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ARTICLES

INFORMATION

FOREWORD

Advancing the Horizons of Acoustics Research

It is with great pride that we present ***Volume 3 of the Journal of Acoustical Society of India (JASI), 2024***. This edition brings together ground breaking research that explores diverse and crucial aspects of acoustics, fostering innovative perspectives and global collaboration.

1. **Acoustics Research in India :** A Bibliometric Study of Papers Published During 2010-2021 meticulously evaluates India's contributions to acoustical science, reflecting the nation's growing prominence in the global research landscape.

2. **Building Acoustics :** A Comprehensive Analysis from India and Around the World delves into modern strategies and global benchmarks in architectural acoustics, enriching design practices for sustainable and effective sound environments.

3. **Acoustical SODAR Systems :** An India and International Perspective highlights advancements in SODAR technology, emphasizing their significance in atmospheric studies and environmental monitoring worldwide.

4. **Sacred Sound on Sacred Grounds :** Acoustical, Soundscaping and Metaphysical Perspective examines the intricate interplay of acoustics and spirituality, fostering a deeper understanding of soundscapes' cultural and metaphysical impacts.

5. **Miscellany of Underwater Acoustics (UA)** offers an insightful exploration into underwater sound propagation, bridging technological innovation with environmental conservation efforts.

This volume celebrates the relentless pursuit of knowledge and the collaborative efforts of researchers worldwide. It is a testament to the growing influence of acoustical sciences in addressing global challenges and enriching human understanding.

On behalf of the editorial team, we extend heartfelt gratitude to the contributors, reviewers, and readers whose dedication ensures the journal's continued success. Let this volume inspire innovation and dialogue, propelling the acoustical community towards greater achievements.

Dr. Mahavir Singh
Managing Editor, ASI

Dr. B. Chakraborty
Chief Editor, JASI

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Acoustics research in India : A bibliometric study of papers published during 2010-2021

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ABSTRACT

Acoustics research has played an important role since ancient times. However, a systematic analysis on this aspect in Indian context is not properly given attention. The present study is an analysis of 2873 publications, India has published in the domain of acoustics during the period of 2010-2021. With mere 2.6% publications in this domain, impact of acoustics research from Indian authors has been better than many developed countries. Citation per paper of Indian authors is fourth best globally. Out of 2873 publications, highest numbers of records were research articles followed by proceeding papers. The output shows a consistent growth of output with a slight decline in the year 2019. Most of the prolific institutions were either Indian Institutes of Technology (IITs) or the National Institutes of Technology (NITs). Among the highly productive institutes, Indian Institute of Science (IISc, Bengaluru) topped the list, while Institute of Chemical Technology (ICT, Mumbai) had the highest value of citation per paper with no uncited paper. Of the 20 prolific authors, four each were from ICT (Mumbai), IIT (Madras) and IISc (Bengaluru). About 25% papers were published in journals with an Impact Factor (IF) of more than four and in contrast only 12% in low impact factor journals. The highest number of papers were published in the journal Ultrasonics Sonochemistry and most of the highly cited papers were also published in the same journal. A consistent growth of papers has been observed in the number of domestic and international collaborative research. Indian Institute of Science had the highest number of papers in collaboration and India had the highest number of collaborative papers with the USA.

1. INTRODUCTION

Acoustics, the subfield of science is the study of the production, control, transmission, reception, and effects of mechanical waves. In simple words, acoustics deals with the process of generation, reception, and propagation of sound. The word acoustics has been derived from Greek language word 'akoueiv', which means to hear[1]. The term acoustics was introduced in 6th century B.C. by Greek philosopher Pythagoras involving various mathematical and physical explanations. In continuation of the development, another Greek philosopher Aristotle made decisive contributions in the study of sound based on the concept of compression and rarefactions of air, which led to the study of wave motion. The properties of acoustics in architecture were initially introduced by Roman architecture and engineer Vitruvius. These properties further led to the wide use of acoustics in ancient buildings, which later on termed as architectural acoustics. From 16th century onward, the area of acoustics further proliferated with inventions from great scientists like Galileo Galilei and Marin Mersenne. During the 19th century, German physicist and physician Hermann von Helmholtz (1821-1894) set up an early breakthrough on physiological acoustics involving biological aspects of hearing. In another development, Gustav Fechner (1801-1887) invented the term psychophysics focusing the relationship between our sensory organs and physical variables around us. Psychoacoustics however has different domains and thus have limited area of application such as auditory perception or hearing on humans as well as nonhuman animals. English scientist Lord Rayleigh (1842-1919) recreated the ancient knowledge of modern experimental acoustics, thus paving the way for the development of the theory of sound. The history of acoustics is incomplete, if we do not mention Alexander Graham Bell (1847-1922), who invented the telephone, which helped the modern era of ICT to flourish at global level. He also co-founded the American Telephone & Telegraph (AT&T) Company, which later became prestigious place to experiment acoustics, speech, and mechanics research during early twentieth century.

Acoustic waves are used to gather the complex information about the three layers of the planet *i.e.* ocean, atmosphere, and solid earth. Many complex phenomena occurring in these layers are thus captured by the radiation of sound. By analysing this captured information, we can determine the place and time of occurrence of these complex phenomena. The ocean and solid rocks are opaque in nature and in this scenario, sound looks only other viable alternative that can be harnessed[2]. The main areas of study of acoustical research are: acoustical oceanography *i.e.* the study of sound and its behaviour in the sea; animal bioacoustics i.e. the study of the production, transmission and reception of animal sounds; architectural acoustics i.e. the study of sound in homes and other buildings and the design of those structures for optimal acoustic performance; biomedical acoustics i.e. applications of ultrasound in thermal ablation, drug delivery, and other therapeutic and diagnostic applications; engineering acoustics i.e. the study of acoustics in various engineering and infrastructure projects; musical acoustics which deals with the generation of sound by musical instruments, the transmission of sound to the listener, and the perception of musical sound; physical acoustics which focuses on the interaction of sound waves with matter and the processes accompanying it; psychological & physiological acoustics which deals with the study of how humans perceive sound; structural acoustics, the study of the mechanical waves in structures and how they interact with and radiate into adjacent media; underwater acoustics, the study of the propagation of sound in water and the interaction of the mechanical waves that constitute sound with the water, its contents and its boundaries. Underwater imaging with the help of low bandwidth acoustic channels has found its wide application in large engineering projects involving underwater pipelines, cables, offshore structures and mines. Its other potential areas of application beneath the sea are: resource exploration e.g. minerals, energy resources and wild fish stock; and protection of underwater environment from climate change perspective[3]. In Indian scenario, three institutions: CSIR-National Institute of Oceanography (NIO); ESSO-National Institute of Ocean Technology (NIOT); and DRDO-Naval Physical and Oceanographic Laboratory have mostly contributed in underwater acoustic research. These three R&D organizations contributed mainly in the technology development. A special issue on the subject was edited by Chakraborty and Latha in 2015[4].

As clear from the above, the applications of acoustics research dates back to centuries. Until during the first two decades of the 20th century, acoustics was confined as a branch of physics. During first half of the same period, it spread its wings in pure and applied acoustics, resulting in the establishment of acoustics as an independent discipline. Consequently, technological breakthrough during the two World Wars established it as an important area to be used for defence purposes[5,6]. To make use of acoustics in our day to day life, almost all the countries have well developed curricula infrastructure on acoustics and its sub-fields. Various universities/institutions in the different nations have been set up to impart the education from certificate to doctorate level. To make the subject more standardised and well developed, there exist nine international organisations to serve the needs of researchers, practitioners, legislators and public. To name few, some of them are International Commission on Acoustic (ICA), Audio Engineering Society (AES), and European Acoustic Association (EAA) funded by eleven European

Acoustical Societies for pan-European cooperation. The ICA is a special commission of International Union of Pure and Applied Physics (IUPAP) set up in 1951 by the International Council of Scientific Unions (ICSU) which was closely associated with UNESCO[6]. Similarly, there are 51 national organisations / societies involved to develop various standards on the area of acoustic research in different nations. They are Acoustical Society of America being on top of the chart followed by similar societies / associations from Japan, Korea, India and other various developed and developing nations. Standards developed by these international and regional bodies are being proliferated further to spread the awareness and benefits of acoustics for the cause of the common man.

Keeping in view the above developments, it was felt necessary to conduct a bibliometric study in the domain of acoustics and its allied areas to examine how the landscape of research in Indian context has changed over a period of 2010-2021.

2. LITERATURE REVIEW

Viator and Pestorius[7] investigated trends in acoustics research for the years 1970, 1980, 1990, and 1999. The source of data for their study was the IEEE transactions-Journal of Acoustical Society of America (JASA). The output data was classified using a method based on the Physics and Astronomy Classification Scheme (PACS). The data was further analysed into different world regions namely North and South America, Eastern and Western Europe, Asia, Africa, Middle East, and Australia / New Zealand. In order to gauge the use of IEEE transactions-JASA as an indicator of international acoustics research, three subject namely underwater sound, nonlinear acoustics, and bioacoustics, were further tracked in 1999, using all journals in the INSPEC database. Research trends indicated a shift in emphasis of certain areas, notably underwater sound, audition, and speech. The study also showed steady growth, with increasing participation by non-US authors, from about 20% in 1970 to nearly 50% in 1999. Motivated by the application of acoustics in engineering, a bibliometric study by Yan *et al.*[8] on Acoustic Emission (AE) based on 9,469 documents consisting only articles, proceeding papers, reviews and letters was conducted for the periods of 1975-2020. The authors have sorted all the documents into different cluster with five different subjects. The source of data was Web of Science (WoS). The subject names were determined by analysing preliminary keywords or AE related papers exported from WoS. These five subjects are of engineering consisting of mechanical, architectural and civil, mining geophysics, metallurgical and material science. Among the organizations, University of Tokyo was major contributor followed by Russian Academy of Science and China University of Mining and Technology. China topped the list of countries with highest papers on AE, followed by the USA and Japan. India also figured among top 10 countries and ranked at eighth position. Majority of the documents were published in Russian Journal of Nondestructive and Materials Evaluation, distantly followed by Material Evaluation, Construction and Building Materials, Soviet Journal of Nondestructive Testing-USSR and Engineering Fracture Mechanics. However the cited sources in the study were drawn mostly from Construction and Building Materials followed by Composites Science and Technology, IEEE Transactions-JASA, and International Journal of Rock Mechanics and Mining Sciences. Scientific literature consisting of AE on coal has been rising since 2010 and more rapidly from the year 2016 onwards[9]. China with 90 percent of publication in this area has been a dominant force at global level, because major infrastructure project like tunnels, slopes, hydropower and other underground are underway in the country for development purposes. To meet the growing energy demand for a large population, the country is heavily dependent on coal mining, AE, thus could substantially detect the location of large quantity of coal reserves. There are many useful applications of acoustic waves in the diverse branches of R&D in industry. Production, testing and operation being an integral part of any manufacturing unit, in each of these three stages, ultrasound and other acoustic waves are used to detect flaws and correction thereon[10].

From health care point of view, the acoustic field as a whole and ultrasound in particular has played a vital role. In this direction, Wang *et al.*[11] made a bibliometric analysis of 1,781 documents to identify publication trends, subject categories, journals used for publishing research results, authors, institutions, and countries in the sub-discipline of ultrasound-assisted degradation of organic pollutants. The study found that the leading subject category is multidisciplinary chemistry, followed by environmental sciences, chemical engineering, environmental engineering, physical chemistry, and acoustics, and there exists difference in the publications of different categories. Ultrasonics Sonochemistry was the most productive journal contributing about 15% of total articles. China was the leading country (30.3%), followed by Iran (15.7%) and India (12.4%). The top three authors are Parag Gogate, Oualid Hamdaoui, and Masoud Salavati-Niasari. The study found a close cooperation between countries and researchers. The study by Chen *et al.*[12] made a bibliometrics analysis of 17,775 documents related to ultrasound publications indexed by Science Citation Index (SCI) from 1991 to 2006. The study examined pattern of authorship, total number of publications in each year, document types, and the authors' keywords. Of the total 17,775 publications, 85% were original articles. The yearly production increased from 740 in 1991 to 1,208 in 2006. The United States topped the list with the most publications. The trend towards prenatal research declined in the last four years, while Doppler ultrasound research increased during 1999-2006. Similarly, Wu *et al.*[13] did a bibliometric analysis of 6,088 papers published between 1998 and 2019 related to ultrasound microbubble using the SCI Expanded Web of Science Core Collection. Quantitative variables for analysis included number of publications and citations, h-index, and impact factor. VOS viewer and Cite Space (software tools for constructing and visualizing bibliometric networks) were used to perform co-authorship, citation, co-citation, and co-occurrence analysis for countries / regions, institutions, authors, and keywords. The study found the USA to be the highest contributor in this field with the majority of publications (2090, 34.3%), citations (90,741, 46.6%) and the highest h-index (138). It has close collaborations with China and Canada. The University of Toronto made highest contributions. However, the research cooperation between institutions and authors was relatively weak. Authors divided the studies into four clusters *i.e.* ultrasound diagnosis, microbubbles characteristics, gene therapy, and drug delivery. The Average Appearing Years (AAY) of keywords in the cluster "drug delivery" was more recent than other clusters. For promising hotspots, "doxorubicin" showed a relatively latest AAY of 2015.49, followed by nanoparticles and breast cancer. In continuation of acoustic intervention in healthcare, another study by Sridharan *et al.*[14] spells out that there are continuous growth of global publications, especially the role of ultrasound in cancer and cancer related pain. The study analysed 3,218 documents from 1100 journal sources related with role being played by the ultrasound techniques in containing cancer and its pain. For a time span of 1987-2022, the publications on the subjects have grown from merely one in 1987 to 390 in 2020. The USA led the list of top countries followed by China, Italy and UK. India is also figured among top 20 countries with the required threshold of publications and citations respectively. The study of voice is essential to gauge the mood of patients and there are studies reporting role of acoustics in the field of speech diagnosis, pathology and therapy by number of diagnostic centres[15]. Using the acoustics speech features, there are potential application to predict speaker's social characteristics such as age, height, gender, race, ethnicity and homeland from the text speech samples. From forensic point of view, these characteristics are also very important to unearth crime related evidence such as threat, ransom or harassment[16].

