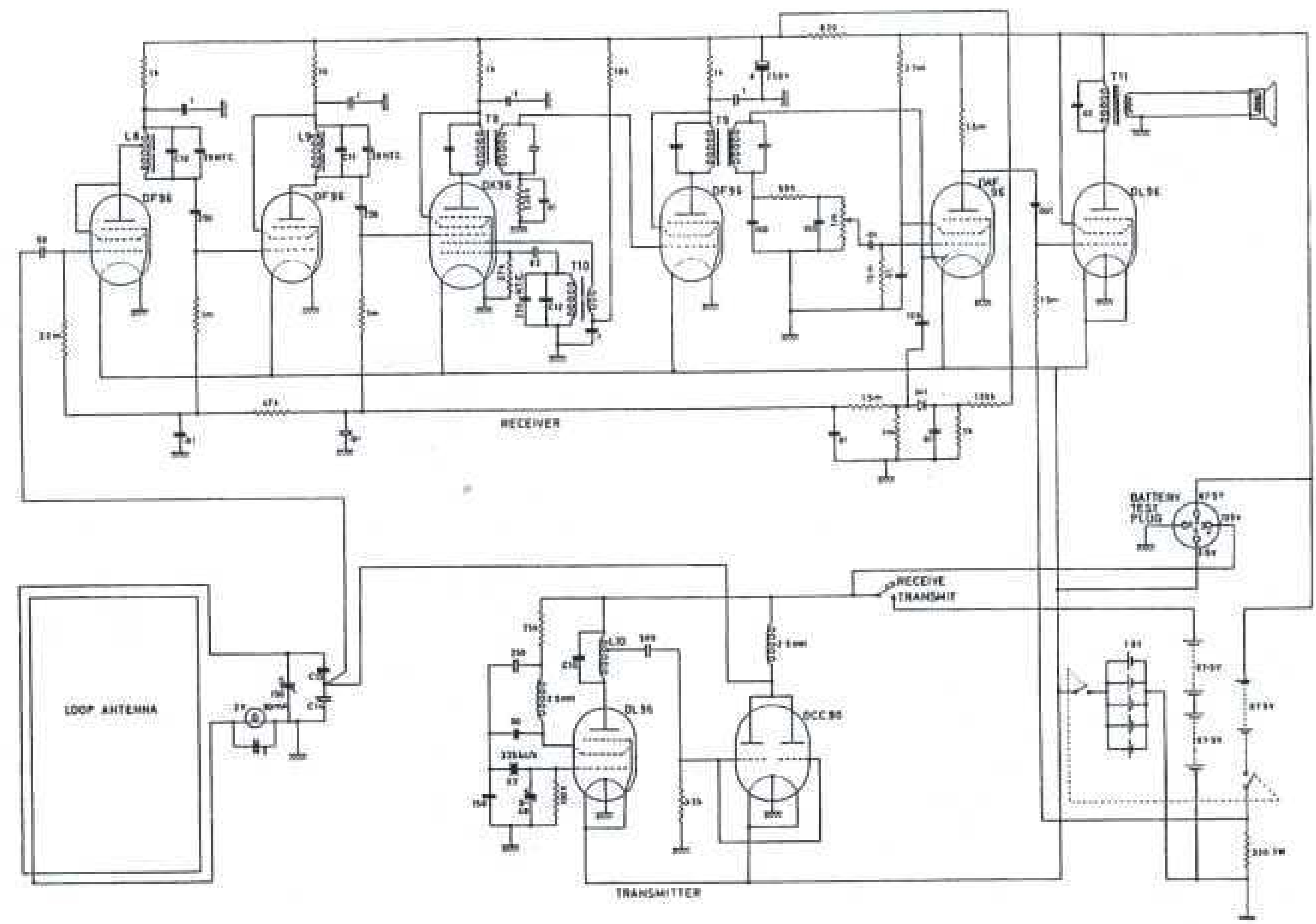


Fig. 5. Circuit diagram of the portable equipment

loop was then brought to resonance and matched to the transmitter by means of a switched capacitor network contained in a suitable housing. The portable antenna, by contrast, still made use of a rigid loop but now it was housed in a light, PVC tube pre-formed into an elliptical shape with major axis of about a metre. This shape had no significance from an electromagnetic point of view but achieved adequate loop area in a physically manageable size. Seven turns of wire were used and their inductance was resonated and matched by preset capacitors.

