Orthogonal Magnetic Loop Antenna for Lightning Detection

Swati Sharma[1], Shoba Krishnan[2] and Ajay Khandare[3]

[1]E&TC VES Institute of Technology, Mumbai
meetswatisharma@gmail.com

[2]HOD, E&TC VES Institute of Technology, Mumbai
shoba.krishnan123@gmail.com

[3]Scienist, S.A.M.E.E.R, IIT Bombay, Mumbai
ajay@sameer.gov.in

ABSTRACT

Lightning discharge emits RF energy over a wide range of frequencies. During cloud to ground lightning, when high currents occur in previously ionized channels, the most powerful emissions occur in the Very Low Frequency range. VLF (very low frequency) refers to radio frequencies spectrum range of 3 kHz to 30 kHz. Detection of lightning makes it possible to avoid various harmful effects occurring due to the discharge. In this paper, we have discussed various methods used to detect lightning in LF/VLF (low frequency/very low frequency) range. Cross magnetic Loop antenna designed and used here to receive lightning in the range of 3 – 30 kHz based on TOA (Time of Arrival) method.

Keywords: LF, VLF, TOA, LPF.

1. INTRODUCTION

Lightning is a natural process defined as the discharge of atmospheric electricity. Exact root cause of lightning is still not found. Existing reasons range from atmospheric perturbations like wind, humidity, friction, and atmospheric pressure to the impact of solar wind and accumulation of charged solar particles. Ice inside a cloud is thought to be a key element in lightning development, and may cause a forcible separation of positive and negative charges within the cloud, thus assisting in the formation of lightning. Not obviously lightning deals with electricity, since electric current doesn't flow through the air. In 10th June 1752, Benjamin Franklin demonstrated electrical nature of lightning by collecting a charge in a Leydon Jar while a kite was struck by lightning. He invented the lightning rod also which is used to protect buildings and ships [1]. An advantageous property of low frequencies in contrast to higher frequencies is thousands of kilometers where they can propagate due to reflections from ionosphere and the ground.

Generally, several short duration pulses are generated during lightning discharge. Due to the current flow, an electric field parallel to the current flow, and a corresponding magnetic field perpendicular to the electric field is generated. Lightning strike is a series of low frequency (1 to 100 kHz) strikes superimposed with high frequency component (100k – 5MHz) sub-pulses. Rise time of a typical strike is less than 5μs with a zero crossing occurrence in the range of 50μs. Antenna System must be able to recognize and capture these induced frequencies. As per the boundaries, lightning electromagnetic wave can be categorized as – near field zone (region < one wavelength from the source); transition zone (region in between near field and far field); far field (region > twice of wavelength away from radiating source). Sensing part of antenna subsystem is vertically polarized as the strike is vertically polarized. Figure 1 shows different zones of em wave categorization.
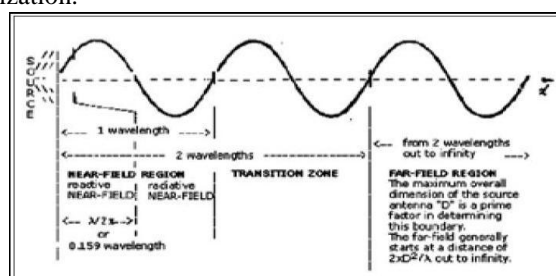

Figure 1 EM wave categorization

The types of lightning are: – cloud to cloud (or intracloud); cloud to air and cloud to ground. Further classification can be simplified and given as: - downward lightning and upward lightning. Peak current value is typically in the range of 10kA. Positive first strike may exhibit peak currents exceeding 100kA. Impulse currents of return strokes have a fast rising front, time ranging from several 100ns and slowly dropping delay. Positive strikes may last significantly longer > 2ms but negative return strokes typically cease after about 100μs. Therefore, positive return stroke currents transfer more charge to ground. Figure 2 shown below represent different types of lightning:-
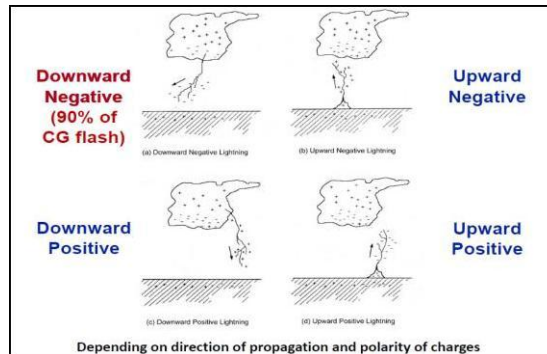

