Signalling To Submarines At Extremely Low Frequencies

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The problem of signalling by radio to and from submerged submarines has presented radio engineers with some of their greatest challenges ever since the inception of wireless communications. The reason, of course, is that the sea is a rather good electrical conductor. As a result, the mass of seawater behaves as both a huge reflector and as an equally large absorber, or attenuator, of electromagnetic waves. The end result of both those effects is that radio signals do not propagate too far under the sea.

But it is possible to send signals to submarines – even over worldwide distances – if extremely low frequencies (known in the nomenclature of such things as ELF) are used. However, for most of their passage they do not travel through the sea but rather in what is called the earth-ionosphere waveguide. This article will trace some of the history of this fascinating subject with particular emphasis on the various US projects that have been described in the 'open' literature.

Background History

At the height of the 'Cold War' the ability to be able to send vital messages to their submarine fleets at operational depth anywhere around the globe was a vital strategic asset much prized by both super powers. Whereas we have a pretty good idea of what the US Navy could achieve (because they told us!), we can but surmise what the Soviet's capabilities were in this area.

It was in May 1971, as a result of a formal statement to the Senate, that we first learnt of the efforts then underway in the United States to equip its fleet of nuclear-powered submarines with a worldwide communications capability [1]. It should be remembered that those submarines could remain submerged for many months at a time and so they constituted a considerable deterrent to any adversary. They were virtually undetectable and could launch their missiles while at operational depths. However, the much-dreaded executive order to do so relied on radio and therefore some way of signalling to the submarine had to be provided. Project Sanguine, which commenced in 1962 with the purpose of developing the means to do this, was then made public.

Sanguine was not the first research programme in this area to be sponsored by the US Navy. As early as 1959, theoretical work was under way to examine the feasibility of communicating with the nuclear-powered submarines that had been launched just a few years before. A report written that year (but only declassified in 1972) by N.C. Christofilos of the Lawrence Livermore Laboratory in California effectively started it all under the name of Pangloss, a term according to the USN that was "an arbitrary definition without intrinsic meaning". [2]. One is immediately reminded of the term R.D.F, the original British name for radar, defined by Robert Watson-Watt in 1938 as "a code name intended to have no identification" but forever misidentified to this day as meaning radio direction finding.

ELF

Christofilos showed that ELF (3Hz to 300Hz) electromagnetic waves, which would penetrate to significant depths within the sea, could be launched by a practicable antenna system suitably located within the continent of the United States.

Since the wavelengths at those frequencies are so long, ranging from more than twice around the circumference of the earth at the lowest frequency to 1000km (or 1Mm for mega metre, as the scientists describe it) at the top end, any antenna was likely to be electrically small, even though its physical dimensions might be hundreds of kilometres in extent. But almost more important to the success of the project than the antenna was the way in which the radio signals would actually propagate between a transmitting antenna on land and a submerged submarine, possibly 10,000km away at operational depth beneath the ocean.

The answer to this question was provided in an erudite research paper written by Dr J R (Jim) Wait in 1960 entitled *Mode theory and the propagation of ELF waves* [3].

Fig.1. Jim Wait photographed by the author while relaxing at an IEEE conference in Canada in 1991

Wait was not a contractor to the US government; he was a research scientist employed at the time by the National Bureau of Standards in Boulder, Colorado where he specialised in the electromagnetic phenomena involved in geophysics; the physics of the earth itself. By the late 1950s, he was already recognised as the theoretician who had provided explanations for many previously intractable problems involving radio waves and antennas operating in close proximity to (and frequently submerged within) the Earth.

From his early work in Canada to his untimely death in Arizona at the age of 74 in 1998, Jim Wait (**Figure 1**) was truly a giant amongst a very select group of theoreticians who unravelled the complexities of electromagnetic phenomena in the geophysical environment. His explanation of the operation of what has subsequently come to be called the 'earth-ionosphere waveguide' is absolutely fundamental to the performance of a submarine communications system.

Radio Waves And Seawater

Seawater is a reasonably good conductor of electricity. It is not nearly as good as any of the metals, of course, but is considerably better than other geophysical substances such as soil and rock, and much more highly conductive than fresh water. Its actual conductivity is about four Siemens per metre (or S/m). By contrast, copper is roughly 10 million times more conductive, while typical soil is about a thousand times less so. It's therefore all relative and one has to consider a number of factors when deciding if a material is indeed a conductor, an insulator or something in between.

Freely propagating radio waves, which consist of electric and magnetic fields at right angles to each other and also to their direction of propagation, are attenuated when travelling through any conducting medium. The effect is best described by the so-called skin effect, or depth of penetration, that indicates how far an electromagnetic wave will penetrate into a conducting material before its amplitude is reduced by a given amount.