Other Applications

By now applications other than underground emergencies suggested themselves, at least to those engaged in the underground radio project. Whereas Wadley's original calculations indicated that a range of the order of 900m might be achievable directly through rock, underground tests showed that this was optimistic. A conservative estimate, based on numerous tests in many mines and at different depths below the surface, showed that 300m was more realistic. However, ranges much greater than this were not uncommon when electric power cables or other continuous conductors spanned the route between two radio installations, while the Americans reported unexpectedly large distances from the sets that they had bought from the Chamber of Mines. In their case the radio signal was trapped within a coal seam by highly conducting layers of rock above and below. It soon became apparent that these various guiding mechanisms would greatly increase the range and this suggested that radio communications could aid in improving the efficiency of mining activities underground.

Resistance to Change

Despite mounting something of a campaign to convince mine managers of the useful role that improved communications underground could play in the day-to-day operations of a mine their reaction was, in the main, rather muted. Miners are, as a breed, conservative and are not given to ready acceptance of new-fangled gadgetry however remarkable it is in the eyes of its designers! What was needed, of course, was a proper operational research study in order to quantify these perceived benefits, particularly in financial terms, but none was ever done. However, interest had certainly been aroused within the Chamber of Mines Research Organization itself and this was most evident amongst those engineers who were endeavouring to replace drilling and blasting by various forms of mechanized mining, such as rock-cutting by hydraulically powered machines. Such activities were, by their very nature, less labour intensive than conventional mining with explosives but they involved equipment that could break down and so would require repair and maintenance. Effective communication between all personnel involved, therefore, was surely vital. Wired telephone circuits would suffice between fixed points but roving maintenance men were always beyond effective reach, until now. However, the objection was that the underground radio was still too big and too cumbersome.

Fig. 6. The 335kHz solid-state 10W SSB transceiver and elliptical loop antenna c.1972

Fig. 7. The 903kHz handheld transceiver being used in a mechanized goldmine stope c.1976

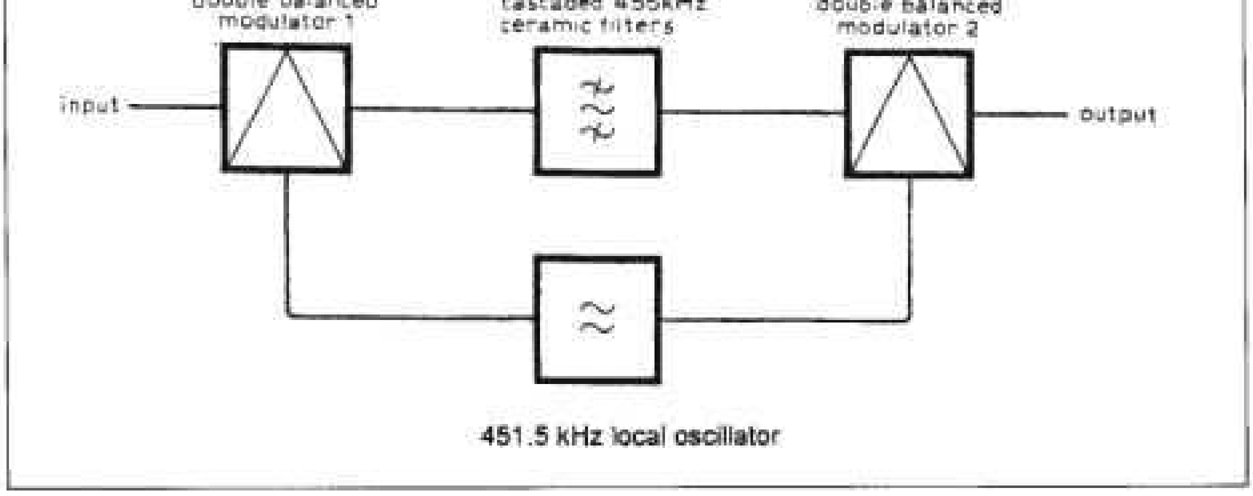


Fig. 8. The 903kHz SSB generator and product detector using ceramic filters driven by a 451.5kHz oscillator

A Handheld Transceiver

In 1974 work commenced at the Chamber's laboratories on developing a handheld radio transceiver that would provide voice communications between miners and maintenance men on the move within the narrow confines of a mechanized gold mine stope. Again it was the Wadley graph that suggested an optimum operating frequency for the equipment. Raising this to about 1MHz would lead to a reduction in range but it would produce a consequential reduction in system loss of more than 40dB. The reduced range could be tolerated because the stope within which the experimental rock-cutting machines were operating was only a couple of hundred metres in extent, and it was well-served by power cables and steel-armoured hydraulic lines. Tests soon showed that 1W PEP at about a megahertz would be more than adequate especially if a higher-powered base station and large loop antenna were set up within the underground store that served as the command centre for the mechanized operations.

