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Submarine Communications

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ABSTRACT

Submarines operating in deep water are virtually cut off from the outer world. It becomes very important and essential to convey survivable and critical informations to the submarine during the time it operates under water. Conventional means of radio communication do not serve any useful purpose as the higher frequencies get attenuated very sharply in sea water. At VLF band, which is presently being used by most of the world Navies, signal can penetrate only upto 8-10 m of depth. This depth is not sufficient under hostile environment. ELF is another band where listening depth is around 100 m but data rate is very low.

This paper summarises the various means of communication used to send messages to submarine while cruising at various depths. It seems that in the near future blue-green laser is going to be the vital means of sending large information to a submarine operating much deeper (500-700 m) with unrestricted speed.

1. INTRODUCTION

Submarines, now-a-days, are very important and vital arm of any defence force. Most of the world Navies today have tactical attack submarines which in the time of war can be used to attack enemy submarines and surface ships. The nuclear powered submarines are capable of launching missiles that can destroy inland enemy targets, thousands of miles away. In this way they act as mobile launching pads whose position can be safely kept hidden from the enemy. To perform this role submarines have to operate for continuous stretch of time spanning over many months away from shores and in the deep sea water. In order to perform their mission successfull, submarines must be able to receive communication from their base stations without exposing themselves to the danger of detection.

2. SUBMARINE COMMUNICATION OF EARLY DAYS

Not so very long ago, radio communication to submarines was carried out mainly in HF, VHF and UHF radio bands; HF when the submarine was operating very far away from the shore and VHF/UHF when it was within the line-of-sight distance. Most of the time submarines would be operating deep inside the water but at preassigned time schedule, they would ascend up to the periscopic depth and raise their antennae above the surface of water in order to communicate with the outer world.

Raising antenna above the surface of water could endanger the submarine to its detection by the hostile forces. The raised antenna could be detected by enemy radars or airborne observers. Also, the enemy satellite could locate the submarine by picking up radio signals transmitted from it.

3. PRESENT DAY COMMUNICATION TECHNIQUES

In order to minimise the risk of detection, a submarine must have the capability to receive communication while remaining submerged at operational depths. This could be possible only by using those radio waves which could penetrate water to a considerable depth.

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It is well known that penetration of radio waves in water is directly proportional to its wavelength (i.e., inversely proportional to its frequency). Thus, longer waves could be used for the purpose stated above, but these waves have their own problems. Their mode of propagation is such that they travel along the ground bounded by two planes, i.e, the earth and ionosphere. This waveguide mode of propagation supports only vertical polarization. Longer the wave length, smaller is the electrical length of the vertical antenna radiator. This reduces radiation efficiency and restricts its bandwidth. At the antenna site, a lot of copper buried in the ground is needed to increase the ground conductivity, to reduce the ground losses and thus to improve the antenna performance.

4. VLF BAND FOR SUBMARINE COMMUNICATIONS

A radio band consisting of frequencies between 10 and 30 kHz, known as VLF band, works out to be the best compromise, considering the above two conflicting requirements. Even at these frequencies antenna structure becomes very huge. Tower height around 300 m are not very uncommon for such stations. Even after costly preparation of ground by burying lot of copper in the fore-ground antenna efficiency greater than 50 per cent is not easier to achieve.

4.1 Propagation of VLF Band

As mentioned earlier, these waves travel along the ground guided by ionosphere and the earth, with E-vector as vertical. The field strength at various distances is as given in Fig. 1. Atmospheric noise at these frequencies is very high[1]. The limit to distance from the transmitter up to which the VLF signal can be picked up is reached when signal field strength gets reduced to a value which is only 10 dB higher than the field strength of atmospheric noise.

As the signal now penetrates in the water to the submarine located below, both signals as well as noise are attenuated alike maintaining constant signal-to-noise ratio till both get reduced so much that receiver thermal noise also becomes an important factor. This is a limiting depth. Only up to this depth the signal can be properly demodulated and received. With the present day state-of-the-art receivers and hull mounted antennae this depth is of the order of 8-10 m.

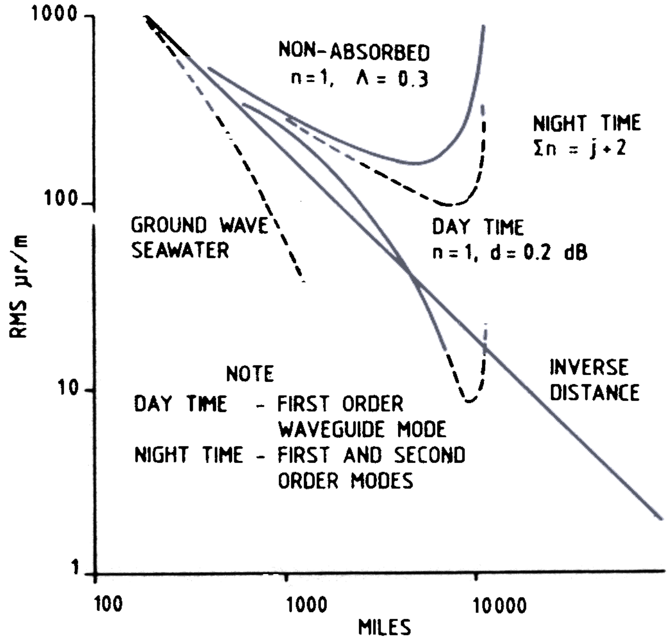


Figure 1. Field strength at various distances.