Figure 2 Lightning flash classification

2. CLOUD - GROUND LIGHTNING FLASH-ANATOMY

Typical constituent of a CG flash is a sequence of individual return strokes transferring significant charge from the cloud to ground, each exhibiting peak currents in the range of a few kA to 300 kA. Nominal duration of each stroke is 20 to 50 microseconds, and is typically separated by 20 to 100 ms time duration. The number of strokes in a flash is frequently referred to as flash multiplicity [2]. Out of all flashes, 30 to 50% flashes contain strokes that produce different ground strike points, separated by a distance of few hundred meters to several kilometers or more. For practical purposes, some researchers have defined a flash as the ensemble of all cloud-to-ground strokes that strike within 10 km of each other within a one second interval [3].

3. RF CHARACTERISTICS OF LIGHTNING

RF energy emitted by cloud discharges and CG flashes consists of a wide range of frequencies. When new channels are created, strong emissions are in the VHF range. When high currents occur in previously established channels, the most powerful emissions occur in the LF and VLF range. Figure 3 shows the radiation field pulse activity in the VLF, LF, MF, and VHF frequency ranges for CG flash and cloud flash.
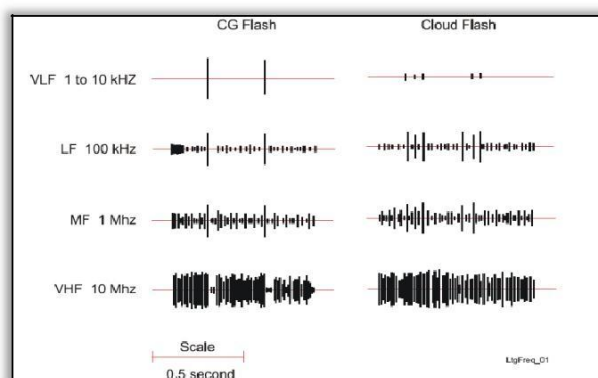

Figure 3 CG and Cloud Flashes at Various Frequency Ranges

Study of lightning processes is associated with the measurements of the electric and magnetic fields related to the motion o fcharge in lightning. Radiating electrical and magnetic field is associated with various physical processes taking place in CG and CC flashes. Information retrieved from the observations depends on the frequency and wavelength of the detected radiation. Signals coming from the very-low-frequency (VLF) range (f = 3 to 30 kHz, λ = 10 to 1 km) and low-frequency (LF) range (f = 30 to 300 kHz, λ = 1km to 100 m) are not suitable to map the lightning channel, but can be used to determine the location of the lightning strike. The radiation fields from CG strokes are strongest in LF & VLF bands due to their channel length and large currents.

Consequently, there are only a few large pulses per flash. Tens to hundreds of small pulses are produced in cloud

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discharges in the LF range, and occasionally pulses comparable to the magnitude of return strokes are produced. In contrast, VHF band contains 100 times as many pulses as in VLF & LF and the amplitudes of the pulses produced by cloud discharges are comparable to those of CG flashes.

Since many years, the LF and VLF signals propagating along the surface of the earth are utilized to detect and locate return strokes in CG flashes. Signals in LF & VLF range are normally much smaller than those of return strokes so sensors operating in this range can also be used to detect and locate cloud flashes by detecting the signal components propagating thousands of kilometers and reflecting between the ionosphere and the ground. Figure 4 shows use of LF & VLF sensor technology in locating CG flashes.
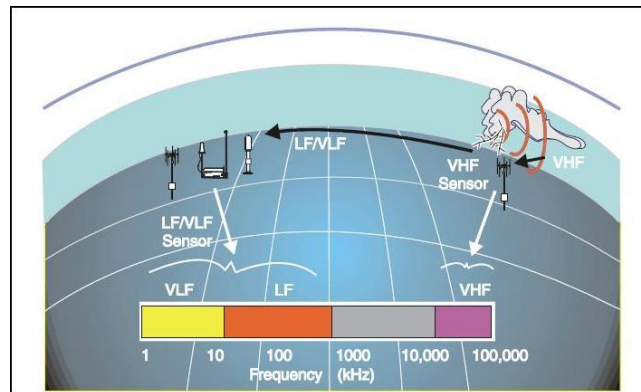

Figure 4 Relationship - Frequency and Lightning Detection Method [4]

Long range propagation in LF & VLF range allows lightning detection in remote areas where installation of sensors is not possible. Sensors that operate in the VHF band are equally sensitive to most processes in both cloud and CG flashes. The sensor networks have limited range due to the line-of-sight propagation [4].