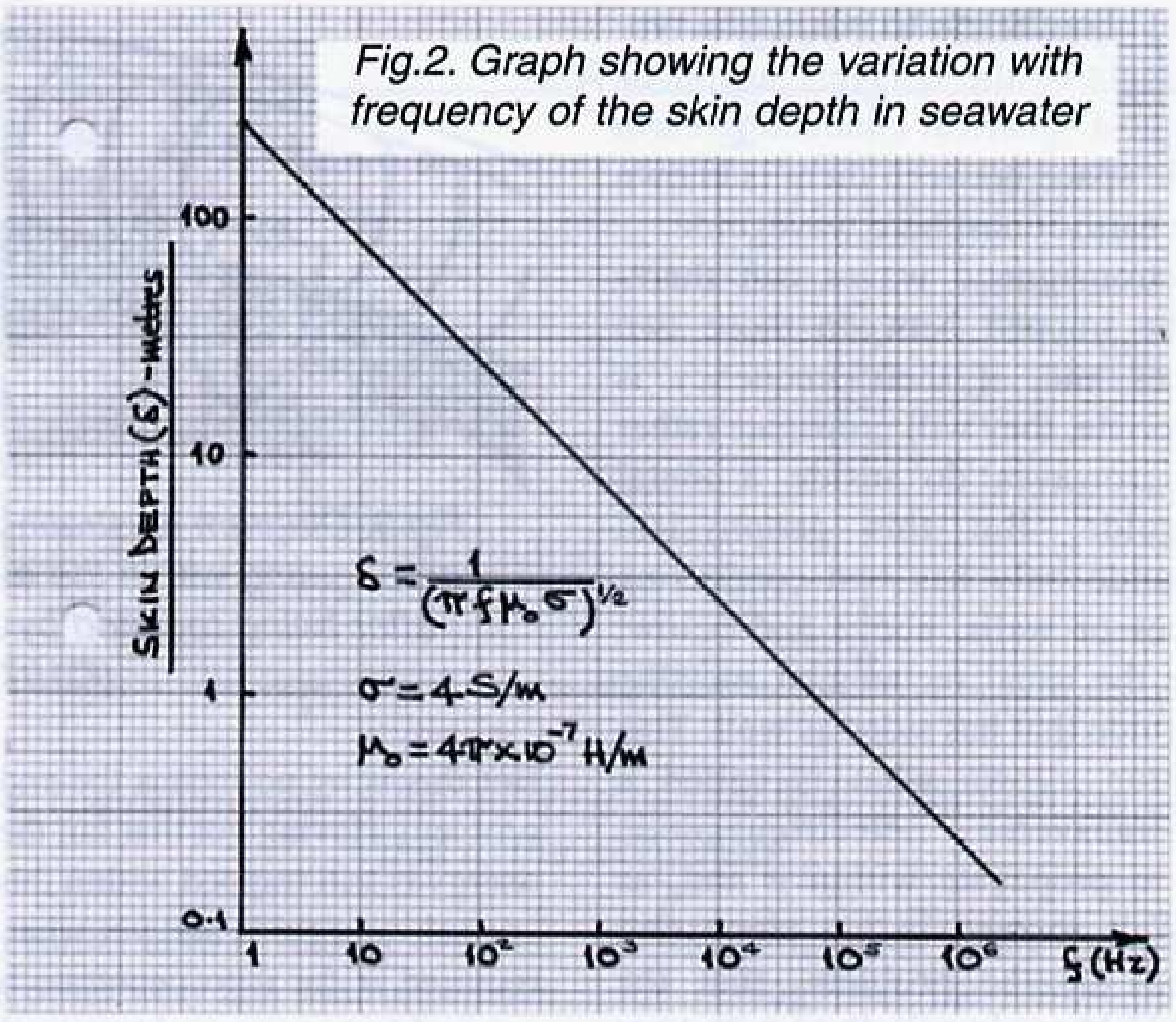

Fig.2. Graph showing the variation with frequency of the skin depth in seawater

In essence, the higher the frequency and the higher the conductivity of the medium the greater the attenuation and so the depth of penetration is least in good conductors and at high frequencies. The effect is not abrupt, however; radio waves will continue to propagate but at exponentially decreasing amplitudes beyond the skin depth but their effectiveness is diminished dramatically.

By definition, the skin depth is that distance within which the amplitude of the RF field has decreased by about 8.7dB from its initial value. And it is the skin depth of seawater that determines how well radio signals will propagate within it. **Figure 2** shows the skin effect at work and it will be noted how the depth of penetration decreases sharply with frequency.

Therefore, to achieve useful propagation distances within the sea requires the use of extremely low radio frequencies. But even then the attenuation suffered by the signal would limit the communication range to just a few skin depths. So Pangloss, Sanguine and their successors actually went to great lengths to keep their signals above the sea in what became known as the 'up, over and down' mode. To do that, however, meant using the ionosphere in a rather unusual way.

The Earth-Ionosphere Waveguide

Everyone reading this will undoubtedly be familiar with the way the ionosphere behaves at HF (3MHz to 30MHz). Depending on the relationship between the transmit frequency and the critical frequencies of the ionosphere's E and F-layers, signals can be returned to earth over distances up to about 4000km in a single hop. In this, its usual mode of operation, the ionosphere functions as a refracting medium that bends an incident signal, sometimes by as much as 180 degrees, and so returns it to the earth at a distant point.

Multiple hops between the earth and the ionosphere then enable worldwide communications to take place. Though the loss in signal strength due to refraction is minimal, each intermediate ground (or sea) hop dissipates some of the incident power in a way that varies with the angle of incidence of the down-coming wave and its frequency. Typically, at an angle of incidence of 30 degrees to the surface, there is a reflection loss of about 7.5dB per hop at 15MHz off the ground, but only about 0.2dB per hop off the sea, because of seawater's much higher conductivity. At lower frequencies, but at the same angle, those losses decrease quite significantly [4].

Quasi Transverse Wave

As we move down in frequency a very long way to the values typical of the power networks of the industrialised world (i.e. 50Hz and 60Hz), the earth and its ionosphere both become remarkably good conductors and so they behave as very effective reflecting surfaces. As a result, a conducting shell at about 80km to 90km (the typical height of the D-layer) surrounds the almost spherical conducting earth and the space between them is known as the earth-ionosphere waveguide.

Electromagnetic waves can therefore be trapped between those two surfaces and, if their frequency is appropriate, they will propagate rather as microwaves do inside a metal waveguide. But this geophysical waveguide only has two conducting surfaces or walls, above and below; unlike the usual rectangular metallic waveguide that has sides as well. This condition allows what is called a quasi-transverse electromagnetic wave to propagate within it and, as Jim Wait showed in his pioneering analysis of the problem, that the quasi-TEM mode will do so with very little loss indeed.

To put all this into perspective, the loss within this natural waveguide amounts to no more than about 1dB per thousand kilometres at a frequency of around 100Hz [5]. Clearly, this channel must have something to offer those wishing to communicate over global distances but, as with all good things, it suffers from some serious disadvantages too.

Disadvantages

The first disadvantage is the problem of launching or radiating radio signals at frequencies where the wavelengths are but a trifling 3Mm at 100Hz and get even longer as we go down towards those power frequencies. Second, is the extremely narrow bandwidth on offer if the carrier frequency is 100Hz or even less. And, as is well-known, atmospheric noise increases significantly as we go lower in the RF spectrum. If those 'sferics are bad at 3.5MHz on a summer evening what must they be like down at ELF? But submariners are hardy souls and must also be natural-born optimists, so they also looked at the other side of the balance sheet.