The transceiver that was subsequently produced is shown in **Figure 7**. It was known as the TXR-1 and operated on 903kHz as a result of the particularly simple method used to generate and detect the SSB signal shown in **Figure 8**. In order to reduce costs as much as possible use was made of 455kHz ceramic filters to produce an upper-sideband (USB) signal. By using two of these filters in cascade, and a crystal oscillator at 451.5kHz, it was possible to achieve adequate rejection of the unwanted sideband. By adding this USB signal to that from the same oscillator in a second balanced modulator an output at 903kHz was produced. The process was merely reversed when receiving.

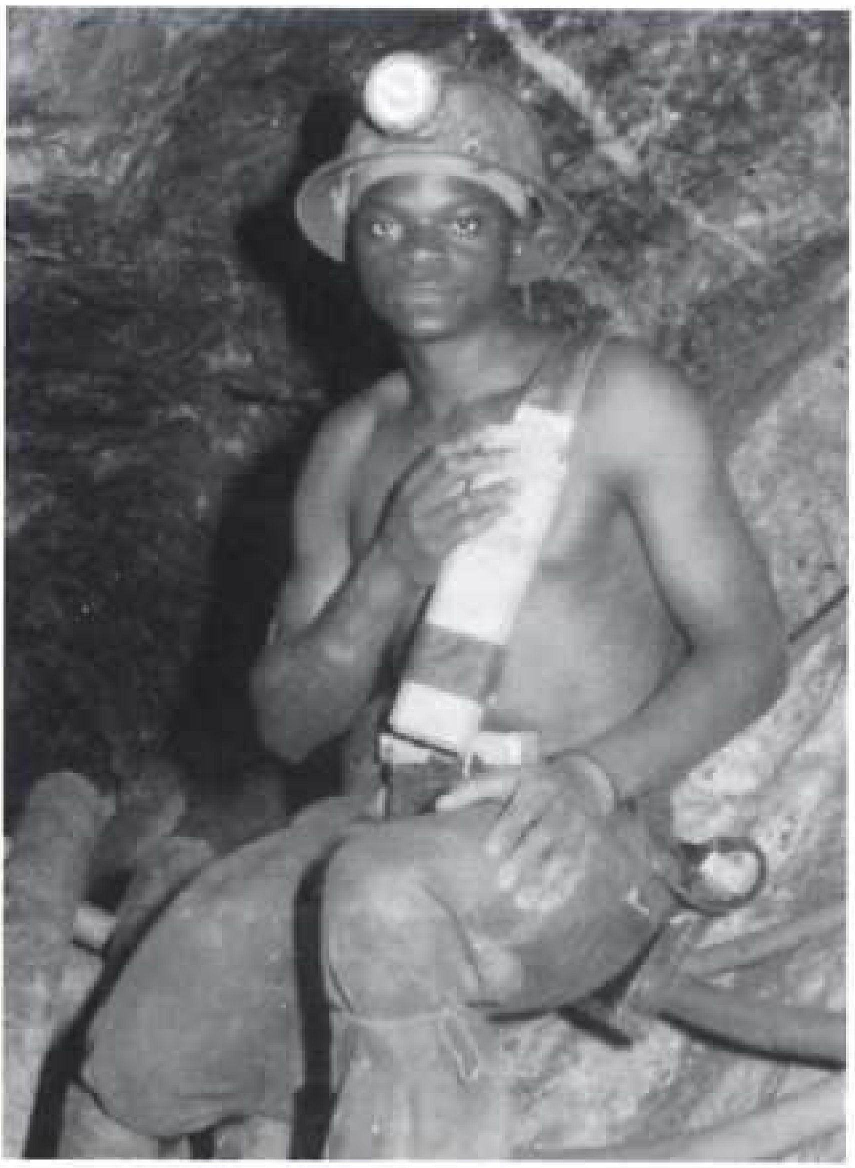
Power amplification at both audio and radio frequencies was straightforward and so a remarkably simple, yet effective, transceiver small enough to be held in the hand was the outcome. The ubiquitous multi-turn loop served as the antenna but now it was made flexible and was worn by the operator in the fashion of a bandolier. Experience had shown that no perceptible change in performance was noted even when the loop changed shape, as it would do during normal use. This finding was significant because rigid loops had plagued all previous designs.