4. TOA BASED LIGHTNING DETECTION SYSTEM

Block diagram of the TOA methodology based lightning detection system is shown below in Figure 5.
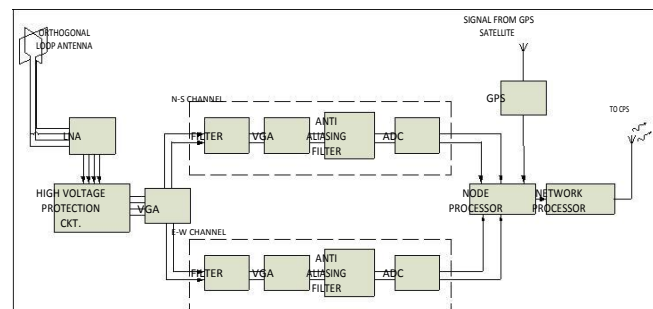
Fig. 5 - Block diagram of lightning detection system

Lightning is received by the orthogonal cross polarized magnetic loop antenna. This received VLF signal will then be given to low noise amplifier for noise removal and amplification. High voltage protection circuit protects the whole system from getting damaged due to sudden high voltages entering into the system. Two channels namely, N-S and E-W are used to filter the signal, remove sampling errors and digital conversion. These separate channels are then fed to node processor block where further processing of signal is done. Particular signal is taken and fed to network processor further and transmitted through GPS antenna. Receiving nodes detect lightning and get position of the flashes.

4.1 **Time-of-Arrival lightning location retrieval**

The name of the technique itself gives hint to the method on which it depends. Numbers of antennas are used to measure arrival times of impulsive emissions at different locations. Impulsive component of the lightning discharge i.e. return stroke peak current is solely used in this method. The difference in time-of-arrival between the antenna pairs is used to produce an ensemble of possible locations where a stroke hits the ground. As discussed earlier, intersection of two hyperboloids gives the direction of the source, whereas three or more time differences are needed to point out the exact location of the source. Causes for the errors in locations extraction can be one of the few mentioned here (i) the

identification of different parts of the received waveform at different stations, (ii) path elongation due to mountains, and (iii) inadequate time synchronization between the stations. The major difficulty in this technique is the identification and correlation of the multiple impulsive events of a single lightning discharge between the various sensors. It can be seen in the figure that the difference of time of arrival for each pair of sensors is confined on a hyperbola. The intersection of the hyperbolas gives the estimated source location. Left side figure shows example of an ambiguous location for a three-sensor hyperbolic intersection. Right side figure shows an unambiguous location using the hyperbolic intersection method for lightning using three sensors.

An antenna is defined by the IEEE Standard Definitions [12] as a "means for radiating or receiving radio waves". It converts the electric energy to electromagnetic energy and vice versa. Antenna enables transmission of energy between guiding device and free space. It acts as the last block in a transmission system and first block in a receiving system. Antennas can be classified based on their radiation principle, physical structure, manufacturing technology, and/or radiation characteristics [13].
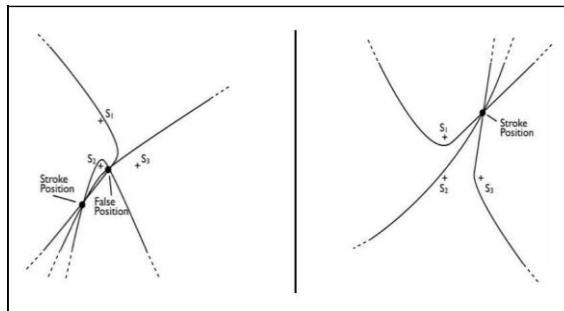
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Fig. 6 - Time-of-arrival (TOA) location technique

Most ground based and airborne sensors are only capable of detecting cloud to ground lightning, which is known to make up only about 25% of total lighting activity. This is further limited by the facts that ground sensors can only detect activity over land, and airborne sensors have a limited observation time. Thus, with these sensors alone, we are incapable of studying lightning activity over the two-thirds of the earth that is covered by ocean. Space based sensors can provide us with literally several times more data than ground based sensors.