Growing concerns for environment and climate change has motivated many studies to link acoustic field with environment sustainability. In top of agenda is the term Soundscape used first time by Southworth[17] in urban planning. It basically defines the relationship between landscape and composition of the sounds surrounding it. Latter, many terms were added into the literature of Soundscape *e.g.* biological, geophysical and anthropogenic sounds. There is growing interest in this field as large numbers of scientific papers have been published over the past decades[18]. To understand the noise pollution reduction strategies, Yap *et al.*[19] analysed 2,970 publications related to Sound Absorption (SA) field. The study found the number of SA publications peaked in 2020. The cumulative publications soared 84% between 2011 and 2020 in 26 fields. The majority (68.3%) of the publications were in Physics and Astronomy 25.4%, Engineering 24.7%, and Materials Science 18.2%. The output was scattered among 160 journals and among them Applied Acoustics with 10.3% publications was the most productive journal. Lin Jia Horng from Taiwan had the most collaboration with 40 authors. The total contributions originated from 79 countries and among these more than half (55.3%) of the total publications is originated from Asia. Among all the countries, China topped the list of publications with 1,046 articles, 35.2% of total publications. Most researchers focused on porous materials, micro perforated panels, polyurethane foam, nonwoven fabrics, and natural fiber. Nonetheless, mechanical, thermal, permeability and porosity properties were commonly examined for sound absorption materials. In the same stream of absorbing noise, the study by Gomes *et al.*[20] is focused on developing alternate material to traditional synthetic or polymer based material. This alternate substitute material is bio-mycelium based foams and composites, a sustainable and potential material suitable for packaging and sound absorption, providing effective absorption of mid to high frequency noise. Traffic noise or the noise produced from the automobiles in is major part of the noise pollution in urban area. They often lead to many medical ailments other than some behavioural problems. But due to sustained efforts of technology intervention and environmental regulatory changes, these problems if not solved permanently but certainly contained to minimum extent[21].

Artificial Intelligence (AI) and Machine Learning (ML) have been in forefront to explore the possibilities to find out solutions using Deep Learning, Convulsion Neural Network (CNN) and other such algorithms. These software techniques have been seen in recent years associating with applied acoustics to offer general purpose solutions for common man. In a study by Huang *et al.*[22] under smart agriculture in Taiwan, AI/ML has come to help local farmers to grow pineapples smartly. There are two varieties of pineapples grown locally. First one is having less watery content and the other having more watery content. Pineapples with more water content can be consumed locally, because it has less shelf life, while the other variety can be sold over-seas to fetch more prices. Here, AI/ML based ultrasonic sensors are used to recognise the above two varieties, which were till now being separated manually. The study proposed an acoustic spectrogram spectroscopy, which used acoustics data to generate spectrograms, thus helping farmers to achieve their objectives to separate two varieties of pineapples. There is couple of other studies[23,24] to analyse the various trends on speech technology to improve various defects and deformities currently existing while studying speech data e.g. noise interference, ambiguous sentences and reception of sound over a long distance. These studies have come up with a solution from Deep Learning to remove noise interference and CNN to remove the ambiguity on understanding the meaning of sentences. Thus speech technology in association with modern AI/ML solutions have been in public domain to switch on navigation map, play favourite music, send and replying text messages, make important calls, connect with smart home devices, order favourite foods, buy online tickets etc. To make the life of visually impaired people more comfortable, the combination of AI/ML in acoustics has come into limelight. Ultrasonic techniques will help these people by scanning the environment and obstacles around them using sound waves from a certain distance, whereas Global Position System (GPS) module is used for real time direction and navigation. The proposed system work from different components namely hardware and software[25]. By focusing AI/ML in acoustics, the IEEE Transactions-Journal of the Acoustical Society of America has published a "special issue on Machine Learning in acoustics"[26]. Underwater acoustic, application of AI/ML was introduced in ocean bed backscatter data in India, and a detailed application of seafloor mapping and classification was presented using the sonas data from Arabian Sea[27].

It has been observed from the literature survey that in few of the bibliometric studies, India has performed quite well and these studies are of recent origin. For example bibliometric study by Yan *et al.*[8] on the publications of AE, India ranked eight globally. In the bibliometric study by Wang *et al.*[11] on ultrasound-assisted degradation of organic pollutants, Indian ranked at third position. Similarly, in other bibliometric study[14] on the role of ultrasound in cancer and cancer related pains, India featured among top 20 countries globally, as far as publications and citations are concerned. In the area of underwater image processing, the position of India is also noteworthy and it ranked third among top 10 contributing countries in the publication indicator[2,28]. It is pertinent here to mention that all these studies are not India specific, but are general review studies, where India has been listed along with other countries. But the present bibliometric study specifically focuses on India covering various important bibliometric indicators exclusively on the subject of acoustics.

3. DATA AND METHODOLOGY

Bibliometric analysis is an important tool for global analysis of publication output in different scientific areas. It is carried out using either Web of Science (WoS) or Scopus database. The WoS is a world leader among citation databases and is produced by Clarivate Analytics of the USA and Scopus is produced by Elsevier. In the present study, authors have used Web of Science Core Collection data base. It is considered as one of the most widely accepted and suitable databases for bibliometric analysis of scientific publications. The search fields of the WoS Core Collection comprise topic, title, author, publication name, year published, address, and author identifiers. Data for the present study was downloaded by giving keyword "Acoustics" in the tag "WC". Here WC stands for web of science subject category. Time period for the data is 12 years from 2010 to 2021. Data for the study was downloaded on 31.10.2022. The downloaded data consist of 2,822 records. Out of these 2,822 records, 2,030 are articles, 703 proceedings papers and 45 review articles. These three categories constituted 2,778 (98.44%) of the total number of records. Rest are letters (26), editorial material (10), corrections (7) and one book review.

3.1 Bibliometric Indicators used

Bibliometric indicators used in the study are :

Total number of publications (TNP) obtained from the downloaded data from Web of Science;

Total number of citations (TNC) obtained from the downloaded data from Web of Science;

Citation per paper (CPP), a ratio of the number of citations to number of papers;

Papers not cited (PnC %) obtained from citation data;

Impact factor of journals where the research results were published obtained from Journal Citation Report (2022); and Domestic and international collaborative index.

3.2 Objectives of the Study

Present study discusses the following bibliometric aspects of Indian scientific research output in the discipline of acoustics:

Distribution of output by type of documents;

Chronological distribution of output during 2010-2021;

Identification of most prolific institutions / authors and to examine the citation impact of their research output using citation per paper (CPP) and papers not cited (PnC %);

Pattern of citations and to identify highly cited authors;

Pattern of communication in terms of publishing country of journals and their impact factor as reflected by JCR 2022 and Pattern of domestic and international collaboration.

4. RESULTS AND DISCUSSIONS

4.1 Geographical Distribution of Output

Based on the complete count of countries, institutions and authors, it is observed that 111,306 papers were published by 162 countries from 2010 to 2021. Of these, 12 countries listed in Table 1 contributed two per cent or more papers individually and remaining 150 countries contributed less than two per cent papers. These 12 prolific countries produced more than three-fourth (77.8%) publications and the share of remaining 150 countries was only 22.2% of the total output. Among the prolific countries listed in Table 1, USA topped the list with about 21% papers closely followed by Peoples Republic of China with 18% papers. These two countries together published about 39% papers. Among the prolific countries, India ranked 10th with 2,873 publications. Among the prolific countries, Canada had the highest (18.8) citation per paper (CPP) followed by Italy with CPP of 17.6. The CPP for India is 16 and is more than several developed countries like France, Germany, Japan and Australia. Among all the countries, Japan and China

Table 1. Geographical distribution of output.

Ranking	Countries	Number of Papers	% of Papers	Number of citations	Citations per Papers
1	USA	23178	20.8	329128	14.2
2	Peoples R China	20411	18.3	238809	11.7
3	England	6992	6.3	119563	17.1
4	France	6768	6.1	99490	14.7
5	Germany	5889	5.3	76557	13.0
6	Japan	4622	4.2	48531	10.5
7	Italy	3842	3.5	67912	17.6
8	Canada	3772	3.4	70914	18.8
9	Australia	2914	2.6	44001	15.1
10	India	2873	2.6	45968	16.0
11	South Korea	2632	2.4	35006	13.3
12	Spain	2584	2.3	38243	14.8
	Sub-total	86477	77.8	1,214,122	14.0
Other 150	countries	24829	22.2	213,529	8.6
	Total	111306	100	1,458,109	13.1

had the lowest CPP. Different bibliometric aspects related to India's output in acoustics research is described in the following paragraphs.

4.2 Distribution of Output by Type of Documents

During the period from 2010 to 2021, Indian scientists working at different academic and research institutes published 2,873 records on different aspects of acoustic research. An analysis of data indicates that the highest number were articles constituting 2,030 (71.9%) records followed by proceeding papers 703 (24.9%) and review articles 45 (1.6%). These three type of documents constituted 2,778 (98.4%) of the total output. Remaining 1.6% records published were letters (26), editorial material (10), and corrections/ book reviews each one. These have not been included in the detailed analysis as their citation impact is very low. Authors have made a detailed bibliometric analysis only of 2,778 records published as research articles, reviews and proceeding papers.

4.3 Chronological Growth of Output

Figure 1 shows the pattern of absolute and annual growth rate of publication output during the study period of 2010-2021. The pattern of absolute output shows a continuous rising trend during the study

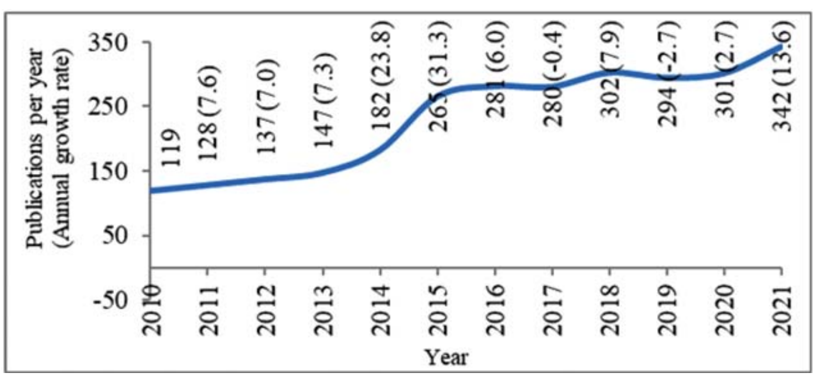

Fig. 1. Pattern of publication output in the field of Acoustics in India during 2010-2021.

period of 2010-2021 with a marginal decline in the number of publications in 2019. It is also observed that the publications approximately tripled in the 12 years period of 2010-2021. However, the annual rate of growth of publications from 2016 onwards shows a declining trend. The highest annual rate of growth (31.3%) was in the year 2015. The compound annual growth rate (CAGR) was found to be 11.13% during the study period of 2010-2021. Except for years 2014, 2015 and 2021, annual growth rate is lower than CAGR for the remaining years.

5. MOST PROLIFIC INSTITUTIONS AND IMPACT OF THEIR OUTPUT

Table 2 list 23 institutions which published 20 or more papers as conference and journal papers. These 23 institutions produced 1,790 papers, slightly more than one-third (37.8%) of the total output. Most of the prolific institutions were Indian Institutes of Technology or National Institutes of Technology except Anna University (an academic institute), Tata Consultancy Services (a private institute) and National Physical Laboratory (a constituent laboratory of CSIR). Among these 23 institutes, Indian Institute of

Table 2. Most prolific institutions and impact of their output.

S. No.	Institutions	TP	TC	CPP	PnC (%)
1	Indian Institute of Science, Bengaluru	272	1967	7.2	49 (18.0)
2	Indian Institute of Technology, Chennai	236	2131	9.0	38 (16.1)
3	Institute of Chemical Technology, Mumbai	161	7523	46.7	0 (0.0)
4	Indian Institute of Technology, Delhi	121	1055	8.7	26 (21.5)
5	Indian Institute of Technology, Guwahati	120	2134	17.8	10 (8.3)
6	Indian Institute of Technology, Kharagpur	119	1981	16.6	12 (10.1)
7	Indian Institute of Technology, Bombay	93	658	7.1	20 (21.5)
8	Indian Institute of Technology, Kanpur	91	685	7.5	11 (12.1)
9	International Institute of Information Technology, Hyderabad	72	955	13.3	9 (12.5)
10	Indian Institute of Technology, Roorkee	52	694	13.4	5 (9.6)
11	Indian Institute of Technology, Dhanbad	51	463	9.1	6 (11.8)
12	National Institute of Technology, Tiruchirappalli	47	1182	25.2	0 (0.0)
13	Indian Institute of Technology , Hyderabad	45	240	5.3	11 (24.4)
14	National Institute of Technology, Rourkela	41	449	10.9	5 (12.2)
15	Vellore Institute of Technology, Vellore	39	867	22.2	5 (12.8)
16	Birla Institute of Technology & Science, Pilani	36	430	11.9	3 (8.3)
17	Annamalai University, Chennai	34	678	19.9	2 (5.9)
18	National Institute of Technology, Warangal	32	1078	33.7	0 (0.0)
19	National Institute of Technology, Karnataka	29	265	9.1	2 (6.9)
20	Indian Institute of Technology, Mandi	27	230	8.5	4 (14.8)
21	Indian Institute of Technology, Gandhinagar	26	335	12.9	1 (3.8)
22	Tata Consultancy Services	26	214	8.2	7 (26.9)
23	National Physical Laboratory, New Delhi	20	243	12.2	0 (0.0)
	Sub-total	1790 (37.8%)	26,464	14.9	226 (12.6)
	Others	2940 (62.2%)	59,869	20.4	964 (32.8)
	Total	4730 (100)	86,333	18.3	1190 (25.2)

*TP = conference papers (CP) + journal papers (JP)

Science (Bengaluru) topped the list with 272 publications closely followed by Indian Institute of Technology (Chennai) with 236 publications. Value of CPP for the total Indian output is 18.3, and for prolific institutions, it is 14.9. It implies that some non-prolific institution published papers which received more citations than prolific institutions. Value of CPP for Institute of Chemical Technology (Mumbai), National Institute of Technology (Tiruchirappalli), Vellore Institute of Technology (Vellore), National Institute of Technology (Warangal) and Annamalai University (Chennai) was more than 18.3, the national value of CPP. For remaining 18 institutions CPP was less than the national value of CPP. Among all the institutes highest value of CPP was for Institute of Chemical Technology, Mumbai followed by National Institute of Technology (Warangal and Tiruchirappalli). Lowest value of CPP was for Indian Institute of Technology (Hyderabad). Value of CPP was less than 10 for several other institutes. This indicates that the impact of these institutes does not commensurate with their output. Of the total papers published by Indian scholars, about 25% papers remained uncited. Among all the 23 institutes, all papers published by Institute of Chemical Technology (Mumbai), National Institute of Technology (Tiruchirappalli), National Institute of Technology (Warangal) and National Physical Laboratory (New Delhi) were cited. Among all the institutes, highest share of uncited papers was for IIT (Delhi, Mumbai, Hyderabad), and Tata Consultancy Services resulting in low CPP for these institutes. Authors explored the reasons for low and high values of CPP for different institutions. A raw analysis of data indicates that institutes having a low CPP published a significant number of papers in conference proceedings which received fewer citations as compared to papers published in the research journals resulting in low CPP. Besides getting low citations, more number of conference papers also remained uncited. On the contrary, institutes having a high CPP published no paper or a very small number of papers in proceedings resulting in high CPP. For instance, of the 272 papers published by Indian Institute of Science (Bengaluru) 162 papers were published in conference proceedings of which about 12.6% papers remained uncited. Institute of Chemical Technology (Mumbai) published all its 161 papers in journals with zero uncited papers resulting in very high CPP. Same argument holds true for high CPP of National Institute of Technology (Tiruchirappalli), National Institute of Technology (Warangal) and National Physical Laboratory (New Delhi).