4.2 New Techniques in Receiving Antennas to Further Increase the Listening Depth

The depth of 10 m is the capability of present day state-of-art receiver system which is not considered safe for the submaraines. There is a need of some kind of break through so that submarines could listen VLF while operating at safer depths of the order of 100 m.

As mentioned earlier, the *E*-vector of the VLF wave is not exactly vertical but has a slight tilt, the exact amount of which depends upon the conductivity of the ground plane[2]. The horizontal component denotes the fraction of energy which leaks into the ground plane, be it earth or sea water. It also denotes that only horizontally polarized wave travels into the sea water. As a result only two types of antennae which can be used to pick these signals are possible, i.e., horizontal wire antenna and the loop aerial. Actually both are used by mounting them on hull, i.e., on the outer surface of the submarine.

If instead of mounting these antennae on the surface of hull, arrangements are made to make them float near the surface of water, within 10 m depth where sufficient signal is available and if arrangements are also made to carry these signals to submarine down below through a cable, the submarine need not come up. Both the trailing wire and trailing buoy (Fig. 2) types of antennae (where buoy carries the loop antenna) can be used[3].

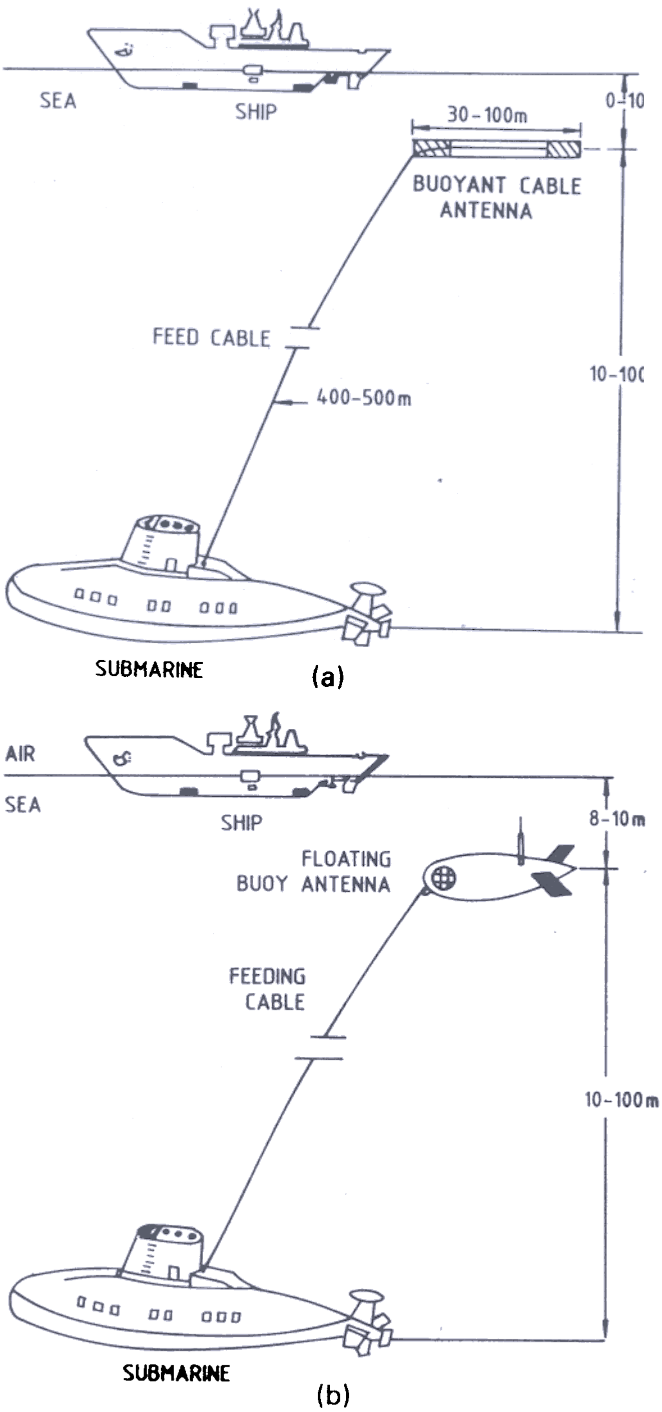


Figure 2. **(a) trailing wire antenna, (b) trailing buoy antenna.**

4.3 Airborne VLF Stations

VLF transmitting stations due to their large sizes and huge antenna structure are very soft and easy targets for enemy attacks. This has brought into use the all weather airborne stations capable of sustained operation even under nuclear environment. A complete communication system is installed in an aircraft (Fig. 3) permitting simultaneous reception from ground or satellite and transmission to submarine. There are at time a number of aircraft afloat operating at different spread out locations. The airborne system, unlike the fixed shore-based one, can be nearer to the field of operation and hence the radiation power of the order of 200 kW is sufficient as against 1 MW in case of a shore-based station [4, 5].