To give an overview about number of sensors, CLDN consists of more than 80 remote, ground-based Vaisala lightning sensors [14]. Minimum number of sensors required to identify a lighting stroke direction and strike point requires four TOA sensors.

5. ANTENNA SUBSYSTEM FOR TOA METHOD

In this section, various sections of an antenna subsystem and the factors which will decide antenna parameters are discussed.

5.1 The Lightning Signals

VLF waves with a frequency range of 3 kHz to 30 kHz have wavelength between 100 km and 10 km. Small loop antenna with circumference less than 1/10000 of wavelength is suitable for this application. Small loop antennas are less sensitive to electric noise of electromagnetic waves when properly shielded and more sensitive to magnetic component of electromagnetic wave, so also known as Magnetic Loops. If the loop is small with respect to the wavelength, the current around the antenna is nearly completely in phase or constant.
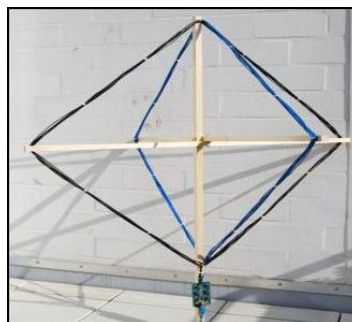

Figure 7 Two orthogonal crossed VLF loop antennas connected to amplifier

To cover all directions, it is advisable to use more than one loop. Suitable solution can be obtained by using two orthogonal crossed loops as used in direction finding applications. The electromagnetic signals of lightning discharges have more or less the form of an impulse and thus emit waves over a wide range of frequencies. Every impulse is unique and visually different. As signal is emitted in a wide frequency range, it is desirable to design receiver system working on wide-band instead of tuned frequency. Large antenna is required to get a high voltage caused due to change of EM field. If the loop has windings (more than one winding), then the wire placed side by side forms a capacitance. Own resonance frequency of the loop antenna is unavoidable so it should be very high to get suppressed by LPF (low pass filter) easily. Use of additional capacitor for tuning is avoided. Fig 7 shows a signal received by two equal sized untuned loops antennas. These loops have no additional tuning capacitor. The resonance frequency of the antenna is approximately 1000 kHz (= 1 MHz). The used amplifier reduces frequencies of 1000 kHz by -72 dB (i.e. 4000 times). Now, the tuned frequency of the antenna is approximately 10 kHz. Since lightning impulses often contain a lot of energy at 10 kHz, the tuned loop antenna gives output as unusable uniform waves at 10 kHz. This shows that it is very important to use a pure loop without any parallel capacitor. A shielding of the E-field can significantly improve the signal to noise ratio, especially in metropolitan areas. This can improve the detection rate of lightning discharges. Wires and copper tubes can be used to shield loop antenna [4].

5.2 Coaxial Cable Antennas

Another type of cheap loop antenna can easily be constructed using coaxial cables. Any arbitrary impedance can be used, but the 75 Ohm versions are very cheap to get. As per reference [4], design provided for coaxial cable based antenna, loop of 3 turns and a diameter of 180 cm is formed with 20 meter coaxial cable. The shield has to be broken in the middle.

Keep 20 cm cable for the connection at both ends. Such a construction will create a loop with an inductance of approximately 60H and a self resonance at 2 MHz. This is as shown in the figure below.
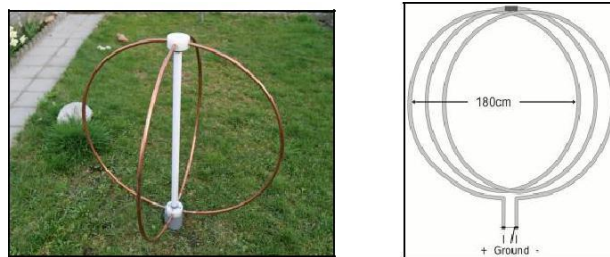

Fig. 8 - Coaxial cable loop antenna

Shielded Antenna

Whilst the loop aerial essentially operates on the magnetic component, there can be a residual pick up of electric component. For applications in direction finding, it is necessary to electrically shield the loop to minimize electric field induction. Practically there seems to be less to gain by reduction in electrical pick-up. Shielding increases the residual capacitance of the loop and reduces the maximum tuning frequency for a given number of turns. Shielding improves SNR (signal to noise ratio) and detection rate of lightning discharges [16]. The level of signal pickup is always low for a loop aerial as compared to the long wire aerial but it can separate out signals even in the presence of localized noise. Suitably designed aerial with highly selective front end tuning system, good signal strength can be received. In terms of some odds, it's very easy to miss a signal if it is incident on the null of the loop.