As we've just seen, the ELF signal, once launched, will travel all the way round the world and suffer a loss of no more than a few tens of decibels in the process. Contrast this with the loss of about 150dB that would be incurred by an HF signal at 15MHz travelling the same distance and yet ignoring all the ground-bounce losses along the way.

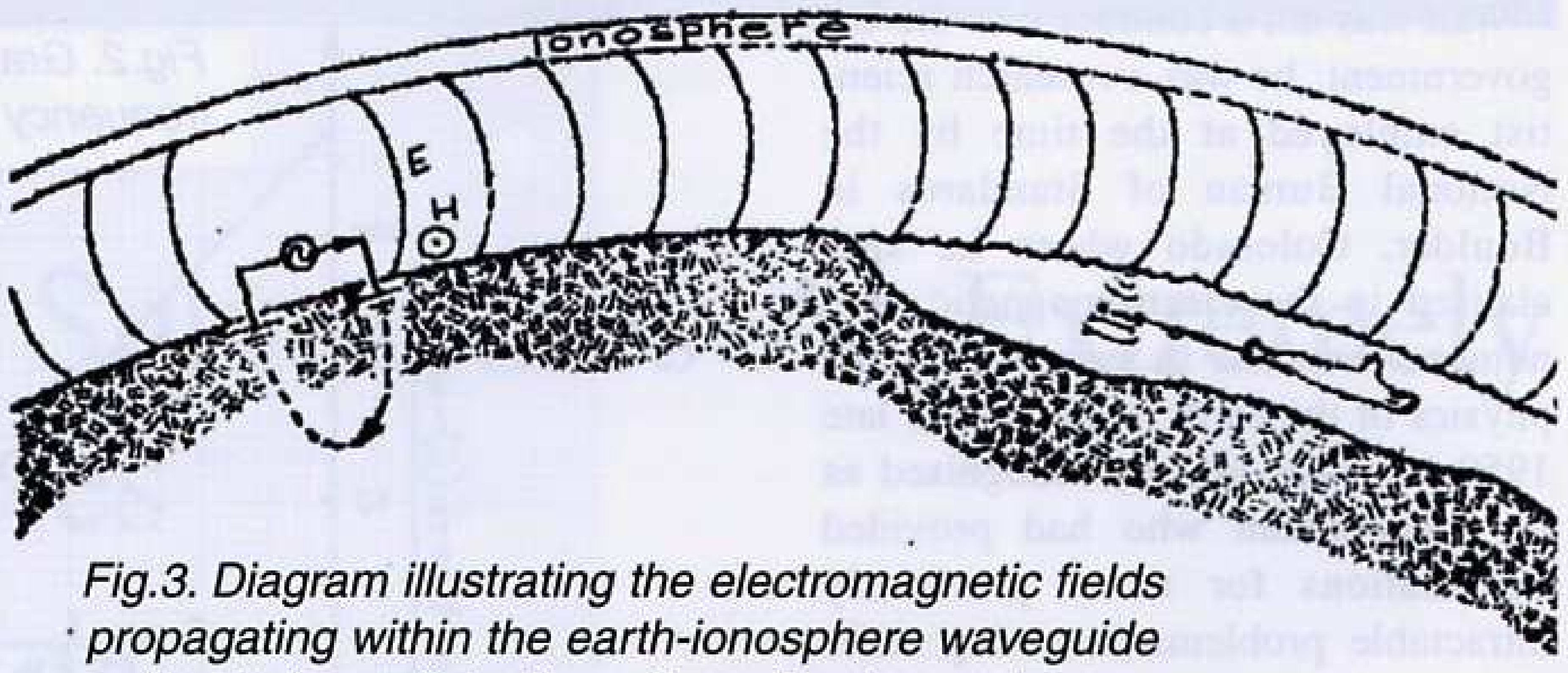

Fig.3. Diagram illustrating the electromagnetic fields propagating within the earth-ionosphere waveguide after being radiated by a Sanguine-type antenna (©1974 IEEE)

But this is by no means the end of the problem. Having got that far, the signal energy is still trapped within this rather special waveguide and yet what is now required is for it to penetrate into the sea and to propagate down to the submarine at its operational depth.

As shown in **Figure 3**, the electric field within the earth-ionosphere waveguide is predominantly vertical while the magnetic field is horizontal. However, that vertical component drags its feet somewhat because the finite conductivity of the land and sea causes it to tilt forwards slightly and so there is also a small horizontal component of the E field travelling in the direction of propagation parallel to the surface.

This horizontal electric field, and the magnetic field at right angles to it, together cause a downward travelling component of power density to exist, and though it suffers quite severe reflection loss at the air-sea interface this electromagnetic field enters the sea and propagates directly downwards to a submarine below. But it is also attenuated by the high conductivity of the seawater and so is related to the skin depth, as mentioned before.

A very simple calculation shows that a signal at 100Hz will be reduced from its value at the surface by about 7dB at a depth of 20m. By contrast, one at 15MHz will have suffered a staggering 2673dB of attenuation at the same depth! Such attenuation is unimaginably large and leads to a signal so weak as to be well nigh non-existent. It is therefore an open and shut case as to what sort of frequencies have to be used if we wish to talk to submariners as they go about their vital task anywhere beneath the surface of the globe.

It will be appreciated, of course, that the word 'talk' is being used rather loosely in this context because the bandwidth (and hence the data rate) available at a carrier frequency of 100Hz is rather limited! For this reason, and the fact that the submarine cannot reply, as will soon become clear, Project Sanguine was known as the 'bell-ringer'.

Project Sanguine

The first experimental evidence that extremely low frequency electromagnetic energy propagated with very little loss over the surface of the earth came from work done at King's College, London in the mid-1950s by Chapman and Macario [6]. They measured the attenuation rates of the 'sferics produced by lightning discharges at considerable distances. Those results, and subsequent experimental work done elsewhere, effectively confirmed the theoretical work of Wait and others and so, based on this evidence, the US Navy launched Project Sanguine in 1962.