A long wire hanging below from aircraft can act as a very good and efficient radiating element of appreciable electrical length and hence with good radiation efficiency.

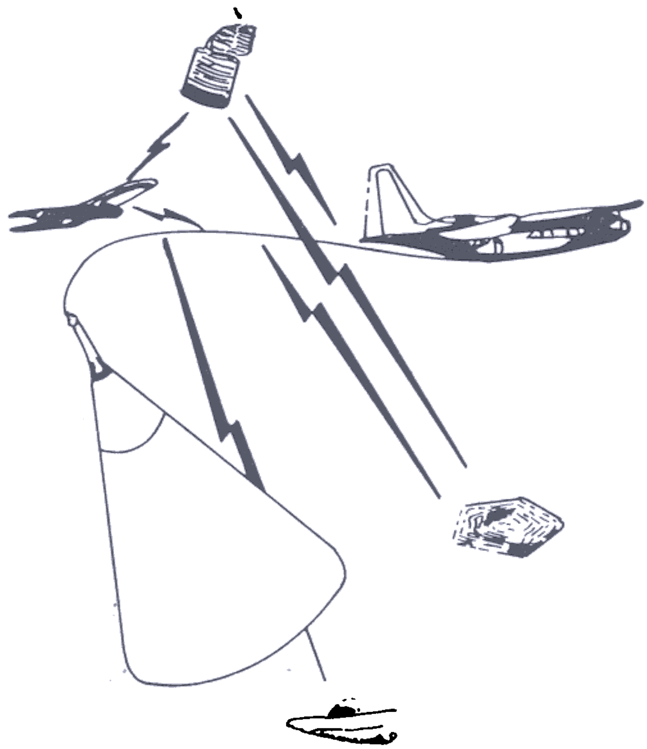


Figure 3. **Complete communication system installed in an aircraft.**

4.4 MSK Modulator

VLF transmitters are very high power stations, usually employing radiated power of the order of 1 MW. Since the radiating elements are of very small electrical length, when tuned, become resonant circuits of very high '*Q*'. This limits the band width, hence the data rates which are possible on this type of channel. Also keying becomes a problem when very high powers and high '*Q*' resonant circuits are involved. MSK modulation is most optimum in this case as it tackles effectively both the problems. Because of its phase coherency during keying, it does not put any undue

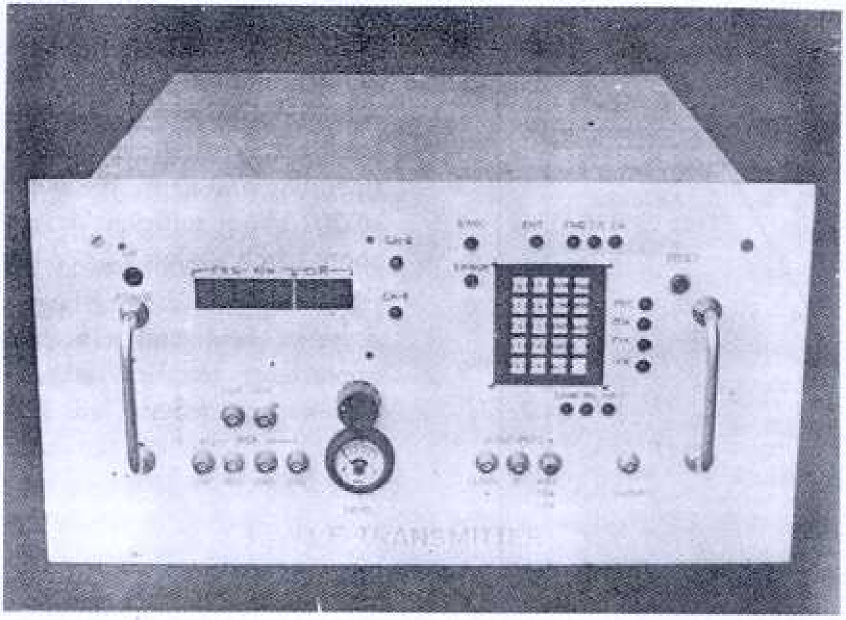


Figure 4. VLF transmitter.

strain on the transmitter components, at the same time, achieves higher data rate in the restricted band width as compared with FSK/OOK which were very extensively used in earlier days.