The Substrata Communicator

The consistently good results achieved with the 903kHz equipment, whether operated directly through rock over distances of the order of 100m or over much greater distances when coupling indirectly into power cables, opened the way for a major development in underground radio communication. Small, portable equipment with an operating life of at least eight hours between recharging the battery was clearly feasible and a concerted design programme began at the Chamber of Mines laboratories in 1976. Within the year the TXR-2 prototype had appeared. This was a sophisticated SSB transceiver capable of operating on any 3kHz channel between 100kHz and 2MHz. It embodied the most up-to-date technology with a receiver that was particularly immune to the effects of strong, adjacent channel signals. This requirement came about because of the perceived need, in practice, to operate a number of the units in close proximity to one another but on different, though adjacent, frequencies. Such a situation would occur were radio communications to assume an increasingly important part in the operation of a mechanised stope.

The similarity of this multi-channel operation with military radio nets was evident and the harsh mining environment made the equipment specification easily the rival of its military counterpart. Commercial production of the equipment was agreed and in 1977 the Chamber of Mines entered into an contract with Racal (South Africa) – though soon to separate from its British parent to become Grinel – to develop such a system based on the Chamber's specifications.

The SC100 Substrata Communicator, as it was called, appeared within a year (see **Figure 9**). It weighed less than 2kg and was a rugged, waterproof transceiver containing a frequency synthesizer for multi-channel operation if required. Its multi-turn loop antenna functioned also as the holding strap which secured the radio around the miner's torso. The SC100 was joined, soon after, by the SC200, (see **Figure 10**), a repackaged unit complete with an adjustable antenna tuning network. Intended specifically for use at the fresh air base by rescue brigadesmen, or whenever a dedicated base station was required, the SC200 could also be operated remotely over a two-wire line from a point up to 20km away. This followed the successful demonstration of remote control by the Chamber's research personnel when an operator on the surface communicated with a roving miner 3km below ground in a stope just 1m high. A remotely controlled base station provided the final radio link to the miner through 100m or more of rock. What was clearly a simple extension