The RCA Company in New Jersey was awarded the first contract to carry out measurements of the propagation of radio signals at frequencies below 100Hz. To do this they used a 176km long antenna strung on telegraph poles in North Carolina. To the uninitiated it looked just like a telephone line or a low voltage power line and no official comment was ever made about it. However, what was not evident to the untrained eye was that the ends of the antenna were grounded. The results of the first experiments were published in 1966 and showed that 78Hz ELF signals propagated as predicted over a distance of at least 4900km to a receiving station at Keflavik in Iceland, with attenuation rates of 1.01dB/Mm at night and 1.29dB/Mm during the day.

Wisconsin Test Facility

Another contract, awarded this time to the Lincoln Laboratory of the Massachusetts Institute of Technology (M.I.T.), made use of a somewhat similar, though shorter, antenna. It was located in Wisconsin and became known as the Wisconsin Test Facility (W.T.F.).

The antenna consisted of two 22.5km long wires, again supported on telegraph poles, and with the two spans aligned roughly at right angles to one another. As in North Carolina, the ends of the two crossed elements were grounded. The reason for this will soon become clear. Two bands of frequencies (40Hz to 50Hz and 70Hz to 80Hz) were selected in order to avoid the 60Hz power line frequency in use in the United States. Each of the antennas was driven at its mid-point by specially constructed transmitters that delivered a maximum of 300A of current to each element of this crossed-dipole array.

Changing the relative phases of the currents made it possible to steer the radiation pattern and, similarly, feeding them 90 degrees out of phase would produce an omni-directional pattern.

The burning question though is how much power does this antenna radiate? It turned out that with 300A flowing in each element the effective radiated power (ERP) at 45Hz was about 0.5W, and it increased by 3dB to about 1W at 75Hz. By far the bulk of the power was just dissipated in the losses of the antenna itself and in those of the earth beneath it.

For all its considerable physical extent, the W.T.F. antenna was electrically very small and so, naturally, was its radiation resistance. Because of those significant losses it was also very inefficient. Yet despite all this, quite useable signals were measured at a ground-based receiver over 11Mm away at Saipan on the Marianas archipelago in the western Pacific. This remarkable result, once again, confirmed the very low path loss within the earth-ionosphere waveguide. It was now obvious that Project Sanguine had considerable potential and so the programme moved on.

Sanguine's antenna

Both the W.T.F. crossed dipole array and the previous single-wire structures used in earlier tests covered a sizeable amount of territory and were apparently horizontally polarised antennas. However, to excite the quasi-TEM mode in the earth-ionosphere waveguide requires the electric field component to be vertically polarised. The usual way of producing such an E-field is by means of a vertical antenna, but that was quite out of the question at the extremely low frequencies involved. So, some other way had to be devised to achieve this and a vertical loop was the obvious candidate.

At first glance, neither that 176km horizontal wire antenna in North Carolina nor the somewhat shorter crossed elements of the WTF resemble loops, let alone loops in the vertical plane. But by earthing the ends of the wires the current is caused to flow through the ground in order to complete the circuit and so the antenna now behaves just like a loop in the vertical plane with its return path through the earth as shown diagrammatically in **Figure 4**.

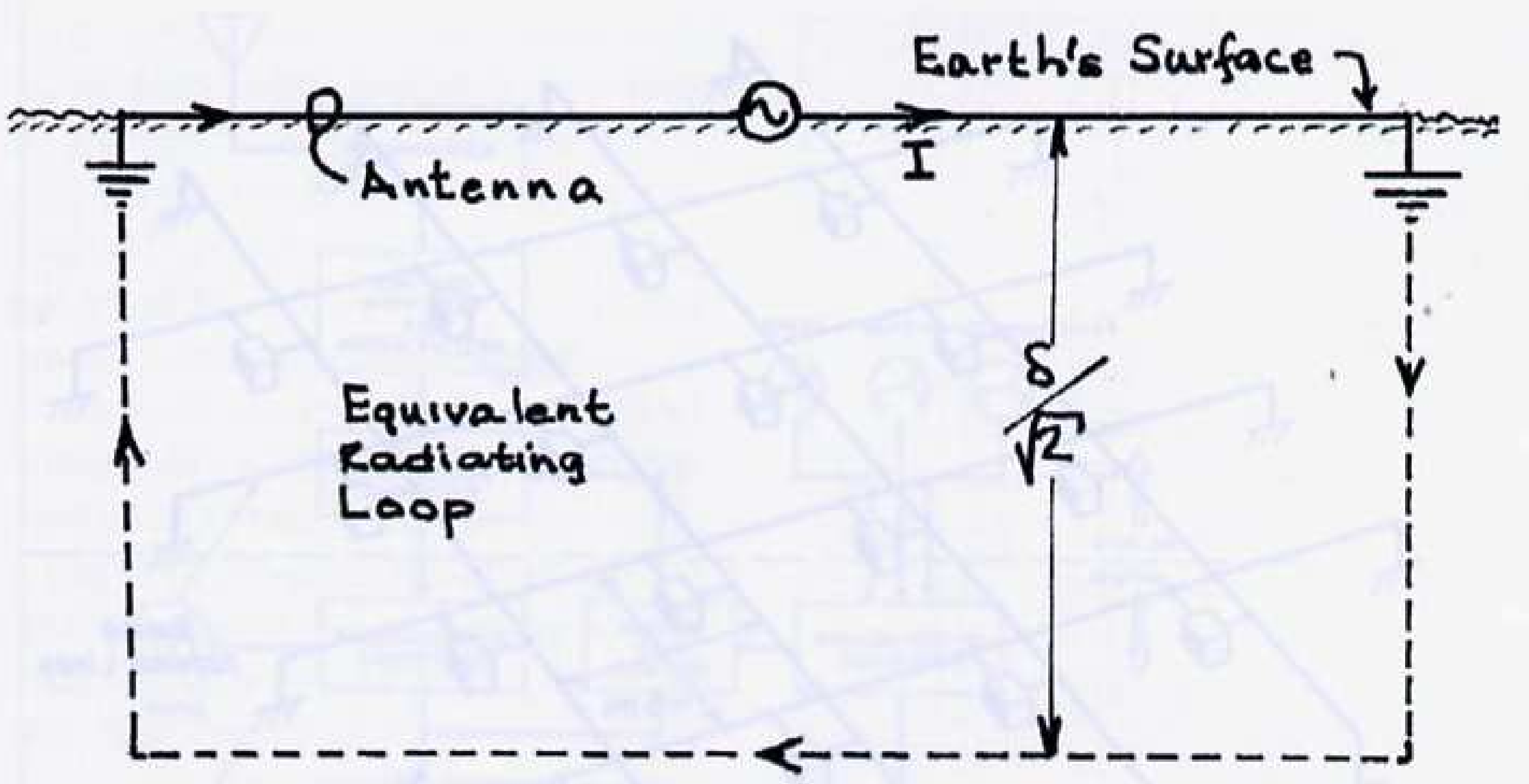

Fig.4. The return path of the antenna current flowing through the earth due to the 'skin effect'