Defence Electronics Applications Laboratory (DEAL) has designed and developed multichannel MSK-modulator. This equipment has been installed at the VLF transmitting site and modulator has been interfaced with high power transmitter and field trials have been conducted (Fig. 4).

4.5 VLF Receiver with MSK-Demodulator

DEAL has also developed a multichannel VLF receiver with MSK demodulation and FEC using DSP techniques. The receiver is capable of reception of VLF broadcast messages around the world, out at sea at various depths of submarine operation (Fig. 5).

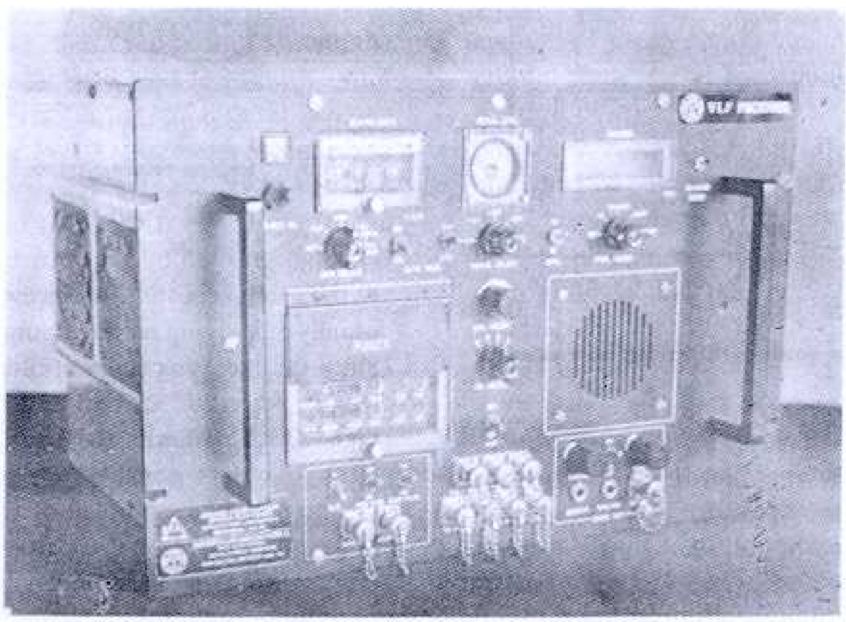


Figure 5(a). VLF receiver.

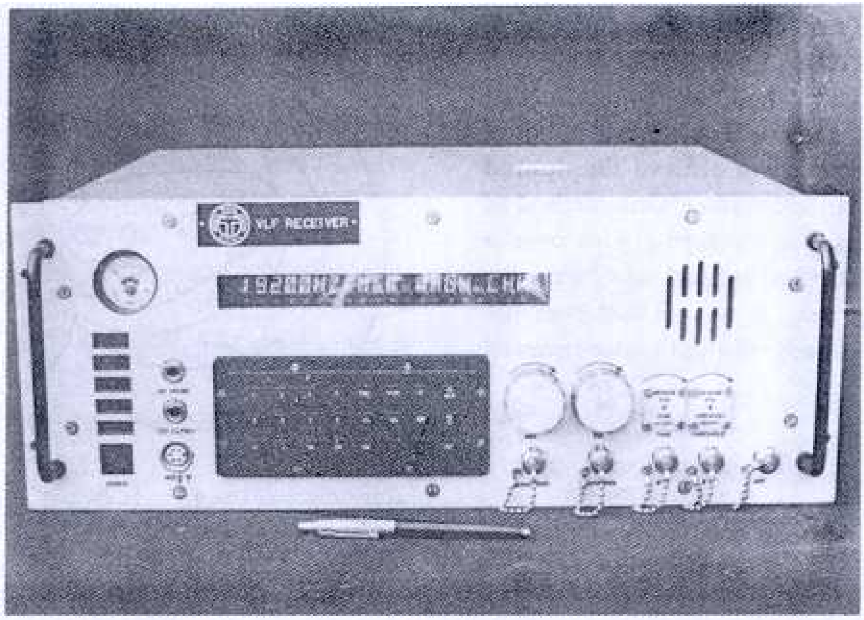


Figure 5(b). VLF receiver (DSP-based).

5. ELF COMMUNICATION

Submarines operating at safer depths of 100 m face difficulty in receiving radio signals while cruising at these depths. This is solved by using a trailing wire or trailing buoy type of antenna. But this cumbersome arrangement not only restricts the cruising speed of the submarine but also leads to the danger of detection by improved detection techniques which have now become feasible. There was, therefore, a need to explore the possibilities of utilising waves of even longer wavelengths than the VLF.