Untuned Loop

Loop aerials can also be operated in a broadband mode and a design procedure for doing this over a range of frequencies is described in the April 1989 issue of Lowdown. The procedure is to load the loop aerial into a fairly low resistance at the preamplifier input, equal in value to the loop inductive reactance at the lowest frequency of the frequency band required. Parallel resonance is set to a frequency calculated from the geometric mean of the lowest and highest frequency required. According to the article, the design produces a loop response which is flat with frequency. Whilst the broadband loop eliminates the complication of loop tuning when changing frequency, the loss of Q multiplication can drop atmospheric noise below the noise floor of the amplifier, thus limiting the sensitivity to weak signals.

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6. EXPERIMENTAL SIMULATION RESULTS

We have tried simulating shielded single turn orthogonal antenna. We can use cooper wire and with the help of load option in the software we can shield it with the thickness whatever required. For single turn loop antenna, results are shown below in figure 9.

The error in the simulation is due to small dimensions of the antenna. For low frequency implementations, we either need a very big antenna or need to have many turns in the antenna. These turns can be implemented in the software either by directly winding wires or we can give different coordinates to all the dimensions (x, y, z- axis). Our aim also includes size of the antenna to be small so that can be fixed at the roof top or at a height of about 5-10mtrs from the ground. So, to avoid big sized antenna, we implement antenna with multiple turns.
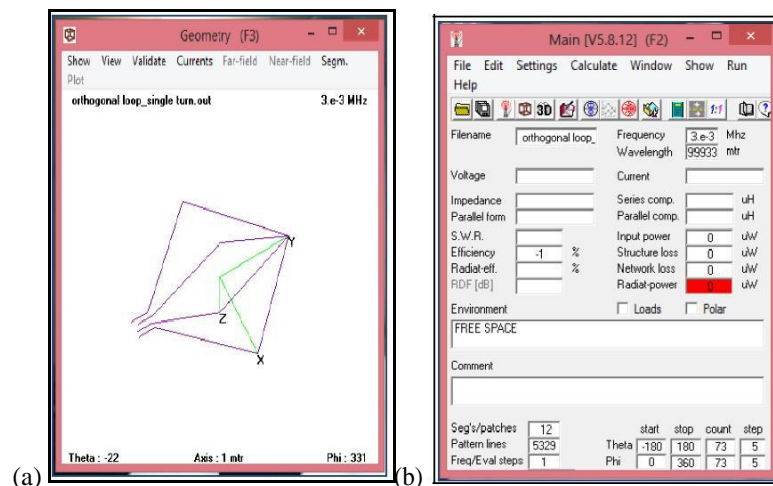
Specifications chosen for implementing antenna in lab after considering various calculations related to loop antenna are:-
No of turns – 8
Diagonal size – 1mm
Wire material - Copper

These are considered as the beginning of trial-and-error method to get results and analyze them.