Clearly, the deeper the current flows within the earth the larger the loop area, and hence the greater its efficiency. As is indicated in the figure, the current penetrates to a depth determined by the skin effect, yet again. Since skin depth is inversely proportional to the square root of the conductivity (see the equation in Fig. 2), poorly conducting ground beneath the horizontal wires will produce the greatest depth of penetration and hence the largest loop area. So geology would play a vitally important role in the design and siting of the antenna.

The site on which the antenna was to be erected had to be very carefully chosen in an area where the underlying geology has the lowest possible electrical conductivity. But just to complicate matters even more, the ends of the wires should be connected to ground where the conductivity is as high as possible in order to minimise losses at those points.

This set of conflicting conditions required a detailed investigation of the geology of the United States in order to select the optimum site for the Sanguine antenna. Eventually, this led to areas in Wisconsin and Michigan that straddled a vast region of poorly conducting pre-Cambrian bedrock. There were also many other factors that played a part as well. Amongst these was the proximity of the antenna to any large conducting structures such as power lines and industrial plant that might affect it. And then there was also the requirement that the site should ideally be far-removed from highly populated areas in case its radiated fields might cause people, their animals and even plant life some harm.

And finally, since this was a military installation of fundamental importance to the security of the free world, it had to be protected against possible attack and so the antenna would be buried at some depth below the surface. A specification was duly drawn up and a massive study ensued [7].

Transmitter Concept

The proposed Sanguine transmitter concept is shown in **Figure 5**. This diagram, which was made public in 1974, is merely indicative of the general idea. It in no way disclosed either the final number of antenna elements

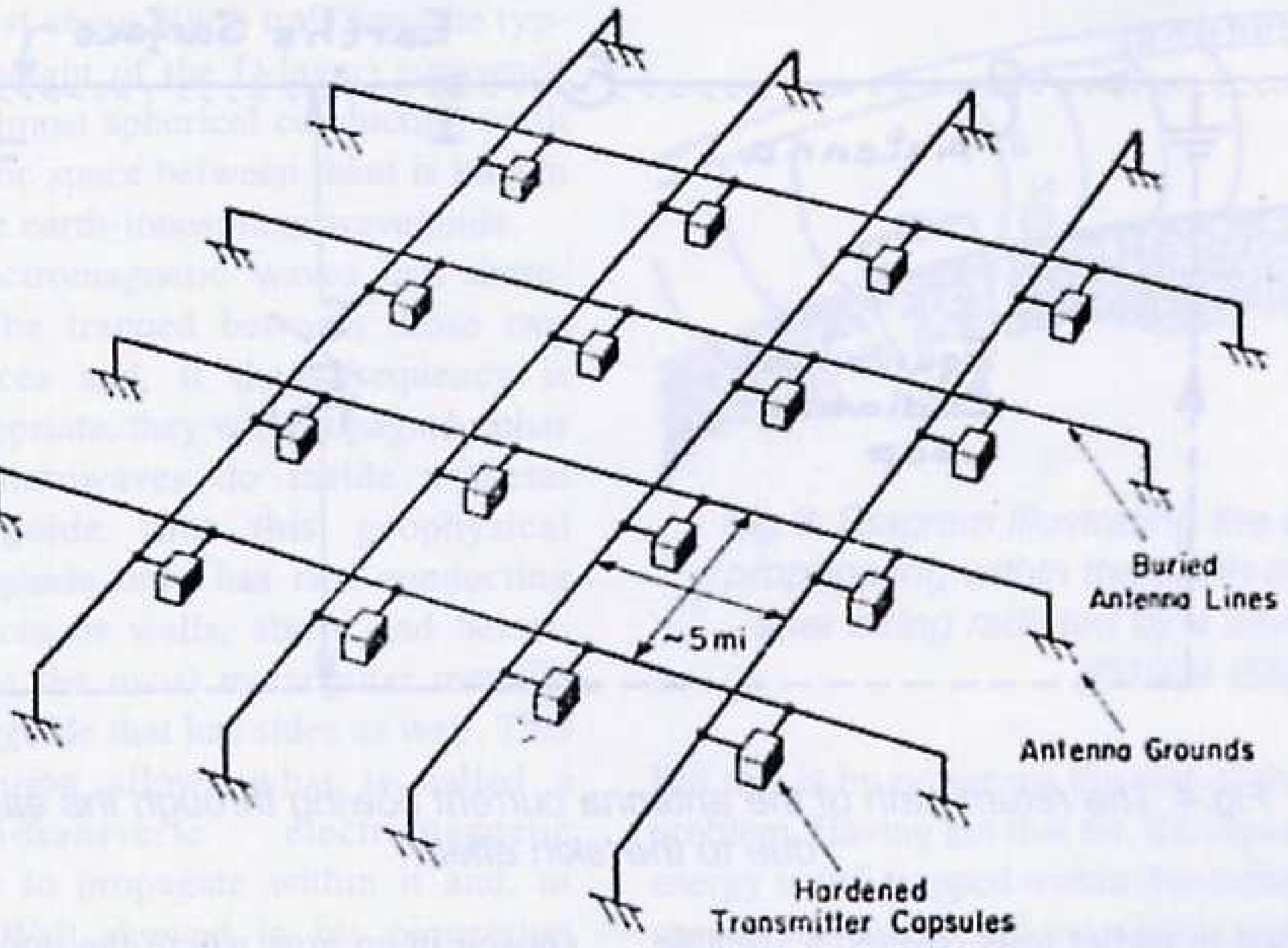

Fig. 5 The proposed layout of the buried Sanguine antenna array showing the hardened transmitter capsules that would allow considerable redundancy (© 1974 IEEE).

selected, or the number of actual transmitter modules to be used. In fact, the reference [7] contained just the simple comment (within parentheses) that "the number of capsules would be significantly more than shown ..." (A much more recent US navy document stated that as many as 100 transmitter modules with a total input power of some15 to 30MW had been envisaged at one stage!). But it did divulge that the whole system was buried and that each capsule would contain two power amplifiers: one for the N-S line and one for the E-W line.