6. MOST PROLIFIC AUTHORS AND IMPACT OF THEIR OUTPUT

Table 3 lists 20 authors who contributed 20 or more papers published either in conference proceedings or in journals. These 20 authors contributed 639 papers. All the prolific authors were affiliated to prolific institutions except Patil, Hemant A, who is affiliated to Dhirubhai Ambani Institute of Information and Communication Technology, Gandhinagar, Gujarat. Four prolific authors each were from Institute of Chemical Technology, Mumbai, Indian Institute of Science (Bengaluru), and Indian Institute of Technology, Chennai. Two authors each were affiliated to Indian Institute of Technology, Guwahati and Gandhi Nagar respectively. Remaining authors listed in the table were affiliated to other institutes and the names of the affiliating institutes are mentioned against each author. Gogate, P.R. of the Institute of Chemical Technology topped the list with 100 publications. The CPP for the total output is 17.4. Of the 20 prolific authors, CPP was less than 17.4 for 12 authors. Authors explored the reason for low CPP for these 12 authors. Analysis of data indicates that like prolific institutions, authors with low CPP published a significant number of papers in conference proceedings which were less cited than journal papers resulting in low value of CPP. For instance, Ghosh Prasanta Kumar and Seelamantula, Chandra Sekhar both affiliated to IISc Bangalore published 34 papers each in conference proceedings with a CPP of 4.1 and 4.2 resulting in low CPP for these authors. Among all the 20 authors, highest CPP (62.4) was for Pinjari, Dipak Vitthal, followed by Rathod, Virendra K. (58.3), Pandit, Aniruddha Bhalchandra, (54.1) and Gogate, Parag R. (46.8). All these authors were affiliated to ICT, Mumbai (Maharashtra). Lowest value of CPP was for Majumdar, Angshul, of IIIT, New Delhi is indicated by low h-index of the author. The h-index was highest (42) for Gogate, P.R. who had a lower value of CPP as compared to Pinjari, Dipak Vitthal.

Table 3. Most prolific authors and impact of their output.

S.No.	Authors	NP	TC	CPP	h-Index
1	Gogate, Parag R., ICT Mumbai, Maharashtra.	100	4681	46.8	42
2	Ghosh, Prasanta Kumar, IISc, Bangalore, Karnataka.	48	219	4.6	10
3	Prasanna, S. R. Mahadeva, IIT Guwahati, Assam.	42	435	10.4	10
4	Seelamantula, Chandra Sekhar, IISc, Bangalore, Karnataka.	42	194	4.6	8
5	Pandit, Aniruddha Bhalchandra, ICT, Mumbai, Maharashtra.	39	2108	54.1	29
6	Yegnanarayana, B., IIIT Language Technol. Res Centre, Hyderabad, Telangana	34	609	17.9	14
7	Munjal, M. L., IISc, Bangalore, Karnataka.	30	244	8.1	9
8	Patil, Hemant A., DAIICT, Gandhinagar, Gujarat.	30	345	11.5	9
9	Ganapathy, Sriram IISc, Bangalore, Karnataka.	28	128	4.6	7
10	Srinivasan, K., IIT Madras, Tamil Nadu.	26	182	6.7	7
11	Anandan, Sambandam, NIT, Tiruchirappalli,	26	749	28.8	16
12	Balasubramaniam, Krishnan, IIT, Madras, Tamil Nadu.	23	296	12.9	10
13	Moholkar, Vijayanand S., IIT Guwahati, Assam.	23	908	39.5	17
14	Rathod, Virendra K., ICT, Mumbai, Maharashtra.	23	1340	58.3	20
15	Sonawane, Shirish H., NIT, Warangal, Andhra Pradesh.	23	976	42.4	17
16	Thittai, Arun K., IIT, Madras, Tamil Nadu.	22	100	4.6	8
17	George, Nithin V., IIT Gandhinagar, Gujarat.	20	312	15.6	10
18	Majumdar, Angshul, IIIT, New Delhi,	20	67	3.4	5
19	Pinjari, Dipak Vitthal, ICT, Mumbai, Maharashtra.	20	1247	62.4	18
20	Umesh, S., IIT Madras, Tamil Nadu.	20	92	4.6	6
	Sub-total	639	15232	23.8	
	Other authors (Give total)	8455	146739	17.4	
	Total	9094	161971	17.8	

DAIICT: Dhirubhai Ambani Institute of Information and Communication Technology

7. PATTERN OF CITATIONS

Citations are a measure of the impact an article makes on the map of scientific world. It is obtained by counting the number of times the article was cited by other articles. High levels of citations to a scientific publication are interpreted as signs of scientific influence, impact, and visibility. An author's visibility can be measured through a determination of how often his/her publications have been cited in the publications by other authors. Table 4 shows the citation pattern of the papers published on acoustics research during 2010-2021. During this period, 2778 papers published in journals and in conference proceedings received 42,731 citations and the average rate of CPP was 17.8. Of the 2,778 papers 355 (12.8%) papers remained uncited and the remaining papers were cited one or more times. Of these, 945 (34%) were cited between one to five times. Remaining 1,478 papers were cited more than five times. About 29% papers were cited between 11-50 times. About 7% papers were cited more than 50 times. Of these a minuscule number of papers received 100 or more citations.

8. HIGHLY CITED PAPERS

Table 5 lists 14 highly cited papers which were cited 150 times or more. These 14 papers received 3,316 (7.8%) of all citations. Further analysis of highly cited data indicate that of these highly cited papers nine papers were published in Ultrasonics Sonochemistry, a journal published from England with an

Table 4. Pattern of citation.

Number of Citations	Papers	Percent	Total citations
0	355	12.8	0
1	259	9.3	259
2	191	6.9	382
3	168	6.1	504
4	167	6.0	668
5	160	5.8	800
6	115	4.1	690
7	100	3.6	700
8	97	3.5	776
9	84	3.0	756
10	76	2.7	760
11-20	418	15.1	6160
21-50	393	14.2	12590
51-99	145	5.2	9906
100 or more	50	1.8	7780
Total	2778	100.00	42731

Table 5. Highly cited papers.

S. No.	Highly cited research papers (with 150 or more citations)	TC
1	*Claudon, Michel, Dietrich, Christoph F., Choi, Byung IHN, *et al.*, Ultrasound in Medicine and Biology, 39(2) 2013, 187-210. University of Nancy, INSERM, France Indian Author - Nitin Chaubal, Jaslok Hospital and Research Centre, Mumbai, Remarks: There are 26 authors from France, Japan, England, Canada, USA, Germany, South Korea, and India etc.	588
2	*Pilli, Sridhar, Bhunia, Puspendu, Yan, Song, *et al.*, Ultrasonics Sonochemistry, 18(1) 2011, 1-18. INRS Eau, Quebec City, PQ G1K 9A9, Canada. Indian author - Bhunia, Puspendu, IIT Bhubaneswar, Orissa, India.	506
3	Ghosh, Vijayalakshmi, Mukherjee, Amitava, Chandrasekaran, Natarajan, Ultrasonics Sonochemistry, 20(1) 2013, 338-344. VIT University, Vellore, Tamil Nadu, India.	259
4	Bagal, Manisha V., Gogate, P. R., Ultrasonics Sonochemistry, 21(1) 2014, 1-14. Institute of Chemical Technology, Bombay, Maharashtra, India.	249
5	Sahidullah, MD., Saha, Goutam, Speech Communication, 54(4) 2012, 543-565. IIT Kharagpur, West Bengal, India.	202
6	Hingu, Shishir M., Gogate, P R., Rathod, Virendra K., Ultrasonics Sonochemistry, 17(5) 2010, 827-832. Institute of Chemical Technology, Bombay, Maharashtra, India.	184
7	Dey, Soumen, Rathod, Virendra K., *et. al.*, Ultrasonics Sonochemistry, 20(1) 2013, 271-276. Institute of Chemical Technology, Bombay, Maharashtra, India.	184

8	Fatima, S., Mohanty, Amiya Ranjan, Applied Acoustics, 72(2-3) 2011, 108-114. IIT Kharagpur, W Bengal, India.	171
9	*Stirnemann, J., Villar, J., Salomon, L. J., *et al.*, Ultrasound in Obstetrics & Gynecology, 49(4) 2017, 478-486. University of Paris 05, AP HP, Matern Necker Enfants Malad, Paris, France. Indian Author - Manorama Purwar, Government Medical College, Nagpur There are 24 authors from France, England, China, Thailand, Pakistan, Brazil, India etc.	169
10	Desai, Srinivas, Black, Alan W., Yegnanarayana, B., *et al.*, IEEE Transactions On Audio Speech And Language Processing, 18(5) 2010, 954-964. International Institute of Information Technology, Hyderabad 500032, Andhra Pradesh, India.	168
11	*Al-Dhabi, Naif Abdullah, Ponmurugan, K., Ultrasonics Sonochemistry, 34, 2017, 206-213. King Saud University, Department of Botany & Microbiology, College of Science, Addiriyah Chair Environment Studies, Riyadh 11451, Saudi Arabia.34, Indian Author - Jeganathan, Prakash Maran, Kongu Engineering College, Department of Food Technology, Erode, Tamil Nadu, India.	166
12	Kumar, Kshitiz, Srivastav, Shivmurti, Sharanagat, Vijay Singh, Ultrasonics Sonochemistry, 70, 2021, (105325), 1-11. AD Patel Institute of Technology, Department of Food Processing Technology, New Vidya Nagar, Gujarat, India.	165
13	Banerjee, Bubun, Ultrasonics Sonochemistry, 35, 2017, 15-35. Indus International University, Una, Himachal Pradesh, India.	155
14	Subhedar, Preeti B., Gogate, Parag R., Ultrasonics Sonochemistry, 21(1) 2014, 216-225 Institute of Chemical Technology, Mumbai, Maharashtra, India.	150
	Total citations	3316

impact factor of 7.5 and it ranked second by impact factor among the list of publishing journals on acoustic research. Of the 14 highly cited papers, four papers (marked with*) were written in International Collaboration (IC). All the Indian authors who were highly cited were affiliated to most prolific institutions except authors listed at serial numbers (#1), (# 3), (# 9), (# 11), (# 12), and (# 13). Among the 14 authors, seven highly cited authors were from most productive institutes namely Institute of Chemical Technology, Mumbai (4), IIT Kharagpur (2), and IIT Bhubaneswar (1).

9. COMMUNICATION PATTERN OF INDIAN SCHOLARS

Communication pattern of Indian scholars have been examined using two different indicators. These are the publishing country of journals and the Impact Factor (IF) of these journals as obtained from Journal Citation Reports (2022). Journals published from the advanced countries of the West command more respect and mainstream connectivity as compared to journals published from developing countries including India. Impact factor is an indicator of the prestige of the journal. Papers published in journals with higher IF by and large indicate more recognition than papers published in journals with low IF. The findings based on this indicator have been described below.

9.1 Distribution of Output by Journals and Proceedings

Table 6 depicts the distribution of papers by publishing country of journals. Analysis of data on papers published by Indian scholars in the domain of acoustics research indicates that 2,278 papers were published

Table 6. Distribution of papers by publishing country of journals.

S. No.	Publishing Countries	Journal articles	Proceeding papers	Total Papers	Percent of Papers
1	USA	582	571	1153	41.50
2	Netherlands	705	20	725	26.10
3	England	679	3	682	24.55
4	France	0	73	73	2.63
5	Poland	41	0	41	1.48
6	Germany	36	2	38	1.37
7	Greece	0	25	25	0.90
8	Singapore	18	0	18	0.65
10	China	0	5	5	0.18
11	Romania	5	0	5	0.18
12	Russia	4	0	4	0.14
13	Switzerland	3	1	4	0.14
14	Belgium	0	3	3	0.11
15	Australia	2	0	2	0.07
	Total	2075	703	2778	100.00

in 34 journal titles published from 15 different countries of the world. However, India did not find a place in the list of these countries. Highest number of papers were published in journals originating from the USA followed by journals from the Netherlands and the England. About 92% of the papers were published in journals originating from these three countries. Remaining 8% papers were published in journals which originated from other seven countries. These countries were Poland, Germany, Singapore, Romania, Russia, Switzerland and Australia. This indicates that Indian authors have a tight grip on the higher echelon of journals published in the domain of acoustics research published by the developed countries.

9.2 Distribution of Output by Impact Factor

Based on the lowest and highest values of impact factor of journals where 2,075 papers were published, authors divided the impact factor into five categories. These categories are ≤ 1.00 (very low), > 1.00 ≤ 2.00 (low), > 2.00 ≤ 3.00 (medium), > 3.00 ≤ 4.00 (high) and > 4 (very high). Distribution of output according to the range of impact factor is depicted in Table 7. It indicates that only a minuscule proportion (18.7%) of papers were published in low and very low impact factor journals and remaining 81.3% were published in journals with medium, high, very high impact factor journals. This indicates that papers published by Indian scholars in the domain of acoustics are well connected to mainstream science as more than three-fourth of papers appeared in medium, high and high impact journals. Of the total papers published in medium, high and very high impact factor journals, about 25% papers were published in journals with very high impact factor. Table 8 lists 34 journals with their publishing country and impact factor where the research results were published. The results above show that research carried out by the Indian authors is well taken by the scientific community all over the world.

Table 7. Distribution of output by impact factor.

Range of Impact Factor	Category	Number of Papers	Percent of Papers
≤ 1	Very Low	250	12.1
>1 ≤ 2	Low	140	6.7
>2 ≤ 3	Medium	614	29.6
>3 ≤ 4	High	537	25.9
> 4.00	Very high	534	25.7
Total		2075	100.0

Table 8. Most common journals used for publishing research results.