Table 1 shows the *e*-folding depths (depth where intensity is reduced by a factor of *e* from its surface value) of various frequency bands. It is apparent from Table 1 that the frequencies around 10-100 Hz will have to be used in order for the submarine to receive signals at 100 m depth without the help of a long trailing wire or buoy type antenna.

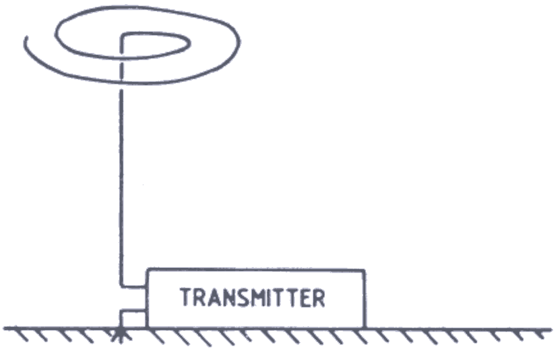
5.1 Break through in the Transmitting Antenna Design

A real breakthrough in the transmitting antenna design was needed before ELF (10-100 Hz) could be considered for submarine communication. Various design approaches were studied and experimented. One approach was to use spiral top loaded antenna (Fig. 6(a)). This needed a massive aerial structure at ELF range and hence was found to be impractical. A vertical wire suspended from helicopter (Fig. 6(b)) was

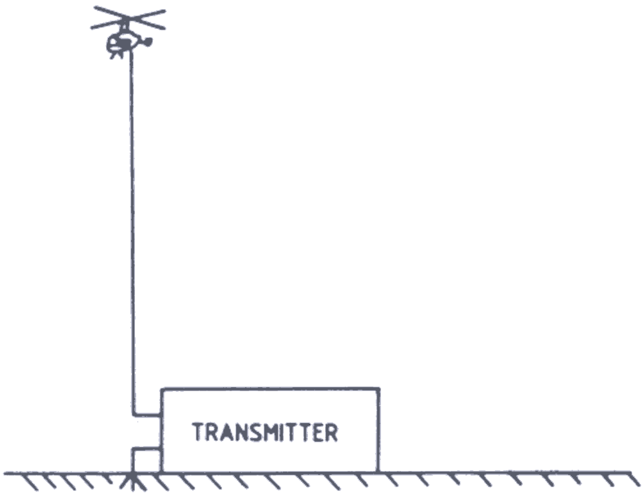
Table 1. *e*-folding depth in various bands

Band designation	Frequency range (Hz)	Wavelength range (m)	*e*-folding depth (m)	Propagation mode
EHF	3×10^{10}–3×10^{11}	10^{-2}–10^{-3}		LOS
SHF	3×10^{9}–3×10^{10}	10^{-1}–10^{-2}		LOS
UHF	3×10^{8}–3×10^{9}	1 – 10^{-1}		LOS
VHF	3×10^{7}–3×10^{8}	10 –1	—	LOS
HF	3×10^{6}–3×10^{7}	10^{2}–10	0.14–0.05	OTH
MF	3×10^{5}–3×10^{6}	10^{3}–10^{2}	0.64–0.14	OTH
LF	3×10^{4}–3×10^{5}	10^{4}–10^{3}	1.4 –0.46	OTH
VLF	3×10^{3}–3×10^{4}	10^{5}–10^{4}	4.6 –1.4	OTH
ELF	3–3×10^{3}	10^{8}–10^{5}	144 –4.6	OTH

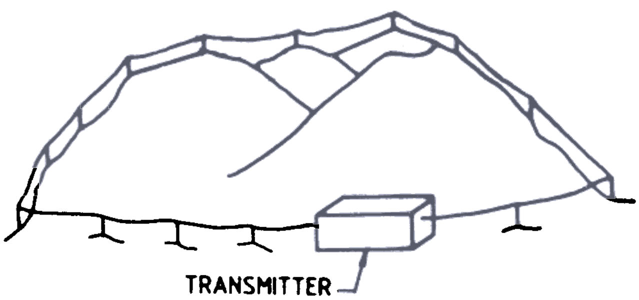
also once considered but due to the huge weight of wire, this idea was also rejected. A third choice was a loop in the vertical plane. At ELF range, calculations showed that cross-sectional area of the order of several hundred square km would be required to achieve the desired amount of radiation from the antenna. One method of providing this large area was by laying wire over a mountain (Fig. 6(c)). Another method was to use an island for the same purpose. A wire is laid over the large island (Fig. 6(d)), the return path is considered