Figure 9 (a) Geometry of orthogonal single turn loop; (b) Result calculations

4NEC2 software doesn't support Multiturn antenna here. Simulation error after simulation one shielded multi-turn antenna was wire overlaid over each other as shown in figure 10.
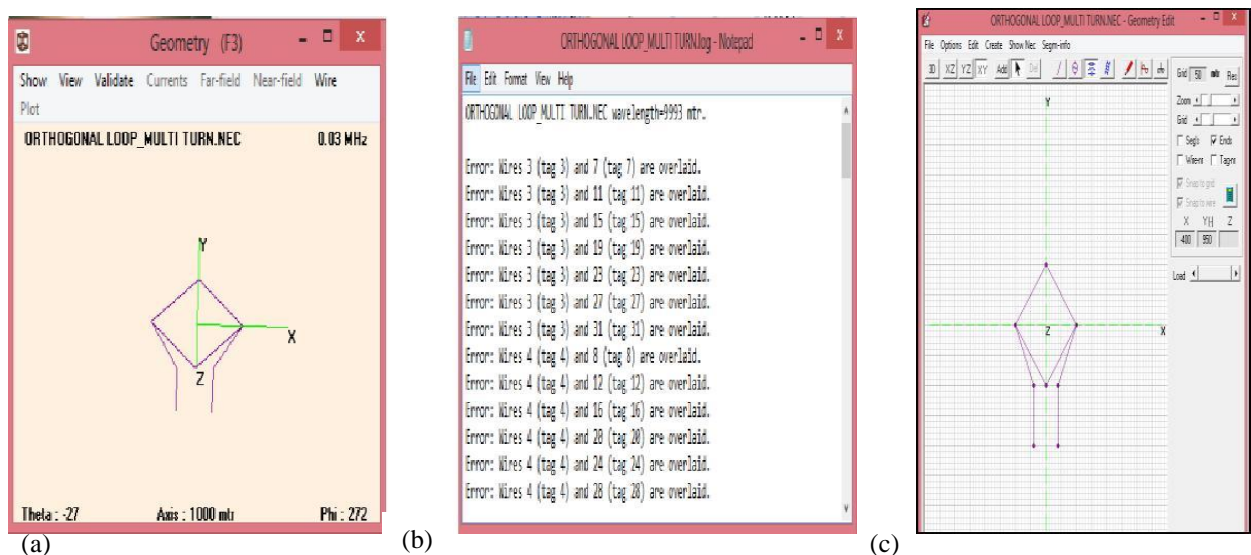
Figure 10 Multiturn Loop antenna: (a) Geometry; (b) Simulation results & (c) Load option - Geometry

Thus this software is not solving our purpose and we need to simulate this antenna on another one with features related to orthogonal and multi-turn design. We are looking forward to use HFSS (High Frequency Structural Simulator) v.12 for the same.

7. CONCLUSION

A properly designed lightning detection system with loop antenna subsystem and a low noise preamplifier is an important part. It enables reception of signals which are to be picked out of noise that can otherwise override the signal. Instead of magnetic loop antenna, electrical loop antenna can also be used to receive the signals. Due to few disadvantages related to electrical antenna for example sensitivity to noise and necessity of lightning protection circuitry, we usually prefer magnetic loop antenna. The signal level received from the loop aerial is low compared to the wire aerial and the signal-to-noise ratio can be limited by the noise generated in the first amplifier. To minimize this problem, a low-noise preamplifier is used, and the loop circuit is tuned so that the signal level into the amplifier is multiplied by the Q factor of the loop circuit. Lightning detection and location principles are in use for some decades now. Networks operating in the LF or VHF range do not reach presently far enough to cover oceanic or other remote areas, as large attenuation of the signals at these frequencies prevent the observation of lightning discharges at large distances. VLF networks come to help in isolated areas as signals at these frequencies can travel relatively with low attenuation over large distances via the Earth-ionospheric waveguide (EIWG). The reliability and quality of the data, related to the detection efficiency (DE), location accuracy (LA) and false alarm rate (FAR), differs between the existing operational LLS (Lightning Location System).

Simulation of the antenna is performed on 4NEC2 simulation software for wired antennas which shoed results for single and Multiturn loop antennas. More featured software's like HFSS are o be used later for the same purpose to simulate antennas. Simultaneous work is going on practically implementing antenna and testing parameters on the basis of trial-and- error method.

8. ACKNOWLEDGEMENT

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AUTHOR

Swati Sharma received her B.E degree from SIGCE, Pune University in 2009 and presently pursuing M.E degree from V.E.S.I.T, Mumbai University in Electronics and Telecommunication. She worked in RFID industry for HF and UHF technology. She has work as a faculty member at SIGCE, Mumbai. She has presented few National presentations on technologies like Nanotechnology. Presently she is working on VLF antenna as ME project.

Shoba Krishnan received her B.E degree from VRCE, Nagpur University in 1983 and M.E degree from VJTI, Mumbai University in 1999.She has been a faculty member at VESIT, Mumbai since 1987.At present she is working as HOD, Electronics and Telecommunications Department. Her areas of research are Microwave Optical & Wireless Communications. She has more than 50 publications in International Conferences and reputed journals.

Ajay Khandare received his B.E. degree from V.J.T.I University in 1996. He joined SAMEER in 1997. He has worked in Design & Development of the Atmospheric instrumentation. His main area of work is RF & Radar signal processing. He has successfully worked in systems like Wind Profiler/Radio Acoustic Sounding System at 404.37MHz for Indian Meteorological department, CW RASS for BRNS, Radio Theodolite at 1680MHz for Indian Meteorological department, Radio-Sonde for Indian Meteorological department, Digital Ionosonde for Dibrugarh University. He has more than 25 national/international publications.