S. No.	Journal Title (Publishing Country)	No. of Papers	Impact Factor
1	Ultrasonics Sonochemistry (The Netherlands)	504	7.491
2	Journal of Vibration and Control (England)	256	3.095
3	Applied Acoustics (England)	193	2.639
4	Journal of Sound and Vibration (England)	178	3.665
5	Journal of the Acoustical Society of America (USA)	135	2.37
6	International Journal of Acoustics and Vibration (USA)	98	0.581
7	Ultrasonics (Netherlands)	87	2.89
8	Speech Communication (Netherlands)	65	2.723
9	Journal of Vibration and Acoustics-Transactions of the ASME (USA)	57	1.583
10	IEEE-ACM Transactions on Audio Speech and Language Processing (USA)	50	3.919
11	Wave motion (Netherlands)	49	2.195
12	Archives of Acoustics (Poland)	41	0.913
13	Journal of Clinical Ultrasound (USA)	36	0.869
14	IEEE Transactions on Ultrasonics Ferroelectrics and Frequency Control (USA)	35	3.688
15	Noise Control Engineering Journal (USA)	34	0.466
16	Journal of Ultrasound in Medicine (USA)	32	2.153
17	Acta Acustica United with Acustica (Germany)	27	0.762
18	Shock and Vibration (England)	27	1.543
19	Ultrasound in Medicine and Biology (USA)	23	2.998
20	Ultrasound in Obstetrics & Gynaecology (USA)	21	7.299
21	Acoustics Australia (Singapore)	18	1.891
22	Journal of Low Frequency Noise Vibration and Active Control (England)	18	2.837
23	IEEE Transactions on Audio Speech and Language Processing (USA)	16	3.919
24	Ultrasonic Imaging (USA)	14	1.825
25	International Journal of Aeroacoustics (USA)	13	1.115
26	Eurasip Journal on Audio Speech and Music Processing (England)	12	2.114
27	Acoustical Physics (USA)	10	0.856
28	Medical Ultrasonography (Romania)	5	1.611
29	Photoacoustics (Germany)	5	8.484
30	Journal of the Audio Engineering Society (USA)	4	0.833
31	Journal of Theoretical and Computational Acoustics (Singapore)	5	1.171
32	Ultraschall in der Medizin (Germany)	4	6.548
33	Sound and Vibration (USA)	2	3.655
34	Phonetica (Switzerland)	1	1.759
	Total	2075	

9.3 Distribution of Papers in Proceedings

Indian authors presented 703 papers at 35 proceedings held in different parts of the globe. Table 9 lists title of four conference proceedings where 50 or more papers were presented. Among these, highest number 444 (63.2%) papers were presented at IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP) from 2010 to 2021, followed by 71 (10.1%) in Annual Conference of the International Speech Communication Association (INTERSPEECH) from 2015 and 2016. A total of 619 papers were presented in the top four conference proceedings, whereas, remaining 84 (12%) papers were presented in rest of 31 different conferences held in different parts of the globe. Largest share of conference papers in IEEE sponsored Conferences is again a sign that quality and premium research is being presented by Indian authors at the various forums and organizations.

Table 9. Distribution of output by conference proceedings.

S. No.	Conference/Proceedings	Number of Papers	% of Papers
1	IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP) from 2010 to 2021	444	63.2
2	Annual Conference of the International Speech Communication Association (INTERSPEECH 2015 and 2016)	71	10.1
3	Proceedings of the 23rdInternational Congress on Sound and Vibration:	53	7.5
4	European Signal Processing Conference (EUSIPCO 2020 and 2021)	51	7.3
	Sub-total	619	88.1
	Other 31 conferences	84	11.9
	Total	703	100.0

10. PATTERN OF COLLABORATION

Of the 2,873 papers published by Indian scientists, 2,088 (72.7%) papers were published in domestic collaboration and 605 (21.1%) in international collaboration. This indicates that the share of papers in domestic collaboration was about three and half times more than those in international collaboration. Details about the pattern of collaboration have been described below.

10.1 Growth Pattern of Domestic and International Collaborative Papers

Pattern of growth was examined for total number of papers in domestic collaboration (TNPDC), total domestic links (TDL), domestic collaborative links per paper (DCLPP), total number of papers in international collaboration (TNPIC), total international links (TIL), and international links per paper (ILPP). Domestic and international links per paper were obtained by dividing the total number of links with the total number of papers. Table 10 presents data on these parameters. It indicates that the number of domestically co-authored papers increased from 97 in 2010 to 250 in 2021 with a compound annual growth rate (CAGR) of 9.9, and the number of internationally co-authored papers increased from 17 in 2010 to 83 in 2021 with a CAGR of 17.2. Thus, the international co-authored papers increased at a faster rate than domestic co-authored papers. The number of total international links also increased at a rate slightly higher

Table 10. Pattern of domestic and international collaboration during 2010-2021.

PY	TNPDC	Total domestic Links (TDL)	DCLPP	TNPIC	Total international links (TIL)	ILPP
2010	97	163	1.7	17	51	3.0
2011	106	177	1.7	12	25	2.1
2012	103	191	1.9	30	50	1.7
2013	108	210	1.9	30	61	2.0
2014	134	268	2.0	42	72	1.7
2015	228	365	1.6	31	52	1.7
2016	221	387	1.8	53	108	2.0
2017	211	425	2.0	61	112	1.8
2018	226	465	2.1	69	143	2.1
2019	210	437	2.1	77	142	1.8
2020	194	440	2.3	100	242	2.4
2021	250	512	2.1	83	195	2.4
Total	2088	4040	1.9	605	1253	2.1
CAGR	9.9	12.1		17.2	14.4	

than the domestic links. Analysis of data for domestic and international links per paper indicate that domestic links per paper varied between 1.7 and 2.3 during 2010-2021, whereas the pattern of links per paper for internationally co-authored papers varied between 1.7 and 3.0. Highest domestic links per paper was in the year 2020 and it was highest in the year 2010 for international collaborative papers.

10.2 Most Prolific Institutions and the Pattern of their Collaboration

Table 11 lists the 23 most prolific institutions along with the values of Domestic collaboration index (DCI) and international collaboration index (ICI). These two measures have been suggested by Garg and Padhi[29] which have been described below. The value of DCI or ICI = 100 suggests that a country's collaborative effort corresponds to world average. DCI or ICI > 100 indicates collaboration higher than the world average and DCI or ICI < 100 reflects less than average collaboration.

Domestic Collaborative Index (DCI)	International Collaborative Index (ICI)
$DCI = \frac{Di \div Dio}{Do \div Doo} \times 100$ where	$ICI = \frac{Ii \div Iio}{Io \div Ioo} \times 100$ where
D_i = Number of domestically co-authored papers for block i;	I_i = Number of internationally co-authored papers for block i
D_{io} = Total output of block i	I_{io} = Total output of block i
D_o = Total number of domestically co-authored papers	I_o = Number of internationally co-authored papers for all the blocks
D_{oo} = Total output	I_{oo} = Total output

Of the total papers published in domestic and international collaboration, these 23 institutions (Table 11) contributed 1676 total collaborative papers. Of these, 1355 papers were published in domestic collaboration and 321 in international collaboration. Among these institutions, Indian Institute of Science (Bangalore) had the highest number of papers in domestic as well as in international collaboration. Almost all the papers by these 23 institutions were published either in domestic or international collaboration. For example, all the 272 papers published by Indian Institute of Science were published either in domestic or international collaboration. The value of DCI for seven institutions was more than 200. These seven institutions were IIT Kharagpur (206), IIT Dhanbad (209), NIT Rourkela (204), NIT Karnataka (211), IIT Mandi (201), Tata Consultancy Services (209) and National Physical Laboratory (215). This indicates that the domestic collaboration for these institutions is much higher than the Indian average. On the contrary, these institutions had a low value of ICI indicating that international collaboration for these institutions is much less than the Indian average. Value of ICI is highest for National Institute of Technology (416), Tiruchirappalli followed by International Institute of Information Technology (250), Hyderabad, Birla Institute of Technology & Sciences (239), Pilani and Indian Institute of Technology (215), Kanpur. This implies that these institutions published more papers in international collaboration than the Indian average.

11. COLLABORATING COUNTRIES FOR INDIA IN ACOUSTICS RESEARCH

Of the 2,778 papers contributed by Indian scholars, 2088 papers resulted in domestic collaboration and 605 papers in international collaboration. However, due to multilateral collaboration in some papers, number of international collaborative papers increased to 893. In a paper individual country is counted

Table 11. DCI and ICI values for different institutions.

#	Primary collaborator	ICP	DCP	TCP	ICI	DCI	TNP
1	Indian Institute of Science, Bangalore	58	214	272	167	178	272
2	Indian Institute of Technology, Madras	44	191	235	146	183	236

3	Institute of Chemical Technology, Mumbai	20	141	161	97	198	161
4	Indian Institute of Technology, Delhi	7	67	74	45	125	121
5	Indian Institute of Technology, Guwahati	23	97	120	150	183	120
6	Indian Institute of Technology, Kharagpur	11	108	119	72	206	119
7	Indian Institute of Technology, Bombay	20	15	35	168	37	93
8	Indian Institute of Technology, Kanpur	25	64	89	215	159	91
9	International Institute of Information Technology, Hyderabad	23	49	72	250	154	72
10	Indian Institute of Technology, Roorkee	7	44	51	105	192	52
11	Indian Institute of Technology, Dhanbad	4	47	51	61	209	51
12	National Institute of Technology, Tiruchirappalli	25	22	47	416	106	47
13	Indian Institute of Technology, Hyderabad	8	37	45	139	186	45
14	National Institute of Technology, Rourkela	3	37	40	57	204	41
15	Vellore Institute of Technology, Vellore	8	31	39	160	180	39
16	Birla Institute of Technology & Sciences, Pilani	11	24	35	239	151	36
17	Anna University, Chennai	6	27	33	138	180	34
18	National Institute of Technology, Warangal	7	24	31	171	170	32
19	National Institute of Technology, Karnataka	2	27	29	54	211	29
20	Indian Institute of Technology, Mandi	3	24	27	87	201	27
21	Indian Institute of Technology, Gandhinagar	4	22	26	120	192	26
22	Tata Consultancy Services	2	24	26	60	209	26
23	National Physical Laboratory, New Delhi	0	19	19	0	215	20
	Sub-total	321	1355	1676	140	171	1790
	Others	284	733	1017	76	56	2940
	Total	605	2088	2693	100	100	4730

ICP: Number of International collaborative Papers, DCP = Number of Domestic collaborative Papers, TCP = Total number of collaboration Papers

Table 12. Pattern of international collaboration.

#	Collaborating countries	Number of papers	Number of papers (%)
1	USA	178	19.9
2	United Kingdom	55	6.2
3	Canada	52	5.8
4	Australia	46	5.2
5	Taiwan	45	5.0
6	China	39	4.4
7	Saudi Arabia	37	4.1
8	Germany	32	3.6
9	France	28	3.1
10	Italy	27	3.0
11	South Korea	25	2.8
12	Singapore	24	2.7
13	Japan	22	2.5
14	Ireland	16	1.8
15	Netherlands	15	1.7
16	Switzerland	15	1.7
	Sub-total	656	73.5
	Other 50 countries	237	26.5
	Grand Total	893	100

only once if it occurred more than once. For example, say USA is occurred two times in a paper, it is counted only once. Here England, Scotland and Wales have been clubbed as United Kingdom (UK). Table 12 lists 16 countries which published 15 (1.7%) or more papers in collaboration. The share of collaborative papers by these countries constituted about three-fourth (73.5%) papers in international collaboration. Among these countries which had collaboration with India, highest share of collaborative papers ~ 20% was with USA. The share of collaborative papers with the UK and Canada was about 6%.

12. KEYWORD ANALYSIS

Keyword analysis gives an idea about the frequency at which specific keywords appear together (co-occurrence) in a designated set of articles or documents and also helps in identifying the research frontiers. Deployment of this technique reveals the formation of clusters, its size, and its interwoven ties among them. More the dense network reflects more ties among various subjects.

There are 11896 keywords including keywords provided by the authors and keywords added by Web of Science. Out of them, 2884 keywords occurred two times, 1490 keywords appeared three times, 983 keywords occurred 4 times, 730 keywords occurred 5 times, 251 keywords occurred 10-19 times, 73 keywords occurred 20-49 times and 25 keywords occurred 50 times or more. The 25 keywords with a frequency of 50 or more are tabulated in Table 13 along with their links and Average Normalized Citation (ANC). Ultrasound and vibration are the two most frequently occurring keywords in this study. Ultrasound refers to sound with a frequency above 20,000 Hz. It is inaudible to human ears as the audible range of

Table 13. Analysis of keywords with frequency greater than 50.

S. No.	Keywords	Frequency	Links	Average normalized citations
1.	Ultrasound	247	456	2.1023
2.	Vibration	106	197	0.9979
3.	Model	98	218	0.7287
4.	Propagation	84	135	0.6993
5.	Design	83	186	0.9823
6.	Identification	75	145	0.8266
7.	Optimization	74	224	3.102
8.	Cavitation	71	227	2.6719
9.	Performance	65	185	1.405
10.	Noise	65	144	0.8059
11.	Classification	64	104	0.9914
12.	Nanoparticles	63	205	2.4125
13.	Algorithm	60	118	0.957
14.	System	58	176	1.5671
15.	Intensification	57	161	3.0441
16.	Stability	57	147	1.2654
17.	Speech	57	85	0.5793
18.	Hydrodynamic Cavitation	54	148	3.2558
19.	Diagnosis	54	99	1.5128
20.	Recognition	54	93	0.7501
21.	Ultrasonication	53	184	3.1758
22.	Extraction	53	144	2.4887
23.	Behavior	52	143	1.119
24.	Kinetics	51	197	2.6129
25.	Degradation	50	181	2.8893

frequencies for humans is 20 Hz to 20,000 Hz. Vibration is used to detect early failure in a system. It indicates that the most important issues tackled by the Indian scientist in acoustics research and related to problems inaudible, invisible to the human senses. Others keywords seems to be mostly related to propagation and quality of sound.

As explained in the VOSviewer manual, "the normalized number of citations of a document equals the number of citations of the document divided by the average number of citations of all documents published in the same year and included in the data that is provided to VOSviewer. Intensification and ultrasonication are the two keywords with highest (> 3) ANC. These are followed by keywords like degradation, kinetics, extraction, cavitation, nanoparticles and ultrasound with ANC less than 3 but greater than 2. There are keywords like vibration, model, propagation, design and identification which have occurred more frequently than the keywords mentioned above, but ANC of these keywords is much less.