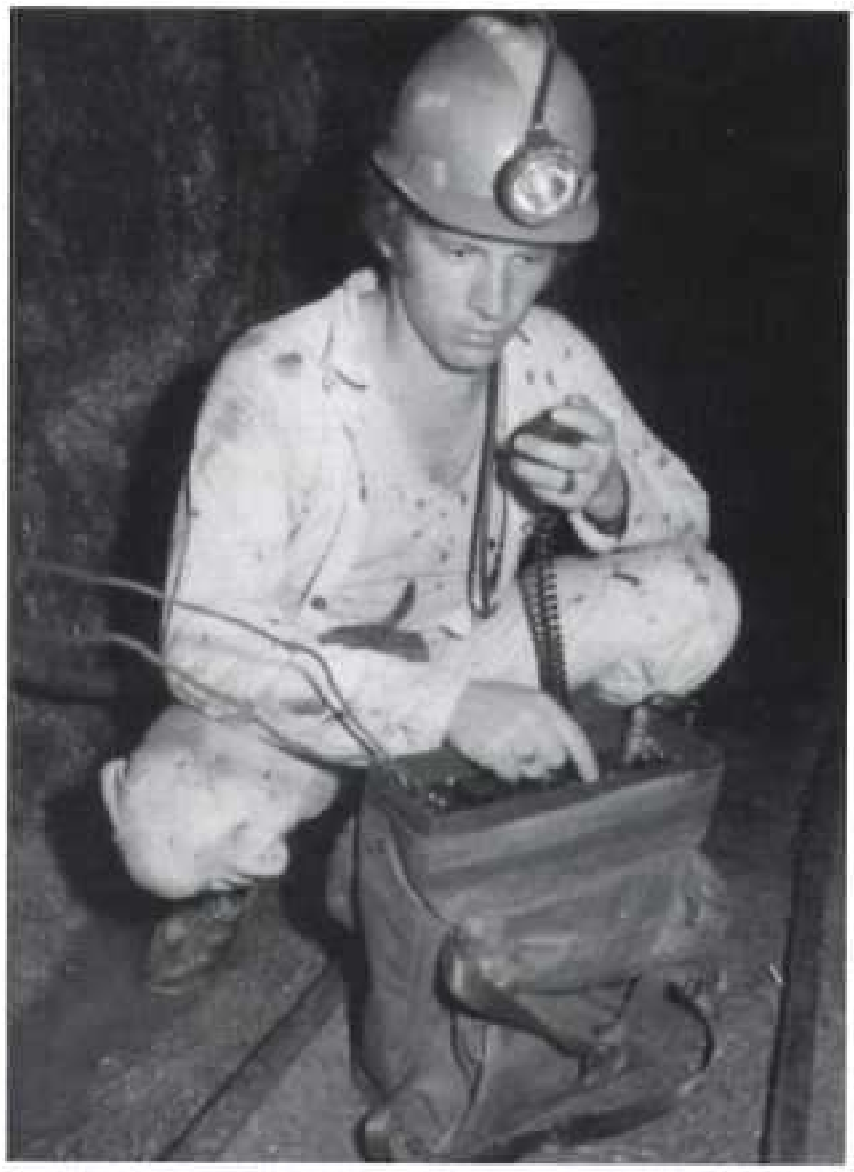


Fig. 9. SC100 Substrata Communicator and its bandolier antenna in use underground c.1981

Fig. 10. SC200 base-station transceiver.

of the use of a master or base station within a radio network, this feature was important because it meant that the radio system could easily be linked to the mine's telephone network for use during either normal operations or in an emergency.

Commercial Exploitation

By 1980 more than 100 of the SC100/200 radios were in service in South African gold and coal mines and numerous demonstrations were given within the industry by the commercial company formed to market this equipment. Interest had been aroused abroad as well, but there was competition.

Research in England and on the Continent had gone in a different direction. Due to the nature of the mines (mainly coal), which were highly mechanized, a communication system based upon radiating transmission lines, known as "leaky feeders", was the favoured technique. These lines were slung throughout the travelling ways and working areas of a mine and provided excellent voice contact between VHF radios within their immediate vicinity. Transmission directly through the rock and coal was not a requirement and the radios were seen, primarily, as part of the coal production process and not as emergency aids in a crisis. This was precisely opposite to the South African gold mining experience and reflected the nature of mining itself.

Elsewhere, in Australia and Canada, the South African system was looked at with interest. But South Africa's own mines were slow to react. Though recognising the radios' worth, both during emergencies and, increasingly, for some day-to-day mining activities, the equipment was seen to be somewhat peripheral – and it was expensive. Its manufacturer, too, was primarily concerned with producing military communications hardware, for which there was a ready market. The expected saturation of the mines with radios did not occur, at least not at the rate the manufacturers had hoped for, and soon the project foundered, yet again. Like the sunspot cycle, to which it was often jocularly compared, South Africa's forays into mine communications seemed to peak about once per decade. Maybe they will come again? **RB**

Bibliography

1. C. I. Colburn, C. M. Bouton and H. B. Freeman, *Underground Signalling With Radio Sets*, US Bureau of Mines Report 2407, 1922.
2. E. E. Bramall, *Wireless Communications in Mines*, The Institution of Mining Engineers, 69, Feb.1925, pp.179-185.
3. B. A. Austin, *Schonland – Scientist and Soldier*, Institute of Physics Publishing, Bristol, 2001; (ch.10: underground radio; ch.11: South African radar; chs.16, 24: Wadley, underground radio).
4. D. J. Vermeulen and P. J. Blignaut, *Underground Radio Communication and its Application for use in Mine Emergencies*, Trans. South African Institute of Electrical Engineers, 52, April 1961, pp.94-109.
5. A. G. Emslie and R. L. Lagace, *Propagation of Low and Medium Frequency Radio Waves in a Coal Seam*, Radio Science, 11, April 1976, pp.253-262.
6. B. A. Austin and G. P. Lambert, *Electromagnetic Propagation Underground with Special Reference to Mining*, Trans. South African Institute of Electrical Engineers, 76, Jan.1985, pp.1-5.