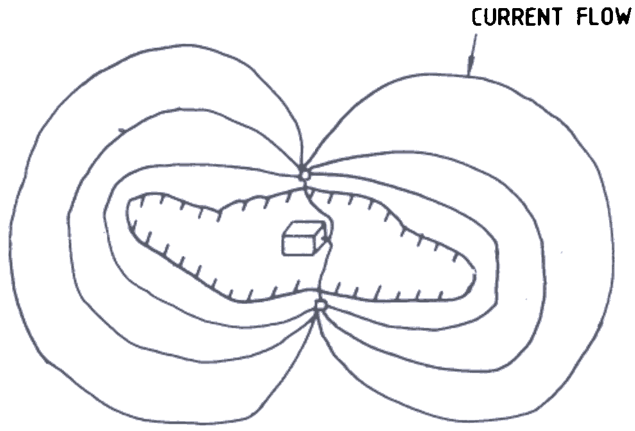
(a)



(b)



(c)



(d)

Figure 6. Various design approaches for the ELF transmitting antenna: (a) spiral top loaded antenna, (b) wire suspended by helicopter, (c) mountain loop, and (d) island slot.

to be through sea water which has much higher conductivity than earth. All these schemes proved to be impractical and hence were discarded. The transmitting antenna finally selected was a horizontal wire antenna[6].

5.2 Horizontal Wire Antenna

A long horizontal wire as shown in Fig. 7 is laid over the ground or buried underneath. Wire can be buried at considerable depth without significant loss in radiated power. The wire is insulated throughout its length, only at the ends it is bare to provide good ground contact. The wire is fed in the centre. The return path is through ground. The field radiated by loop antenna is proportional to its area. The equivalent area of the loop is $l \, . \, \delta/2$ where l is the length of the wire and δ is the skin depth, which in turn is equal to $(2/\omega\mu\sigma)^{0.5}$ where σ is conductivity[7, 8].

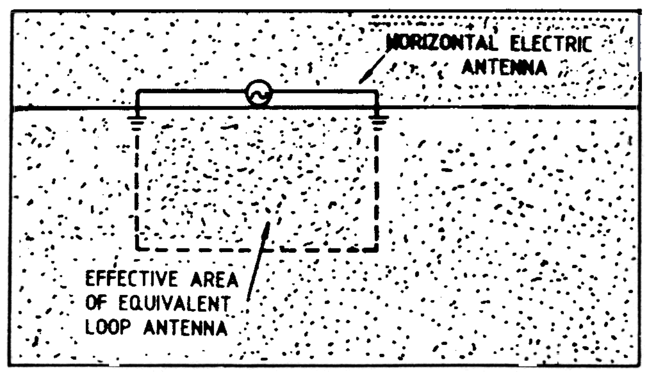


Figure 7. Horizontal electric antenna and the effective area of the equivalent loop antenna.

Skin depth is inversely proportional to the earth conductivity. Hence land of poor conductivity is preferred as it will result in larger area. Better conductivity is needed only near the ends. To increase *l* we can lay a number of wires in parallel. The effective length will be the sum of all the lengths. To keep voltages and current uniform along the length, distributed feeding is used. This loop antenna is directional. To make it omnidirectional, similar array of antenna lengths perpendicular to it are used. The final shape is shown in Fig. 8.

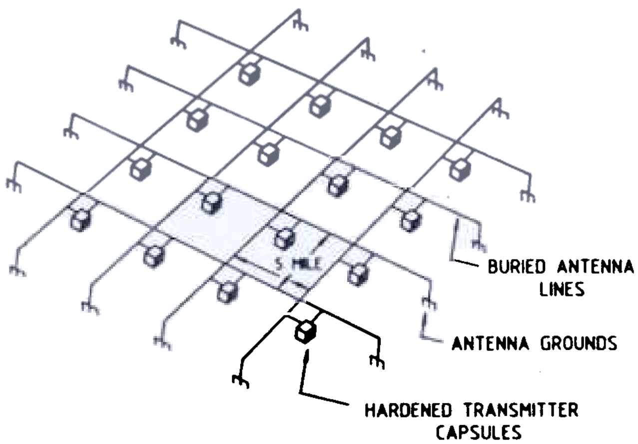


Figure 8. ELF transmitter array.

Besides giving a greater radiation efficiency, this antenna also has a good survivability under nuclear attack. The transmitting array and the transmission system have a good deal of redundancy built into them. This redundancy is achieved as each element of wire is driven with several transmitters (phased together) spaced along the line. By arranging to bypass an inoperative transmitter, remaining transmitters can continue to drive the line. The whole antenna system is buried under ground and hence not detectable by an air observer. Thus, for nuclear attack, it is not a very easy target like VLF transmitting antenna. Moreover, it could continue to operate even after a substantial nuclear attack over the system[8].

5.3 ELF Propagation

The mode of propagation of ELF band is wave-guide mode which is same as that of VLF but with one important difference. The ionospheric height *h* in case of ELF is much less than one wavelength[8]. As a result only TEM mode is possible whereas, many modes can propagate in the case of VLF. Hence, though the wavelength is launched by a horizontal wire radiator, the wave polarization gets changed into vertical polarization as the wave propagates (Fig. 9).