13. MAJOR KNOWLEDGE DOMAINS

The analysis of clustering of keywords gives an additional idea about the domains which are more active in a concerned field of research. The active knowledge domains in the field of Acoustics are mapped in Figure 2 through the co-occurrence network of keywords. In addition, Table 14 enlists the major subject categories contributing in the field of Acoustics. It could be observed that mechanics, mechanical engineering, electrical/electronic engineering, multidisciplinary chemistry (including nano-particles, degradation, synthesis, bio-diesel, oxidation etc.) and health sector (radiology, nuclear medicine, medical imaging etc.) are the 5 major players in this filed with contribution of papers (%) as 25.27, 25.10, 23.32, 18.13 and 9.29, respectively. The other major domains are audiology, imaging science, interdisciplinary

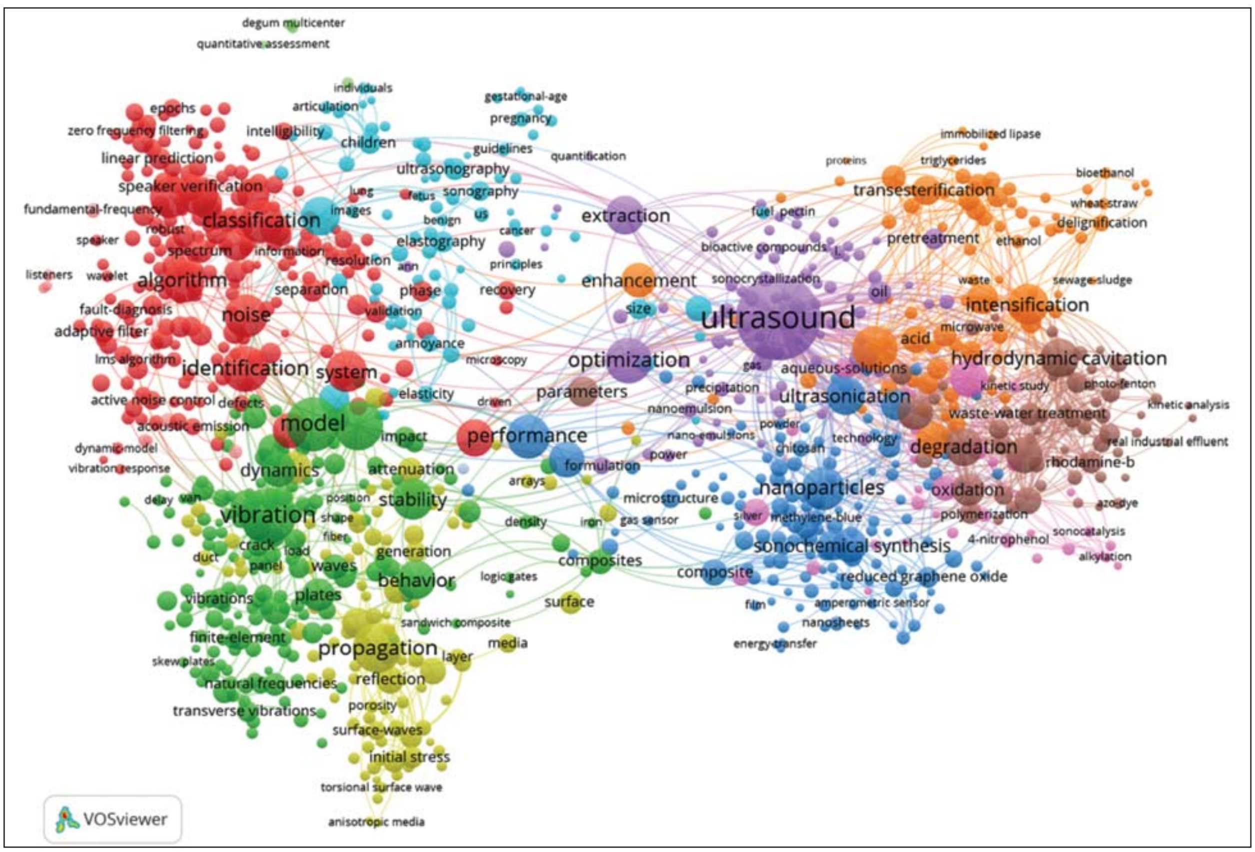

Fig. 2. Mapping knowledge domains in the co-occurrence network of keywords.

Table 14. Subject categories contributing in the field of Acoustics.

S No	Different Subject categories contributing in the field of Acoustics	% of Papers
1.	Mechanics	25.27
2.	Engineering Mechanical	25.10
3.	Engineering Electrical Electronic	23.32
4.	Chemistry Multidisciplinary	18.13
5.	Radiology Nuclear Medicine Medical Imaging	9.29
6.	Audiology Speech Language Pathology	4.77
7.	Imaging Science Photographic Technology	4.14
8.	Computer Science Interdisciplinary Applications	3.66
9.	Computer Science Software Engineering	3.41
10.	Computer Science Artificial Intelligence	2.92
11.	Physics Multidisciplinary	1.78
12.	Linguistics	1.53
13.	Engineering Multidisciplinary	1.43
14.	Obstetrics Gynecology	1.22
15.	Engineering Biomedical	0.94
16.	Telecommunications	0.87
17.	Oceanography	0.59
18.	Engineering Aerospace	0.45
19.	Engineering Marine	0.42
20.	Computer Science Theory Methods	0.38
21.	Remote Sensing	0.24
22.	Instruments Instrumentation	0.21
23.	Mathematics Interdisciplinary Applications	0.17
24.	Physics Applied	0.14
25.	Optics	0.10
26.	Automation Control Systems	0.07
27.	Engineering Civil	0.07
28.	Engineering Industrial	0.07
29.	Geosciences Multidisciplinary	0.07
30.	Biophysics	0.04
31.	Criminology Penology	0.04
32.	Language Linguistics	0.04
33.	Otorhinolaryngology	0.04

computer applications, multidisciplinary physics, linguistics, telecommunication, oceanography, remote sensing etc. Large publications of acoustic research consist of keywords from the domain areas of engineering, thus interweaving closer relationship of engineering and infrastructure developments. Use of acoustic techniques to get the information about the liquid structure, ultrasound as tool for studying electrolyte solutions, and spectroscopy to know the chemical reactions are few applications from the subject domain of multidisciplinary chemistry leaving footprint on landscape of chemistry. Lastly fifth largest subject domain of health sector has also substantial publications. Ultrasound in cancer ailments; pathology and therapeutic uses by diagnostic centres and hospitals are some of reasons for these substantial publications.

14. DISCUSSION

The bibliometric results of this study are based on the papers indexed by Web of Science Core Collection database and it is the first bibliometric study which systematically analyzed the Indian research output in acoustics over the last 12 years period from 2010-2021. The study identified the type of documents, pattern of growth of output, contributing countries, institutions, and authors besides examining their citation impact. It also examined the pattern of citations, highly cited papers and the pattern of domestic and international collaboration. Among the 162 countries which contributed to the publication output in this domain of acoustics, the United States was the most productive country followed by China. Among these countries, India ranked tenth in terms of publication output and the CPP for India was more than several developed countries. The pattern of absolute output shows a continuous rising trend of output during the study period of 2010-2021 with a marginal decline in the number of publications in 2019. Most of the contributing institutions were IITs. Indian Institute of Science (Bengaluru) topped the list but had a low citation impact, as about 60 per cent papers published by IISc were contributed to international conferences which had low number of citations as compared to papers published in scientific journals. Most of the prolific authors belonged to prolific institutions. Of the 14 highly cited papers three papers were published in 2017 and one in 2021 and remaining 10 papers during 2010 to 2016. Of the 2075 papers published in journals, 534 (25.7%) papers were published in journals with impact factor more than seven. This indicates that the output in acoustics research is connected to the mainstream science as the papers published by Indian scholars have appeared in journals published from the advanced countries of the West with high impact factors. Only a minuscule number of papers remained uncited and about seven percent papers were cited more than 50 times. Indian scholars published 893 papers in international collaboration with 66 different countries. Of these, highest share of papers in international collaboration was with the USA.

The keyword analysis shows that ultrasound and vibration are the two most frequently used words whereas intensification and ultrasonication have highest ANC. On the other hand, there are certain keywords with low ANC but high frequency of occurrence such as vibration, model, propagation etc. Similarly, the major sectors in the field are mostly multidisciplinary such as mechanics, mechanical engineering, electrical / electronic engineering, chemistry, health, computer application etc. However, there are certain fields, such as music, perhaps where the application is huge but the current research seems low. The research from India could take advantages of our Vedic wisdom which has been emphasized in many publications[30-32]. Nāda, Shabda, Chants, Sanskrit language, vocal, Rāga, instrumental music, and spirituality, are of varying interest. Exploring these aspects may lead us to new frontiers in the field of acoustics.

15. CONCLUSION

The current study has analyzed present status of research in the domain of acoustics in India. There has been increasing trend of research output except a slight decline in the year 2019. The United States topped the list both in terms of publications output and total citations and India ranked 10th among the 12 prolific countries. Twenty three Indian institutions produced 1,790 papers, slightly more than one-third (37.8%) of the total output. Among these, Indian Institute of Science topped the list with 272 publications closely followed by Indian Institute of Technology (Chennai). Of the 14 highly cited papers, four were published in international collaboration. Research articles have the highest contribution among all forms of publication. Based on the pattern of communication of papers, about 40 per cent papers appeared in journals published from the USA and about 25% papers in journals with impact factor more than four. The share of papers published in domestic and international collaboration during the study period increased considerably. Ultrasound, Vibration, Model, Algorithm, Noise, Classification, Propagation are the major keywords highlighting potential subjects domains of acoustic research. As per findings, Indian authors have been publishing on acoustic research mostly in journals originating from developed countries, however, journals published from India need to pick up pace to match with the best publishing journals.

It is sometimes felt that merger of results of related keywords could have presented more accurate results, which could be considered as a limitation of this study. It is further felt that Indian traditional knowledge and *Vedic* wisdom have still remained under-explored and could open to new frontiers for future.

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Building acoustics : A comprehensive analysis from India and around the world

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ABSTRACT

As urbanization accelerates and environmental concerns become increasingly paramount, the field of building acoustics plays a vital role in creating sustainable and liveable spaces. This paper presents a comprehensive exploration of building acoustics, bridging the gap between India and global practices. We begin by outlining the foundational principles and methodologies that underpin building acoustics, providing a solid framework for understanding how sound management is integrated into architectural and urban design. In the realm of innovations, recent advancements in building acoustics technology are pushing the boundaries of what is possible, offering new tools and techniques for sound insulation, noise reduction, and acoustic comfort. By comparing building acoustics practices and research in India with global trends, this paper highlights the unique challenges faced by the Indian subcontinent and contrasts these with the methodologies employed in other parts of the world. The role of acoustical infrastructures is critical in urban planning, environmental monitoring, and public health initiatives. This paper examines how acoustical strategies are employed to ensure optimal building acoustics, promoting healthier living environments and reducing noise pollution. Through in-depth case studies, we showcase significant projects and breakthroughs, illustrating how innovative approaches to building acoustics are being applied in real-world settings. Addressing current challenges in the field, this analysis also explores emerging trends that are set to shape the future of building acoustics. From balancing acoustic performance with sustainability to integrating acoustics into smart building technologies, this paper offers insights into the evolving landscape of the industry. By presenting scientific data and technical insights, this paper aims to provide a valuable resource for architects, engineers, urban planners, and researchers. It underscores the critical importance of building acoustics in fostering sustainable urban development, bridging the gap between India and the world.

1. INTRODUCTION

As cities around the world grow and urbanize at an unprecedented pace, the role of building acoustics has become increasingly critical in shaping liveable, sustainable, and healthy environments. Building acoustics, which encompasses the control of sound within buildings and the mitigation of noise pollution, is a key factor in ensuring the well-being and comfort of urban residents. This paper aims to establish the importance of building acoustics in modern urban development, with a particular focus on bridging practices between India and global standards. By examining the foundational principles of building acoustics, recent technological innovations, and comparing practices and research across different regions, this study seeks to provide a comprehensive understanding of how acoustics can be leveraged to enhance urban life.

1.1 Objective

The primary objective of this paper is to highlight the critical role that building acoustics plays in urban development. It seeks to demonstrate how effective acoustic design can mitigate the negative impacts of noise pollution, which has been linked to various health issues such as stress, sleep disturbances, and cardiovascular problems (World Health Organization, 2011). Furthermore, this paper will explore how integrating building acoustics into urban planning and design can improve productivity, enhance the quality of life, and contribute to the creation of healthier environments. By bridging the gap between Indian and global practices, this paper aims to foster knowledge exchange and encourage the adoption of best practices worldwide.

1.2 Scope

This comprehensive analysis will cover the following key themes: foundational principles and methodologies in building acoustics, recent advancements in acoustic technologies, a comparative analysis of building acoustics practices in India and globally, the role of acoustical infrastructures in urban planning and public health, in-depth case studies of significant projects, and the current challenges and emerging trends in the field. Each section will provide technical insights and present scientific data to support the discussions, offering a detailed exploration of the multifaceted nature of building acoustics.

1.3 Importance of Building Acoustics

The importance of building acoustics extends beyond mere noise control; it is about creating environments that promote well-being and efficiency. In urban settings, noise pollution is a pervasive issue that affects millions of people daily. According to the European Environment Agency (2020), around 20% of Europe's population is exposed to noise levels that are potentially harmful to health. This exposure has been associated with a range of adverse health outcomes, including increased risk of heart disease, hypertension, and cognitive impairment in children (Basner *et al.*, 2014). In India, with its rapidly growing urban population and high-density living conditions, the challenge of managing acoustic environments is even more pronounced.

Effective building acoustics can significantly improve the quality of life by reducing the stress and health risks associated with noise pollution. It can also enhance productivity in workplaces and educational institutions, where optimal acoustic conditions are crucial for concentration and learning. Moreover, building acoustics plays a vital role in residential buildings, where it contributes to the overall comfort and privacy of inhabitants. By focusing on the integration of acoustic design in urban planning, this paper underscores the importance of acoustics as a key component of sustainable urban development.

2. FOUNDATIONAL PRINCIPLES AND METHODOLOGIES IN BUILDING ACOUSTICS

Definition and Scope : Building acoustics is the science of controlling sound within and around buildings. It involves the management of sound transmission, insulation, absorption, and reflection to create environments that are acoustically comfortable and conducive to their intended use. Whether it is reducing external noise in residential areas, enhancing speech clarity in educational institutions, or controlling sound reflections in concert halls, building acoustics is an integral aspect of architectural design.