In addition, we learnt that the capsules would be offset from the antenna lines so that if they were attacked the antenna lines themselves would not be damaged. Also, there was considerable redundancy within the system and so it was easily reconfigurable in the event of damage. It was noted, especially for the benefit of those concerned about the possible environmental impact, that the land above the antenna installation would be put to normal use, farming presumably, and only the transmitter sites would be made inaccessible to the public.

To allay concerns about possible biological effects of the near fields from the antenna some additional details were provided. The current in the antenna elements would be about 100A and it would produce an E-field directly above the conductors of the order of 0.1V/m, while the H-field would be about 0.1G (or 10^{-5}T). To put those into perspective, the paper pointed out that they are of the same order of magnitude as the fields from commercial power systems and, even more reassuringly, that they are "much smaller than the fields surrounding many household appliances in everyday use".

Submarine Test

In December 1972 the crucial demonstration took place during which it was shown that the ELF concept would indeed allow messages to be sent from CONUS (the Navy's quaint acronym for the Continental USA) to a submerged submarine at its operational depth a considerable distance away beneath the Atlantic Ocean. Modulated signals were transmitted from the W.T.F. at a power rather less than that proposed for Sanguine and at a frequency of 76Hz.

The data rate, which is usually determined by the time allotted for transmission and the content of the message, was set at just 0.03b/s. This was done to reduce the signal-to-noise ratio at long ranges in order to test to its limits the special receiver on board the submarine. The test message was most apt under the circumstances: "ex scientia tridens!", the motto of the US Naval Academy, which is roughly translated as: 'From knowledge, seapower!' [7].

The test vessel was the *USS Tinosa* (SSN 606) **Figure 6**, in transit from Naples in Italy to its homeport of New London, Connecticut and the test message was received consistently throughout the voyage. The operational depth of the *Tinosa* during the tests varied from about 85m to almost 100m, with the limit being reached when the electrical noise generated by the submarine equalled that from the 'sferics caused by worldwide lightning activity up above.

Submarine Equipment

Of particular interest are the antenna and the receiver used by the submarine. As discussed above, the signal from the CONUS transmissions propagates directly downwards into the sea due to the horizontal E-field it produced on the surface. Hence, the submarine's antenna must respond to this horizontal electric field and the most effective way of doing this is to use two widely separated conducting electrodes towed behind the vessel. The further apart the electrodes are,

Fig. 6. The USS Tinosa *that was involved in the ELF underwater sea trials in December 1972*

the greater their sensitivity. But that towed antenna will also generate noise itself by virtue of its motion through the conducting seawater and it will also pick up the noise produced by the submarine.

The electrochemistry involved in all of this is complicated and need not concern us here. Suffice it to say that the sensing electrodes were of special construction and were to be towed as far behind the submarine as possible. The actual antenna towed by the *Tinosa* consisted of two titanium electrodes spaced 300m apart, with their the mid-point at 300m from the submarine. It will now be appreciated, in light of the transmitter and antenna requirements that had to be satisfied on land, that the submarine was incapable of replying to these signals. For this reason the communications system was referred to as the 'bell ringer'. Its purpose was simply to alert the submarine to take some particular action.

Sanguine receiver

The block diagram of the submarine's receiver is shown in **Figure 7**. It was necessary to use a receiver of sophisticated design in order to reduce to a minimum the power requirements of the transmitter in view of the great costs involved in that land-based installation. The receiver therefore represented quite a revolution for its time in that most of the signal processing was done in software running on an onboard minicomputer.

In the context of the modern 'software defined radio' or SDR, this Sanguine system was clearly already making use of such techniques more than thirty years ago. Nearly all its elements including coherent detection, non-linear noise processing, sequential decoding as well as a specially developed ocean compensation filter were implemented in computer code running on a small minicomputer, the Varian 620/L-100, which was the state-of-the art at that time.

The only analogue section of the receiver was connected directly to the towed antenna. It provided some low-noise pre-amplification and a notch filter to remove power line noise. In addition, it included appropriate low-pass and high-pass filters to set the front-end bandwidth as determined by the