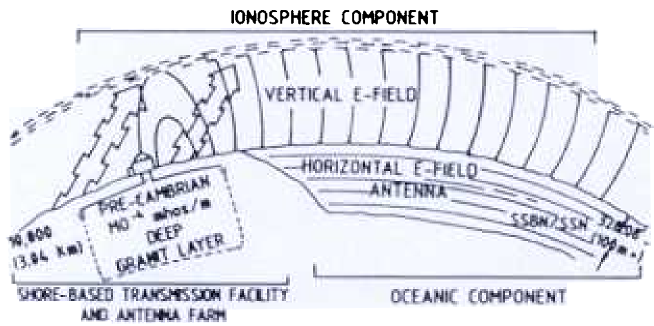


Figure 9. Change of wave polarisation into vertical polarisation.

6. OPTICAL COMMUNICATION[9]

Although ELF techniques may improve present submarine radio communication capabilities, they cannot provide ideal capabilities of high data-rate covert transmission and reception at any depth and speed. New methods using optical communication may come closer to provide these ideal capabilities. It has been found that light particularly from blue green laser (i.e., 475 nm) has the ability to penetrate sea water. While ELF radio waves have an *e*-folding depth of up to 144 m, blue-green light waves have *e*-folding depths ranging from <10 m to >50 m depending on the clarity of the local seawater as shown in Fig. 8. The clarity of sea water varies from place to place, but does not change very much over time. Sea water may be classified into various 'ocean optical types' (Fig. 10) depending on its clarity, ranging from the clearest (1) to the most turbid (III).

Many types of submarine optical communication systems are possible. One system proposed in the United States is designed to provide one-way communications from shore to submarine Fig. 11. The transmitter would be a blue-green laser which produces light pulses of one joule energy and one microsecond duration; this transmitter could be stationary, or it could be carried by a land vehicle or an airplane. The transmitter would aim its pulsed beam at a relay satellite, which would reflect the beam to a submarine's location in a distant ocean. As the beam re-enters the atmosphere, it would have a cross-sectional area of about 10 km; scattering of light by clouds would reduce

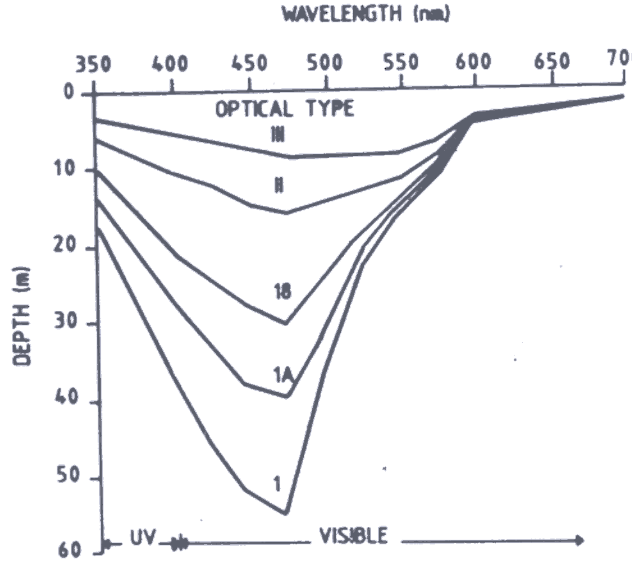


Figure 10. Range of e-folding depths.

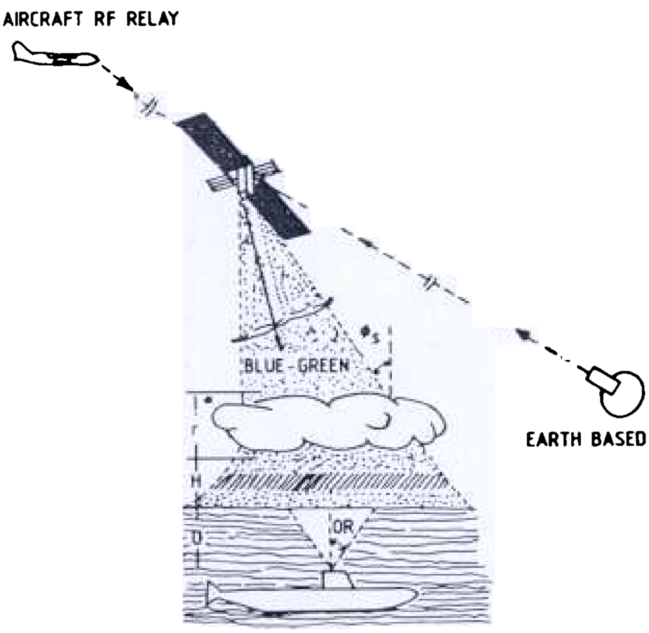


Figure 11. Satellite-based blue-green laser strategic submarine communications system.

the pulse energy to some extent but would not increase its diameter very much. The beam would enter the water and propagate downward, decreasing in intensity as the light is absorbed and scattered by sea water.