Its significance extends beyond mere comfort; it is also about health, safety, and functionality. The proper implementation of acoustic principles can prevent hearing damage, reduce stress, and increase productivity (Beranek & Vér, 2006).

KEY PRINCIPLES

2.1 Sound Transmission and Insulation

Sound transmission refers to the movement of sound waves through different materials and structures. It is a critical aspect of building acoustics, particularly in environments where noise control is essential. Sound transmission class (STC) ratings are commonly used to quantify how well a building component, such as a wall or floor, attenuates airborne sound (Harris, 1991). High STC ratings indicate better sound insulation, which is crucial in residential and office buildings to ensure privacy and reduce disturbance from external noise sources.

2.2 Sound Absorption

Sound absorption is the process by which materials, surfaces, and objects take in sound energy rather than reflecting it. Materials with high absorption coefficients, such as acoustic panels, carpets, and ceiling tiles, are used to reduce reverberation and echo within spaces (Everest & Pohlmann, 2009). Effective sound absorption is vital in spaces where clear communication is necessary, such as classrooms, auditoriums, and meeting rooms. The use of sound-absorbing materials helps create acoustically balanced environments by minimizing unwanted reflections and controlling reverberation times.

2.3 Noise Control Strategies

Noise control involves the reduction of unwanted sound from various sources, both external (traffic, industrial noise) and internal (HVAC systems, machinery). Techniques for noise control include the use of barriers, enclosures, and active noise control systems (Lemaire, 2018). In urban settings, noise control is particularly important to mitigate the effects of traffic noise and other environmental sounds that can negatively impact the quality of life and health of residents. Implementing noise control strategies at the design stage can significantly enhance the acoustic performance of buildings.

2.4 Room Acoustics and Reverberation Control

Room acoustics focuses on how sound behaves within an enclosed space. Key considerations include the control of reverberation times, which is the time it takes for sound to decay after the source has stopped. Optimal reverberation times vary depending on the function of the space: shorter times for clarity in speech-dominated environments like classrooms, and longer times for richness in music venues like concert halls (Kuttruff, 2009). The design of room acoustics involves careful selection of materials, room geometry, and surface treatments to achieve the desired acoustic characteristics.

METHODOLOGIES

2.5 Measurement Techniques for Sound Insulation and Absorption

Accurate measurement of sound insulation and absorption is crucial for evaluating the acoustic performance of building materials and designs. Standardized testing methods, such as the use of reverberation chambers and impedance tubes, allow for precise determination of absorption coefficients and transmission loss values (ISO 354:2003). Field measurements, such as noise level monitoring and sound pressure level (SPL) assessments, are also conducted to evaluate the acoustic environment *in situ*.

2.6 Modelling and Simulation Tools for Acoustic Design

Advanced modelling and simulation tools play a vital role in acoustic design, allowing architects and engineers to predict and optimize the acoustic behaviour of spaces before construction. Techniques such as ray tracing and finite element analysis (FEA) enable detailed analysis of sound propagation, reflection, and absorption (Long, 2006). These tools can simulate the impact of various design elements on room acoustics, helping to identify potential issues and refine solutions. For instance, software such as EASE (Enhanced Acoustic Simulator for Engineers) and Odeon are widely used in the industry for acoustic modelling and simulation.

Standards and Regulations : Building acoustics is governed by a range of international standards that ensure consistency and quality in acoustic design. The International Organization for Standardization (ISO) provides guidelines such as ISO 717 for rating sound insulation in buildings and building elements, and ISO 11654 for sound absorbers for use in buildings. The American National Standards Institute (ANSI) also sets important standards, including ANSI S12.2 for the criteria of sound control in buildings (ANSI/ ASA S12.2-2019). Compliance with these standards ensures that buildings meet the necessary acoustic performance requirements, contributing to safer and more comfortable environments.

These standards not only guide the design and construction of buildings but also serve as benchmarks for evaluating acoustic performance. Adhering to these regulations helps mitigate the negative effects of noise pollution and creates spaces that support the health, well-being, and productivity of occupants.

3. INNOVATIONS AND RECENT ADVANCEMENTS IN BUILDING ACOUSTICS TECHNOLOGY

The field of building acoustics has seen significant advancements over the past decade, driven by the growing demand for quieter and more comfortable living and working environments. These innovations encompass a range of materials, products, and technological tools that improve acoustic performance, optimize sound control, and integrate smart technologies into buildings. This section explores the latest developments in building acoustics, focusing on advanced soundproofing materials, cutting-edge technological tools, and emerging technologies that are transforming the way we approach acoustic design.

MATERIALS AND PRODUCTS

3.1 Advanced Soundproofing Materials

Modern building acoustics heavily relies on advanced soundproofing materials designed to mitigate noise transmission and enhance sound insulation. Among the most widely used materials are acoustic foams and mass-loaded vinyl (MLV).

- ***Acoustic Foams :*** These materials are designed with an open-cell structure that traps sound waves and dissipates their energy, thereby reducing echo and reverberation. Acoustic foams are particularly effective in controlling mid to high-frequency sound waves, making them ideal for use in studios, auditoriums, and other environments where sound clarity is crucial (Saha & Biswas, 2017).
- ***Mass-Loaded Vinyl (MLV) :*** MLV is a flexible, high-density material that is effective in blocking sound transmission. Due to its thin profile and ease of installation, MLV is widely used in walls, ceilings, and floors to prevent noise from passing through. Studies have shown that MLV can achieve sound transmission class (STC) ratings as high as 32-34, significantly enhancing the soundproofing capabilities of building structures (Moeck, 2015).

3.2 Innovations in Building Materials for Enhanced Acoustic Performance

Innovations in building materials have led to the development of products specifically engineered for acoustic performance. For instance, sound-absorbing concrete, which incorporates materials like rubber particles and expanded polystyrene beads, offers improved noise reduction capabilities compared to traditional concrete (Browne *et al.*, 2019). Additionally, the use of composite materials, such as gypsum boards combined with viscoelastic layers, provides superior sound insulation while maintaining structural integrity (Rocca, 2018).

Moreover, advancements in nanotechnology have introduced nano-coatings that enhance the acoustic properties of surfaces by altering their interaction with sound waves. These coatings can be applied to windows, walls, and other surfaces to reduce sound transmission without significantly adding to the weight or thickness of the building components (Pelegrino *et al.*, 2020).

TECHNOLOGICAL TOOLS

3.3 Acoustic Simulation Software

The use of acoustic simulation software has revolutionized the field of building acoustics by allowing architects and engineers to model and predict the acoustic performance of spaces before they are constructed. Software such as EASE (Enhanced Acoustic Simulator for Engineers), Odeon, and SoundPLAN provides detailed analyses of sound propagation, reverberation, and sound pressure levels. These tools use algorithms and ray tracing techniques to simulate how sound interacts with different materials and geometries, enabling precise adjustments to be made to optimize acoustic performance (Yang & Hodgson, 2018).

For example, using EASE, engineers can simulate the impact of different acoustic treatments on a concert hall's sound quality, ensuring optimal listener experience and clarity. Similarly, SoundPLAN can be used to create noise maps for urban planning, helping to identify potential noise issues and implement mitigation measures before they become a problem.

3.4 Smart Building Technologies Integrating Acoustics

The integration of smart technologies into building acoustics has opened new possibilities for real-time noise monitoring and control. Internet of Things (IoT) devices equipped with sensors can continuously monitor noise levels within a building, providing data that can be used to adjust acoustic settings dynamically. These systems can automate the control of sound masking devices, soundproofing mechanisms, and HVAC systems to maintain optimal acoustic conditions based on real-time inputs (Heaton *et al.*, 2020).

Smart acoustic management systems, such as those developed by companies like Ecophon and Saint-Gobain, allow building managers to monitor and control noise levels remotely, ensuring that acoustic comfort is maintained throughout the day. These systems not only improve the acoustic environment but also enhance energy efficiency by optimizing HVAC operations based on acoustic needs.

EMERGING TECHNOLOGIES

3.5 Use of Artificial Intelligence and Machine Learning in Acoustic Analysis

Artificial intelligence (AI) and machine learning (ML) are emerging as powerful tools in the field of acoustics, offering new ways to analyze and manage sound. AI algorithms can process vast amounts of acoustic data to identify patterns and predict noise levels in various scenarios. Machine learning models can be trained to optimize acoustic designs by learning from previous projects and continuously improving based on new data (Cai *et al.*, 2021).

For instance, AI-powered acoustic analysis can be used to automate the identification of noise sources in complex environments, such as industrial plants or busy urban areas. This technology can also facilitate the design of personalized acoustic solutions tailored to the specific needs of a building's occupants, enhancing comfort and productivity.

3.6 Acoustic Metamaterials and Their Applications

Acoustic metamaterials represent a ground-breaking innovation in building acoustics, offering unprecedented control over sound waves. These materials are engineered to have unique properties that do not occur naturally, such as negative refractive indices. Acoustic metamaterials can manipulate sound waves in ways that traditional materials cannot, such as bending, absorbing, or even rendering sound waves invisible (Zhu *et al.*, 2014).

Applications of acoustic metamaterials include the development of ultra-thin soundproofing panels that provide high levels of noise reduction without the bulk of conventional materials. These panels can be used in a wide range of applications, from residential buildings to transportation infrastructure, to enhance acoustic performance without compromising space or aesthetics. Additionally, metamaterials are being explored for use in creating acoustic cloaking devices, which can render objects acoustically undetectable, offering potential applications in both military and civilian contexts.

4. COMPARATIVE ANALYSIS OF BUILDING ACOUSTICS PRACTICES AND RESEARCH: INDIA VS. GLOBAL TRENDS

As urbanization intensifies across the globe, the need for effective building acoustics has never been more pressing. In India, where rapid urban growth has led to increasingly dense living conditions, building acoustics is critical to ensuring the comfort and well-being of inhabitants. This section provides a comparative analysis of building acoustics practices and research in India versus global trends, highlighting current practices, challenges, and opportunities for adopting global innovations in the Indian context. It also examines the contributions of Indian and global research communities, emphasizing the importance of collaboration and knowledge exchange.

CURRENT PRACTICES IN INDIA

4.1 Overview of Building Acoustics Standards and Practices in India

In India, the awareness and implementation of building acoustics are gradually gaining traction, primarily driven by the increased recognition of noise pollution as a significant urban issue. The National Building Code (NBC) of India, last revised in 2016, includes guidelines for sound insulation and control within buildings (Bureau of Indian Standards, 2016). The code outlines standards for sound insulation in walls, floors, and ceilings, focusing on residential, commercial, and industrial buildings. However, these standards are not yet uniformly enforced across all regions, leading to inconsistencies in acoustic performance.

Additionally, local bylaws and state-specific regulations may impose certain acoustic requirements, but these are often fragmented and lack the comprehensive approach seen in international standards. For instance, in major cities like Mumbai and Delhi, the enforcement of noise regulations tends to be more stringent due to higher noise pollution levels. Despite these efforts, there remains a significant gap between the intended regulations and their practical implementation.

4.2 Challenges Specific to the Indian Context

Several challenges impede the effective implementation of building acoustics practices in India:

- ***Urban Density :*** Indian cities are among the most densely populated in the world. High population density and proximity of buildings increase the transmission of noise from one structure to another, making it difficult to achieve effective sound insulation (World Bank, 2020). Urban density also complicates the use of traditional noise control measures, such as barriers and buffer zones, due to space constraints.
- ***Construction Practices :*** The construction industry in India often faces constraints related to cost and material availability, which can lead to compromises in acoustic design. The use of low-cost materials and the lack of specialized acoustic treatments in buildings are common issues. Additionally, construction practices may not always align with the best acoustic standards, leading to poor sound insulation and high levels of internal noise (Singh *et al.*, 2019).
- ***Public Awareness :*** There is a general lack of awareness about the importance of building acoustics among both developers and the public. This often results in acoustics being overlooked in the design and construction phases. Educating stakeholders about the benefits of good acoustics is

crucial to driving demand for better acoustic practices.

GLOBAL TRENDS

4.3 Best Practices from Leading Countries in Building Acoustics

Countries such as the USA, UK, and Germany are at the forefront of building acoustics, with well-established standards and innovative practices:

- ***United States :*** The American National Standards Institute (ANSI) and the Acoustical Society of America (ASA) set rigorous standards for building acoustics, covering aspects such as noise reduction, sound isolation, and speech privacy (ANSI/ASA S12.2-2019). The U.S. Green Building Council's LEED certification also includes points for acoustic performance, promoting sustainable building practices that consider noise control.
- ***United Kingdom :*** The UK's Building Regulations Approved Document E provides comprehensive guidelines for sound insulation in dwellings, schools, and healthcare buildings (HM Government, 2015). The regulations mandate minimum sound insulation levels and encourage the use of sound-absorbing materials to improve internal acoustics.
- ***Germany :*** Germany is known for its stringent noise control standards, such as DIN 4109, which specifies requirements for sound insulation in buildings. German practices emphasize the use of high-quality materials and precision construction techniques to achieve superior acoustic performance (DIN, 2016). Moreover, Germany's commitment to research and development in building acoustics has led to the adoption of advanced technologies and innovative materials.

4.4 How Global Innovations Can Be Adapted to Indian Conditions

Adapting global innovations in building acoustics to the Indian context requires consideration of local challenges and conditions. For example :

- ***Cost-Effective Solutions :*** Given the cost constraints in India's construction industry, adopting affordable soundproofing materials and techniques is crucial. Research into locally available materials that can provide effective sound insulation at a lower cost would be beneficial. For instance, using recycled materials such as rubber or natural fibers in acoustic panels could offer a sustainable and cost-effective solution.
- ***Modular and Scalable Solutions :*** Modular acoustic solutions that can be easily scaled and adapted to different building types are well-suited to the Indian market. Prefabricated acoustic panels and modular soundproofing systems can be quickly installed and customized for various applications, from residential buildings to commercial spaces.
- ***Public Awareness Campaigns :*** Raising awareness about the importance of building acoustics through public campaigns, workshops, and training programs can drive demand for better acoustic practices. Collaboration with industry bodies, academic institutions, and government agencies can help disseminate knowledge and promote best practices.

RESEARCH AND DEVELOPMENT

4.5 Analysis of Research Contributions from India versus Global Contributions

Research in building acoustics is gaining momentum in India, with several academic institutions and research organizations conducting studies on noise control and acoustic design. However, the volume and impact of research from India still lag behind leading countries. According to a bibliometric analysis of acoustics research publications, India accounted for less than 5% of global publications in building acoustics between 2010 and 2020 (Scopus, 2021). In contrast, countries like the USA, China, and Germany have made substantial contributions, driving innovation and setting benchmarks for the industry.