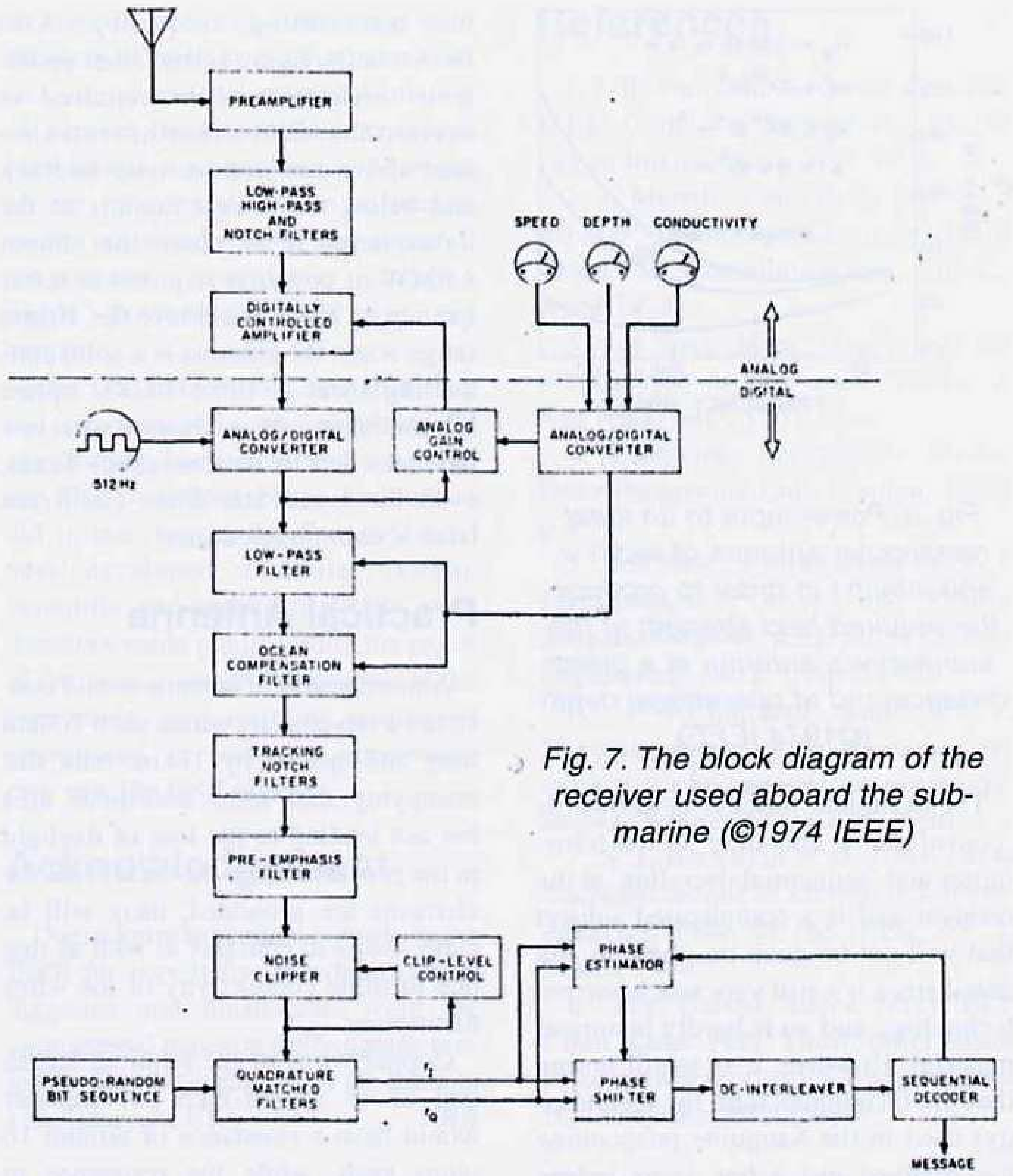

Fig. 7. The block diagram of the receiver used aboard the submarine (©1974 IEEE)

512Hz sampling rate of the analogue to digital converter. The output of the A/D converter was then applied directly to the Varian computer.

It will be noted that data related to the boat's speed and depth, and the conductivity of the seawater, were converted into digital form and used to drive an AGC circuit that controlled the gain of one of the analogue amplifiers. This was done to optimise the dynamic range of the receiver, especially in the presence of atmospheric noise produced mainly by lightning over global distances. Since nearby lightning produces very sharp electrical impulses that contain much of the energy of the atmospheric noise, a simple amplitude clipper would reduce that noise considerably. The technique had shown itself to be very effective in existing VLF receivers and increased the signal-to-noise ratio by some 10dB [7]. However, in this undersea application the conductive ocean introduced an effect not seen on the surface.

Seawater, by virtue of its electrical parameters, behaves like a low-pass filter. It's therefore said to be a dispersive medium in that it distorts the frequency spectrum of any signal passing through it. The effect is to smear out, or stretch, the spiky nature of those nearby lightning strikes thus making it difficult for the receiver's coherent detector to discriminate between the wanted signal and the atmospheric noise. It was the purpose of the ocean compensation filter to produce the inverse effect and so present the clipper with a restored spiky version of the nearby lighting impulses.

Tracking Notch Filter

The tracking notch filter's purpose was to remove manmade interference caused by the submarine's own power systems, from nearby ships and from land-based electric power systems at 50Hz and 60Hz. Since the filter must remove the unwanted noise, which may well vary in frequency, while not introducing excessive distortion into the signal path it had a narrow notch whose centre frequency was adaptive so that it tracked the noise. Coherent detection then followed by using the most efficient scheme possible to optimally decode the transmitted signal.

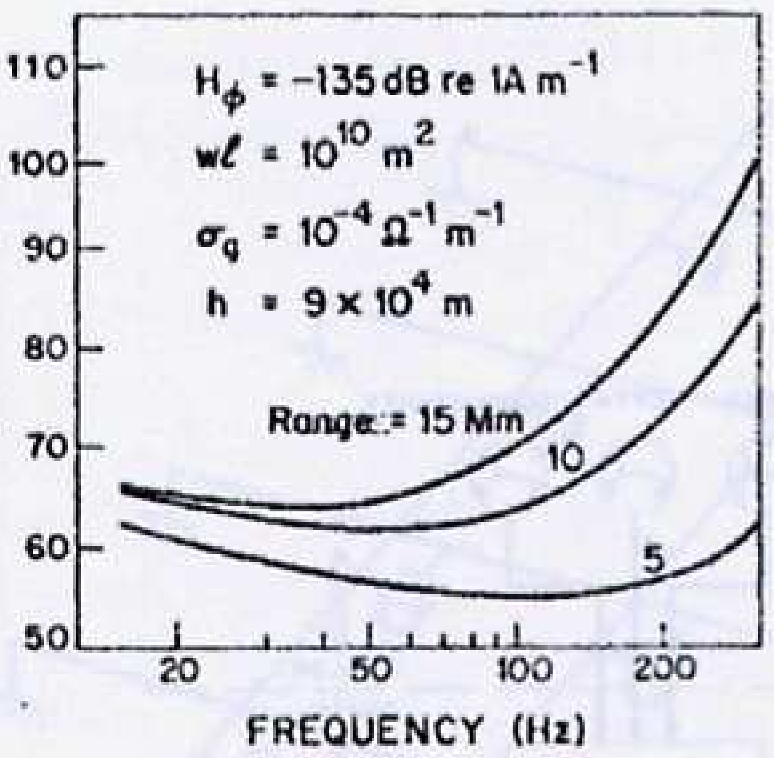

Fig. 8. Power input to an ideal rectangular antenna of width w and length l in order to produce the required field strength at the submarine's antenna at a given distance and at operational depth (©1974 IEEE)

The complete process is known as 'convolutional encoding' at the transmitter and 'sequential decoding' at the receiver and is a complicated subject that will not be gone into here in any detail since it's still very much current technology and so is hardly historical material. However, it is worth noting that the techniques (and the technology) used in the Sanguine programme had evolved just a few years before and they owed their existence to the massive effort that went into the US manned space flight programme, and particularly the quest to land a man on the moon before the end of the 1960s.