At a depth of several *e*-folding depths, the intensity of the laser beam will be very low, especially if there are clouds or polar ice caps above. A very sensitive optical sensor is required to detect the weak laser beam. The detector must also be able to filter out sunlight which, during day time, will accompany the laser beam to the ocean depths. Sunlight may be filtered out by using a detector which is sensitive only to light of the laser beam's wavelength. Sunlight consists of a continuum of wavelengths, most of which will be ignored by a wavelength-selective sensor.

There are many types of wavelength-selective optical sensors, but most types are sensitive only to light coming from one particular direction. For submarine communication purpose, it is necessary to use a sensor which is sensitive to light propagating downward at various angles from the large illuminated area of the ocean's surface. Only a few types of sensors have this capability. One such sensor invented only a few years ago is called the QLORD, (quantum-limited optical resonance detector) (Fig. 12). This device uses a

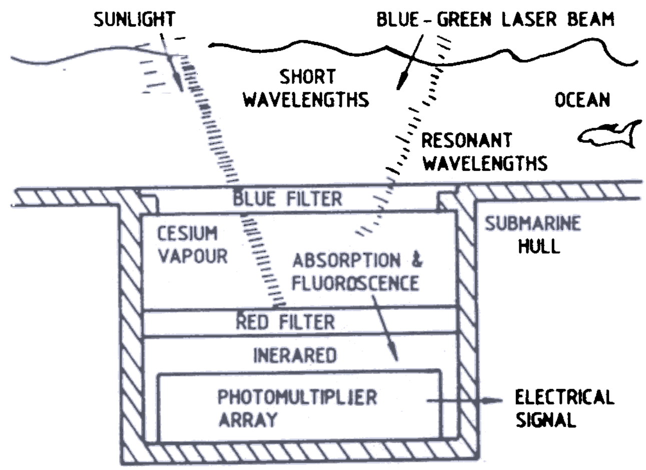


Figure 12. Quantum-limited optical resonance detector.

photomultiplier tube to detect photons (light particles) and has a special filter consisting of a layer of cesium vapour sandwiched between a blue filter (which absorbs long wavelengths) on the outside and a red filter (which absorbs short wavelengths) on the inside. The blue-green laser light, which must have a wavelength of exactly 456 or 459 nm, passes through the outer blue filter and is absorbed by the cesium vapour. When the cesium atoms absorb light of this wavelength, they emit fluorescence at infrared wavelengths. The infrared radiation then passes through the inner red filter and activates the photomultiplier tube.

Long-wavelength sunlight cannot enter the QLORD; it is absorbed by the outer blue filter. Short-wavelength sunlight can pass through the blue filter but most wavelengths of sunlight will not be absorbed by the cesium vapour. Instead the short-wavelength sunlight will pass through the cesium vapour and will be absorbed by the inner red filter. This does not produce fluorescence, and so it does not activate the photomultiplier tube.

QLORD sensors could be mounted on the hull of a submarine. With these sensors, the submarine could receive laser signals at a depth of about 700 m in optical type-I water on a clear day or night, or about 570 m on a cloudy day or night. Operation beneath the polar icecap would be more limited. These depths compare very favourably to the antenna depths at which VLF and ELF signals can be received. Another advantage of optical communication is the higher data rate. Moreover, optical communications can be received while cruising at any speed.

7. ACOUSTICAL COMMUNICATION

In addition to radio and optical techniques, several other methods of submarine communication are possible. For example, submarines can communicate using acoustical techniques. Sound waves can be transmitted for thousands of miles under water, especially if the sound is generated and received in a layer of water known as the deep sound channel which lies about 1200 to 1800 m deep. However, multipath interference (self-interference of the transmitted signal with its echoes from the ocean floor, the ocean surface, and refractivity gradients) limits the data rate achievable at long ranges. Moreover, sound waves which propagate at about 1500 m/s would require an hour or more to reach distant submarines, and long-range acoustical communications are vulnerable to jamming. The propagation delay can be reduced by using arrays of acoustical transmitters on underwater buoys connected by cable to the mainland; however, these could be located by the enemy in peace time and destroyed quickly in war time. Acoustical methods are presently used for submarine-to-ship and submarine-to-submarine communications[11].

8. CONCLUSION

The various approaches for sending messages to submarines operating under water have their own merits and demerits. Since our naval VLF transmitting station is operational, there is a need to equip all submarines with multichannel MSK-receivers along with trailing wire/trailing buoy types of antennae so that our submarines can receive VLF broadcast messages operating thousands of km from shore stations and completely hidden under water at around 100 m depth in open sea.

The much promising means i.e., the optical communication using blue-green laser is yet another possible approach which can be comfortably handled at DEAL, Dehradun.

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