Despite these disparities, Indian researchers have made notable contributions in specific areas, such as the development of low-cost acoustic materials and studies on urban noise pollution (Kumar *et al.*, 2018). Enhancing research capabilities and increasing investment in acoustic research can help bridge the gap and foster innovation in the Indian context.

4.6 Collaborative Efforts and Knowledge Exchange Opportunities

Collaboration between Indian and international research institutions, industry bodies, and government agencies can facilitate knowledge exchange and drive advancements in building acoustics. Initiatives such as joint research projects, international conferences, and academic exchange programs can help Indian researchers access global expertise and resources. Furthermore, partnerships with industry leaders can accelerate the development and adoption of innovative acoustic solutions in India. By leveraging global best practices and adapting them to local conditions, India can enhance its building acoustics capabilities and improve the quality of urban living.

5. THE ROLE OF ACOUSTICAL INFRASTRUCTURES IN URBAN PLANNING, ENVIRONMENTAL MONITORING, AND PUBLIC HEALTH INITIATIVES

As the global population increasingly converges in urban areas, managing the acoustic environment has become a critical component of sustainable urban development. The integration of acoustical infrastructures in urban planning, environmental monitoring, and public health initiatives is essential to address the growing concerns of noise pollution and its impact on human health and the environment. This section delves into the role of acoustics in urban design, the techniques used for environmental noise monitoring, and the implications of noise pollution on public health.

URBAN PLANNING

5.1 Integration of Acoustics in Urban Design and Planning

Urban planning that incorporates acoustics considers the spatial distribution of noise sources and sensitive receptors, such as residential areas, schools, and hospitals. By designing urban landscapes with acoustic comfort in mind, planners can create environments that minimize noise exposure and enhance the quality of life. Acoustical planning involves strategies such as:

- ***Zoning Regulations :*** Designating zones based on noise sensitivity helps in segregating noisy activities (*e.g.*, industrial operations, transportation hubs) from quiet zones (*e.g.*, residential neighbourhoods, parks). This approach reduces the overall noise exposure for sensitive populations (Brink *et al.,* 2018).
- ***Buffer Zones and Sound Barriers :*** Natural or constructed barriers, such as green belts, trees, and walls, can be used to shield residential areas from noise. These buffers not only block noise but also provide aesthetic and environmental benefits (Jang *et al.,* 2020).
- ***Building Orientation and Design :*** Positioning buildings and windows away from major noise sources and using materials with high sound insulation properties can significantly reduce indoor noise levels. Incorporating sound-absorbing materials in building facades, roofs, and interiors is also a key strategy (Öhrström *et al.,* 2006).

5.2 Use of Noise Mapping in City Planning to Mitigate Noise Pollution

Noise mapping is a powerful tool for visualizing and analysing the distribution of noise across urban areas. It helps urban planners identify noise hotspots and evaluate the effectiveness of noise mitigation measures. Noise maps are generated using data from various sources, including traffic flow, industrial activities, and population density.

- ***Strategic Noise Mapping :*** In Europe, the Environmental Noise Directive requires member states to create noise maps for major roads, railways, airports, and agglomerations with more than 100,000 inhabitants (European Environment Agency, 2020). These maps guide the development of action plans to reduce noise exposure and improve the acoustic environment.
- ***Noise Monitoring Networks :*** Real-time noise monitoring networks, integrated with smart city infrastructure, provide continuous data on noise levels. This data can be used to update noise

maps dynamically and assess the impact of urban developments and traffic management policies on noise pollution (Păcurar *et al.*, 2021).

ENVIRONMENTAL MONITORING

5.3 Techniques for Monitoring Environmental Noise

Monitoring environmental noise is crucial for understanding the extent of noise pollution and its sources. Techniques used for noise monitoring include:

- ***Fixed Noise Monitoring Stations :*** These stations are strategically placed in high-traffic areas, industrial zones, and other noise-prone locations to continuously record sound levels. Data from these stations are used to assess compliance with noise regulations and identify trends in noise pollution (Ali & Tamura, 2003).
- ***Mobile Noise Monitoring Units :*** Mobile units equipped with sound level meters can be deployed to various locations to measure noise levels. These units offer flexibility and can be used to monitor noise in areas where fixed stations are not feasible.
- ***Citizen Science and Crowdsourcing :*** Mobile applications and community-based monitoring programs allow citizens to participate in noise monitoring. These initiatives provide valuable data and raise public awareness about noise pollution (Stevens *et al.*, 2013).

5.4 Impact of Noise Pollution on Wildlife and Ecosystems

Noise pollution not only affects humans but also has significant impacts on wildlife and ecosystems. Elevated noise levels can interfere with animal communication, breeding, and feeding behaviours, leading to reduced biodiversity and changes in species composition (Barber *et al.*, 2010).

- ***Disruption of Animal Communication :*** Many species rely on sound for communication, navigation, and predator avoidance. Noise pollution can mask these sounds, making it difficult for animals to communicate, find mates, and detect predators (Shannon *et al.*, 2016).
- ***Altered Ecosystem Dynamics :*** Noise can disrupt predator-prey interactions, leading to changes in population dynamics and ecosystem structure. For example, noise from human activities can deter predators, allowing prey species to thrive and alter the balance of the ecosystem (Francis & Barber, 2013).

PUBLIC HEALTH

5.5 Effects of Noise Pollution on Public Health

Noise pollution is recognized as a major public health issue, with a range of adverse effects on physical and mental health. Chronic exposure to high noise levels is associated with:

- ***Cardiovascular Diseases :*** Studies have shown that long-term exposure to noise increases the risk of hypertension, heart disease, and stroke. Noise-induced stress triggers physiological responses, such as increased heart rate and blood pressure, contributing to cardiovascular problems (Basner *et al.*, 2014).
- ***Hearing Loss :*** Prolonged exposure to loud noise can lead to noise-induced hearing loss (NIHL), which is irreversible. This condition is prevalent in industrial settings and among individuals exposed to high levels of noise in their daily lives (Nelson *et al.*, 2005).
- ***Mental Health Issues :*** Noise pollution can cause sleep disturbances, stress, anxiety, and depression. Sleep disruption, in particular, has been linked to cognitive impairment, reduced productivity, and overall lower quality of life (Stansfeld & Matheson, 2003).

5.6 Policies and Initiatives to Promote Healthier Acoustic Environments

Governments and organizations worldwide are implementing policies and initiatives to combat noise pollution and promote healthier acoustic environments:

- ***Regulatory Frameworks :*** Many countries have established noise standards and regulations to limit exposure to harmful noise levels. For example, the World Health Organization (WHO) has issued guidelines on community noise and environmental noise, recommending exposure limits to protect public health (WHO, 2018).

- ***Urban Noise Action Plans :*** Cities are developing noise action plans to identify noise sources, set targets for noise reduction, and implement measures to achieve these targets. These plans often include public awareness campaigns, traffic management strategies, and noise abatement measures (Omlin *et al.*, 2011).
- ***Designing Quiet Spaces :*** The creation of quiet zones in urban areas, such as parks and green spaces, provides residents with areas to escape noise and enjoy peace and tranquillity. These spaces contribute to mental well-being and offer opportunities for relaxation and social interaction (Dzhambov *et al.*, 2018).

6. IN-DEPTH CASE STUDIES SHOWCASING SIGNIFICANT PROJECTS AND BREAKTHROUGHS

The application of innovative acoustic design solutions in real-world projects has demonstrated the significant impact that thoughtful acoustics can have on urban living, sustainability, and public health. This section presents three in-depth case studies that illustrate successful applications of acoustical design in high-density urban areas, sustainable buildings, and public spaces using noise mapping. These examples showcase how effective noise control strategies, advanced materials, and innovative approaches can lead to improved acoustic environments.

CASE STUDY

6.1 Acoustic Design in High-Density Urban Areas

Example of a Successful Project in a High-Density City: Mumbai : Mumbai, one of the most densely populated cities globally, faces significant challenges related to noise pollution due to its bustling traffic, crowded residential areas, and ongoing construction activities. A notable project that addressed these challenges is the Lodha World Towers complex, located in the heart of Mumbai. This residential skyscraper project implemented a comprehensive acoustic design strategy to mitigate noise from the surrounding environment.

Strategies Used to Achieve Effective Noise Control :

- ***Building Envelope Design:*** The Lodha World Towers incorporated high-performance acoustic glazing, which includes multiple layers of glass with interlayers designed to reduce sound transmission. This glazing achieves a sound transmission class (STC) rating of 45-50, significantly reducing the intrusion of external noise (Nair, 2017).
- ***Use of Sound-Absorbing Materials:*** To minimize noise within the building, sound-absorbing materials were used extensively in common areas such as lobbies, corridors, and recreation rooms. Acoustic ceiling panels, carpets, and wall coverings were chosen for their ability to absorb sound and reduce echo, enhancing the acoustic comfort for residents (Gupta & Kumar, 2018).
- ***Mechanical System Noise Control:*** The building's HVAC systems, a common source of noise in high-rise buildings, were fitted with vibration isolators and acoustic dampers to prevent the transmission of noise through the building structure. This strategy ensured that mechanical noise did not disrupt the residents' living environment (Jain & Singh, 2019).

6.2 Acoustic Innovations in Sustainable Building

Green Building Initiatives Incorporating Advanced Acoustics : The Bullitt Center in Seattle, USA, is a prime example of a sustainable building that incorporates advanced acoustics. Dubbed the "greenest commercial building in the world," the Bullitt Center is designed to meet the Living Building Challenge, which is one of the most rigorous sustainability standards globally. Acoustic performance is a critical aspect of the building's overall sustainability, as it directly impacts occupant health and well-being.

Examples of LEED-Certified Buildings with Exceptional Acoustic Design :

- ***Use of Eco-Friendly Acoustic Materials:*** The Bullitt Center uses sustainable acoustic materials, such as recycled cotton insulation, to provide sound absorption and thermal insulation. This material is not only effective in controlling sound but also contributes to the building's sustainability goals by using recycled content (Brown *et al.*, 2019).
- ***Natural Ventilation and Acoustic Control:*** One of the challenges of sustainable buildings is balancing natural ventilation with noise control. The Bullitt Center utilizes operable windows and louvers that allow for natural ventilation while incorporating acoustic baffles to minimize noise intrusion from the outside. This design ensures a quiet indoor environment without relying heavily on mechanical ventilation systems (Peterson & Lee, 2018).
- ***Daylighting and Sound Control:*** Large windows and skylights provide ample natural light, reducing the need for artificial lighting. To prevent sound reflections and control noise levels, the building's interior features sound-absorbing panels strategically placed to manage acoustics while maintaining visual openness (Johnson & Miller, 2020).

6.3 Use of Acoustic Mapping in Public Spaces

Analysis of a Project Using Noise Mapping for Public Health Improvement : The city of Paris, France, implemented an innovative noise mapping project to address urban noise pollution and its effects on public health. This project, known as "Bruitparif," involved creating detailed noise maps of the city, identifying noise hotspots, and developing targeted noise reduction strategies.

Impact Assessment of Noise Control Measures :

- ***Noise Mapping and Hotspot Identification:*** The Bruitparif project involved deploying over 150 noise monitoring stations across Paris, collecting data on noise levels from traffic, railways, and airports. The data was used to create detailed noise maps, highlighting areas with high noise exposure (Levy-Lambert *et al.*, 2017). These maps provided valuable insights into the spatial distribution of noise and its sources, enabling targeted interventions.
- ***Public Awareness and Participation:*** One of the key aspects of the project was engaging the public through workshops, seminars, and an online platform where citizens could access noise maps and report noise issues. This participatory approach increased public awareness about noise pollution and its impact on health, empowering residents to advocate for quieter neighbourhoods (Cartier *et al.*, 2019).
- ***Implementation of Noise Reduction Measures:*** Based on the findings from noise mapping, Paris implemented several noise reduction measures, including speed limits in residential areas, noise barriers along busy roads, and restrictions on night-time flights at Charles de Gaulle Airport. These measures resulted in a measurable reduction in noise levels, with a reported decrease of up to 3 dB(A) in some areas (De Kluizenaar *et al.*, 2019).

7. CURRENT CHALLENGES AND EMERGING TRENDS IN BUILDING ACOUSTICS

Building acoustics plays a pivotal role in ensuring the comfort, health, and productivity of occupants in various types of buildings. As urban environments become more complex and the demand for sustainable, multi-functional spaces increases, the field of building acoustics faces several challenges and opportunities. This section explores the current challenges in achieving optimal acoustic performance, while balancing sustainability and cost, and identifies emerging trends that are shaping the future of building acoustics.

CHALLENGES

7.1 Balancing Acoustic Performance with Sustainability and Cost-Effectiveness

Achieving high acoustic performance in buildings often requires the use of specialized materials and technologies, which can be costly. This presents a challenge in balancing acoustic requirements with the need for sustainability and cost-effectiveness, particularly in the construction of affordable housing and public buildings.

- ***Cost Constraints:*** High-performance acoustic materials, such as advanced soundproofing panels and specialized insulation, can be expensive. Developers and architects must consider budget constraints when designing acoustic solutions, which can lead to compromises in acoustic quality (Kang, 2017). In many cases, the challenge is to find cost-effective alternatives that do not sacrifice acoustic performance.
- ***Sustainability Considerations:*** Sustainable building practices prioritize the use of eco-friendly materials and energy-efficient designs. However, some sustainable materials may not have optimal acoustic properties. For example, lightweight building materials, which are often preferred for their low environmental impact, may not provide sufficient sound insulation (Eriksson *et al.*, 2019). Integrating acoustic performance with sustainability requires innovative approaches to material selection and building design.

7.2 Integration of Acoustics in Multi-Functional Spaces

Modern buildings are increasingly designed as multi-functional spaces that accommodate a variety of activities, each with different acoustic requirements. For example, open-plan offices, which promote collaboration, need to balance speech privacy with speech intelligibility. Similarly, mixed-use buildings that combine residential, commercial, and recreational spaces must manage diverse acoustic needs.

- ***Flexible Acoustic Solutions:*** Designing for flexibility requires acoustic solutions that can adapt to different activities and occupancy levels. This may involve the use of movable partitions, adjustable soundproofing panels, and adaptive sound masking systems (Parkin *et al.*, 2020). The challenge lies in designing systems that can be easily reconfigured while maintaining consistent acoustic performance.
- ***Sound Zoning:*** Creating acoustic zones within multi-functional spaces can help manage noise levels and maintain acoustic comfort. This involves strategic placement of sound-absorbing materials, acoustic barriers, and sound diffusers to create distinct acoustic environments (Bradley & Wang, 2018). Effective sound zoning requires careful planning and design to avoid conflicts between different activities.