Sanguine: The Numbers

As part of their contract to the US Navy the designers of the Sanguine system at the M.I.T. Lincoln Laboratory produced what they called a 'transmitter sizing calculation'. Its purpose was to determine the optimum frequency of operation and the transmitter power necessary to achieve a data rate of one bit per second at a range of 10Mm, or a quarter of the earth's circumference. Since the numbers involved are of quite remarkable orders of magnitude they are reproduced here to demonstrate the sheer numerical size of Sanguine.

Jim Wait's mathematics produced the equation that set down the defining factors. When represented graphically it yielded the graphs in **Figure 8**, where the input power needed to generate the minimum field strength at three specific ranges is plotted against the transmitting frequency. Also shown in the figure is the rather prodigious area of antenna required to develop that field strength when situated above low conductivity bedrock and below the lowest regions of the ionosphere. It is clear that about 1.6MW of power is required at a frequency of 75Hz to achieve the 10Mm range when the antenna is a solid conducting sheet of some 10,000 square kilometres in extent. Despite what one has been led to believe about Texas, even the Lone Star State could not have accommodated that!

Practical Antenna

A more practical antenna would consist of a ten parallel wires, each 100km long and spaced by 10km, thus still occupying that same enormous area but not leading to the loss of daylight in the process! Since the ends of all the elements are grounded, there will be earth losses to consider as well as that due to finite conductivity of the wires themselves.

Copper wires of the required length and about a half-inch in diameter would have a resistance of around 16 ohms each, while the resistance to ground adds a further couple of ohms at each end. In addition, the depth of penetration of the current into the earth is 5.8km at 75 Hz, so further loss occurs as the current returns through the bedrock to the opposite terminal of each antenna element.

Knowing the field strength required, and thus the current needed to produce it, meant that all the information was now to hand to calculate the power input to the more realistic Sanguine antenna. It turned out to be 3.88MW. But the power actually radiated by this gigantic antenna was just 69W! Put another way, the Sanguine antenna had a radiation efficiency of less than 0.002 per cent and so its gain was minus 43dBi.

The impedance of each element of this antenna was found to be 38 + j135 ohms. Therefore, the Q is 3.6 and the -3dB bandwidth is 21Hz at the 75Hz carrier frequency. This is certainly wide enough to accommodate the binary convolutional coding of the transmitter at a data rate of 1b/s. Measurements of worldwide atmospheric noise, and that produced by the motion of the submarine itself, had shown that at speeds of up to 13 knots this Sanguine system was capable of meeting the 1b/s data rate down to a depth of around 80m. Below that depth signalling would still be possible but at a slower data rate.

From Sanguine to Seafarer to 'ELF'

Sanguine had been shown to work in concept and various sea trials had shown simpler prototypes to do so as well under comparable (and realistic) conditions. But despite all that Sanguine was never built.

In 1977 the US Navy, in the face of considerable opposition from sections of both the House of Representatives and the Senate, shelved the scheme. Its projected cost was given as the overriding reason but anti-nuclear lobbyists had also managed to garner some support in their campaign against it. In addition, the change of government from Republican to Democrat in the United States in January of that year brought in Jimmy Carter.

The new President had a somewhat different view of the strategic nuclear deterrent and its ancillary systems to that of his predecessor, Gerald Ford. Changes, therefore, were almost inevitable. But Navy planners had seen this political shift coming, while further studies had shown that a less elaborate system could still meet the needs of the submarine fleet and so Sanguine now became Seafarer.

Seafarer (an acronym for Surface ELF Antenna For Addressing Remotely Employed Receivers) would be called Sanguine-lite these days. Of most significance was the scaling down of the land-based antenna to a much less elaborate configuration that required just a single transmitter to drive it. And Seafarer would occupy a significantly smaller area of real estate, shrinking significantly from Sanguine's 4000 square mile grid of wires. And, most importantly, the Seafarer antenna would not be buried. This meant that it was not protected against possible attack.

The site at the W.T.F. in Clam Lake, Wisconsin, would still be used but another in Michigan would join it with the two systems being interconnected for purposes of command and control by 150 miles of cable and microwave links. The antennas still resembled power lines slung from wooden utility poles and far fewer transmitter modules were involved. However, within a year Seafarer itself stumbled in the face of a lukewarm government and in 1978 it was postponed indefinitely though the scientific research programmes continued, if in a somewhat lower gear. But democratic politics is dynamic and when the Reagan government took over in 1981 the situation turned right round.

Seafarer was renamed and became Project 'ELF' and was soon to become an important component of the new US Strategic Defense Initiative. The Wisconsin and Michigan sites functioned together, as before, and the system became fully operational in October 1989 [8]. Even though the Soviet Union collapsed in 1991, ELF continued to operate until it was eventually terminated in 2004.

Conclusion

Sanguine and its various offspring represented supreme examples of electronic engineering pitting itself against some formidable natural obstacles. They had but one purpose, of course; one-way signalling with submerged nuclear submarines. That fact alone, and the resulting blanket of secrecy that normally envelops such things, could so easily have put all the theoretical and experimental results obtained during the research programme completely beyond reach. Fortunately, this did not happen.

The US authorities knew that they had no monopoly of scientific and engineering know-how and others, if they had so desired, could (and indeed did in the case of the Soviet Union) have developed a similar system. Scientific and technical details were therefore made public within the pages of the most appropriate journals at the time while, quite naturally, nothing of operational or strategic importance ever saw the light of day.

Acknowledgement

Due acknowledgement is made to the IEEE for permission to extract certain diagrams and illustrations from the monumental paper on the Sanguine project by Bernstein et al [7] at the Lincoln Laboratory, M.I.T.

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