7.3 Addressing the Gap between Academic Research and Practical Application

While academic research in building acoustics has led to significant advancements in understanding sound behaviour and developing new technologies, there remains a gap between research findings and their practical application in the construction industry. Bridging this gap is essential to ensure that the latest acoustic innovations are effectively implemented in real-world projects.

- ***Knowledge Transfer:*** Effective communication and collaboration between researchers, architects, and builders are crucial for translating research into practice. Industry partnerships, workshops, and training programs can facilitate the exchange of knowledge and promote the adoption of new acoustic technologies (Rindel, 2010).
- ***Standardization and Guidelines:*** Establishing standardized guidelines and best practices based on the latest research can help practitioners implement advanced acoustic solutions. Regulatory bodies and industry organizations play a key role in developing standards that reflect current research findings and technological advancements (Cowan, 2016).

EMERGING TRENDS

7.4 Acoustic Solutions for Smart Cities

As cities become smarter and more connected, the integration of acoustic solutions into smart city infrastructure is gaining momentum. Smart cities leverage technology to improve urban living, and acoustics is a critical component of this vision.

- ***Real-Time Noise Monitoring:*** IoT-enabled noise sensors and monitoring systems provide real-time data on noise levels across urban areas. This data can be used to identify noise hotspots, monitor compliance with noise regulations, and inform urban planning decisions. For example, the city of Barcelona has implemented a network of noise sensors to monitor and manage noise pollution as part of its smart city initiatives (P?curar *et al.,* 2021).
- ***Adaptive Noise Control:*** Smart cities can implement adaptive noise control systems that respond to changing noise conditions. For instance, traffic management systems can dynamically adjust traffic flow based on noise levels, and buildings can use automated sound masking systems to maintain acoustic comfort (Bennett *et al.,* 2019). These adaptive systems enhance the quality of life for urban residents by reducing noise pollution and creating quieter environments.

7.5 Increasing use of Biophilic Design Principles to Enhance Acoustics

Biophilic design, which emphasizes the integration of natural elements into the built environment, is gaining popularity for its positive effects on well-being and productivity. Biophilic design principles can also be applied to acoustics, creating environments that not only look natural but also sound natural.

- ***Natural Soundscapes:*** Incorporating natural soundscapes, such as the sound of water, birdsong, or wind, can enhance the acoustic environment and reduce stress. Studies have shown that natural sounds can improve mood, increase concentration, and promote relaxation (Alvarsson *et al.,* 2010). Integrating water features, green walls, and other natural elements into building design can create pleasant acoustic experiences.
- ***Use of Natural Materials:*** Materials like wood, bamboo, and cork are not only sustainable but also have favorable acoustic properties. These materials can absorb sound and reduce reverberation, contributing to a comfortable acoustic environment (Jiang *et al.,* 2019). Biophilic design that incorporates natural materials can achieve both aesthetic and acoustic goals.

7.6 The Role of Virtual and Augmented Reality in Acoustic Design

Virtual reality (VR) and augmented reality (AR) technologies are transforming the field of building acoustics by enabling immersive and interactive acoustic simulations. These technologies allow architects, engineers, and clients to experience the acoustic environment of a building before it is constructed.

- ***Virtual Acoustic Simulations:*** VR technology can simulate the acoustic performance of different design options, allowing users to hear how sound behaves in a space. This immersive experience helps designers identify potential acoustic issues and make informed decisions about materials and layouts (Vorländer, 2020).
- ***Augmented Reality for Acoustic Analysis:*** AR can overlay acoustic data onto real-world environments, providing a visual and auditory representation of how sound interacts with different elements. This capability is useful for on-site acoustic analysis and troubleshooting, enabling quick adjustments to improve acoustic performance (Picinali *et al.,* 2018).

8. PRESENTATION OF SCIENTIFIC DATA AND TECHNICAL INSIGHTS

The analysis of building acoustics relies heavily on scientific data and technical insights to inform design decisions, optimize performance, and assess the impact of sound on occupants and building systems. This section discusses methodologies for data collection and analysis in building acoustics, presents examples of scientific data, highlights key findings from recent studies, and explores the relationship between acoustics and building performance, including energy efficiency.

DATA COLLECTION AND ANALYSIS

8.1 Methodologies for Collecting and Analysing Acoustic Data

Effective acoustic design requires accurate data on sound levels and the acoustic properties of materials and spaces. Several methodologies are used to collect and analyse this data:

- ***Sound Level Measurements:*** The most common method of collecting acoustic data involves the use of sound level meters (SLMs) to measure sound pressure levels (SPL) in decibels (dB). SLMs are used in various settings, from monitoring environmental noise to assessing indoor sound levels in buildings (ISO 1996-1:2016). These measurements provide essential data on noise exposure and are used to evaluate compliance with noise regulations and standards.
- ***Reverberation Time Measurements:*** Reverberation time (RT) is a key acoustic parameter that indicates how long it takes for sound to decay in a space. It is measured using techniques such as impulse response and interrupted noise methods, where the decay of sound is analysed after a loud sound source is stopped. RT measurements are crucial for optimizing the acoustic design of spaces like auditoriums, classrooms, and concert halls (ISO 3382-1:2009).
- ***Acoustic Modelling and Simulation:*** Advanced software tools are used to create acoustic models of buildings and simulate sound behaviour. Programs such as EASE, Odeon, and CATT-Acoustic use ray tracing and finite element analysis to predict sound propagation, absorption, and reflection. These simulations help designers evaluate different acoustic treatments and optimize building acoustics before construction (Vorländer, 2020).

8.2 Examples of Scientific Data on Sound Levels and Their Implications

- ***Urban Noise Levels:*** A study conducted in New York City measured noise levels in various neighbourhoods, revealing that average daytime noise levels in residential areas ranged from 55 to 75 dB(A), exceeding the World Health Organization's recommended limit of 55 dB(A) for outdoor residential areas (WHO, 2018; New York City Department of Environmental Protection, 2020). These findings highlight the need for effective noise control measures in urban planning.
- ***Indoor Acoustic Comfort:*** Research on open-plan offices has shown that speech intelligibility, measured by the Speech Transmission Index (STI), and noise levels, measured in dB(A), are critical factors in employee satisfaction and productivity. An STI value below 0.6 indicates poor speech intelligibility, leading to higher stress and reduced concentration among office workers (Bradley & Wang, 2018). Designing spaces with appropriate sound absorption and masking can significantly improve acoustic comfort.

TECHNICAL INSIGHTS

8.3 Key Findings from Recent Studies on Building Acoustics

- ***Impact of Sound Insulation on Health:*** A study conducted in multi-family residential buildings in Hong Kong found that inadequate sound insulation was linked to increased stress and sleep disturbances among residents (Lam *et al.*, 2017). The study recommended the use of materials with high STC ratings in walls and floors to reduce noise transmission between units, highlighting the importance of sound insulation for health and well-being.
- ***Benefits of Sound Masking Systems:*** In environments where absolute soundproofing is not feasible, sound masking systems have been shown to improve speech privacy and reduce distractions. A study in a hospital setting demonstrated that sound masking reduced patient perception of noise and improved sleep quality, underscoring its effectiveness in healthcare environments (Hongisto *et al.*, 2016).

8.4 Innovative Approaches to Data-Driven Acoustic Design

- ***Machine Learning in Acoustic Analysis:*** The use of machine learning algorithms to analyse acoustic data is an emerging trend. These algorithms can predict sound levels and acoustic outcomes based on large datasets, allowing for more accurate and efficient acoustic design. For example, machine learning models have been used to optimize the placement of sound-absorbing materials and predict the impact of design changes on room acoustics (Cai *et al.,* 2021).
- ***Acoustic Sensing and IoT Integration:*** The integration of acoustic sensors with IoT technology enables real-time monitoring and control of acoustic environments. These systems can adjust sound levels and acoustic settings based on occupancy and noise conditions, providing dynamic acoustic management in smart buildings (Heaton *et al.,* 2020). This approach enhances acoustic comfort and can lead to more energy-efficient building operations.

IMPACT OF ACOUSTICS ON BUILDING PERFORMANCE

8.5 Relationship between Acoustics and Energy Efficiency

Acoustics and energy efficiency are closely related in building design. Effective acoustic treatments can contribute to energy efficiency in several ways:

- ***Thermal and Acoustic Insulation:*** Materials that provide both thermal and acoustic insulation reduce the need for heating and cooling, leading to lower energy consumption. For example, using sound-absorbing materials with high thermal resistance, such as cellulose insulation, can improve both acoustic comfort and energy efficiency (Kosny *et al.*, 2010).
- ***Natural Ventilation and Acoustic Comfort:*** Buildings designed with natural ventilation can achieve energy savings by reducing reliance on mechanical ventilation systems. However, natural ventilation can also introduce outdoor noise into indoor spaces. Acoustic design strategies, such as the use of acoustic louvers and sound baffles, can mitigate this issue, allowing for natural ventilation without compromising acoustic comfort (Peterson & Lee, 2018).

8.6 Acoustic Performance Indicators for Building Assessments

Acoustic performance indicators are essential for assessing the acoustic quality of buildings and ensuring compliance with standards:

- ***Sound Transmission Class (STC):*** STC ratings measure the ability of a building element, such as a wall or floor, to block airborne sound. Higher STC ratings indicate better sound insulation, which is crucial for reducing noise transmission between spaces (ASTM E413-16).
- ***Noise Reduction Coefficient (NRC):*** NRC values indicate the sound absorption properties of materials, with higher values representing greater sound absorption. Materials with high NRC values are used to control reverberation and reduce noise levels in spaces like offices, classrooms, and theaters (ASTM C423-17).
- ***Reverberation Time (RT):*** RT is a key indicator of how sound behaves in a space. Optimal RT values vary depending on the function of the space, with shorter RTs needed for clarity in speech-oriented environments and longer RTs desired for richness in musical performance spaces (ISO 3382-1:2009).

9. CONCLUSIONS

Building acoustics is a critical component of sustainable urban development, impacting the quality of life, health, and productivity of building occupants. As cities grow denser and the need for multi-functional spaces increases, effective acoustic design becomes even more essential. This paper has explored various aspects of building acoustics, from foundational principles to recent advancements, comparative analyses, and the integration of acoustical infrastructures in urban planning and public health. Here, we summarize the key insights, discuss the implications for future research and practice, and issue a call to action for stakeholders in the construction, design, and urban planning sectors.

SUMMARY OF KEY INSIGHTS

9.1 ***Foundational Principles and Methodologies:*** Building acoustics involves managing sound transmission, absorption, and reflection to create comfortable and functional environments. Key principles such as sound insulation, noise control, and room acoustics are essential for ensuring acoustic comfort. Advanced measurement techniques and acoustic modeling tools enable precise analysis and optimization of acoustic performance (Beranek & Vér, 2006; Long, 2006).

9.2 ***Innovations and Recent Advancements:*** The development of advanced soundproofing materials, such as acoustic foams and mass-loaded vinyl, has enhanced the ability to control noise in buildings. The integration of smart technologies, such as IoT-enabled noise monitoring and adaptive noise control systems, represents a significant advancement in managing acoustic environments. Emerging technologies, including AI and acoustic metamaterials, offer new possibilities for innovative acoustic design (Saha & Biswas, 2017; Zhu *et al.*, 2014).

9.3 ***Comparative Analysis:*** A comparative analysis of building acoustics practices in India and globally highlights the unique challenges faced by high-density urban areas, such as those in India. While countries like the USA, UK, and Germany have established robust standards and innovative practices, there is a need for adaptation and localization of these practices to suit the Indian context. Collaborative efforts and knowledge exchange are crucial for advancing acoustic research and practice in India (Singh *et al.*, 2019; HM Government, 2015).

9.4 ***Role of Acoustical Infrastructures:*** Integrating acoustics into urban planning and environmental monitoring is vital for mitigating noise pollution and enhancing public health. Noise mapping and monitoring provide valuable data for identifying noise hotspots and implementing targeted noise reduction measures. The effects of noise pollution on human health and wildlife underscore the importance of acoustic considerations in urban planning (Barber *et al.*, 2010; WHO, 2018).

9.5 ***In-Depth Case Studies:*** Case studies of successful projects in high-density urban areas, sustainable buildings, and public spaces demonstrate the effectiveness of innovative acoustic solutions. Projects like the Lodha World Towers in Mumbai, the Bullitt Center in Seattle, and the Bruitparif noise mapping initiative in Paris illustrate how thoughtful acoustic design can lead to improved living environments and public health outcomes (Nair, 2017; Johnson & Miller, 2020; Levy-Lambert *et al.*, 2017).

9.6 ***Current Challenges and Emerging Trends:*** Balancing acoustic performance with sustainability and cost-effectiveness is a major challenge in building acoustics. The integration of acoustics in multi-functional spaces and the need to bridge the gap between academic research and practical application are critical issues. Emerging trends such as acoustic solutions for smart cities, the use of biophilic design principles, and the role of VR and AR in acoustic design are shaping the future of building acoustics (Kang, 2017; Alvarsson *et al.*, 2010; Vorländer, 2020).

9.7 ***Scientific Data and Technical Insights:*** The collection and analysis of acoustic data are essential for informed design decisions. Sound level measurements, reverberation time, and acoustic modeling provide valuable insights into acoustic performance. The relationship between acoustics and energy efficiency, as well as the use of performance indicators such as STC and NRC, highlights the importance of data-driven acoustic design (ISO 1996-1:2016; ASTM C423-17).

Implications for Future Research and Practice : The growing complexity of urban environments and the increasing demand for sustainable, comfortable, and functional buildings call for ongoing research and development in building acoustics. There is a need to:

- ***Advance Acoustic Materials and Technologies:*** Continued research into new materials and technologies, such as acoustic metamaterials and AI-driven acoustic analysis, is essential for developing more effective and sustainable acoustic solutions. Innovations in materials science and digital technologies will drive the next generation of acoustic products and systems (Zhu *et al.*, 2014; Cai *et al.*, 2021).

- ***Promote Interdisciplinary Collaboration:*** Building acoustics requires collaboration between architects, engineers, urban planners, and acoustic specialists. Interdisciplinary research and practice can lead to more holistic and effective solutions. Academic institutions, industry bodies, and government agencies should foster partnerships and knowledge exchange to address the challenges of building acoustics (Rindel, 2010; Cowan, 2016).
- ***Enhance Education and Training:*** Education and training programs in building acoustics should be expanded to equip professionals with the skills and knowledge needed to implement advanced acoustic solutions. Continuing education and certification programs can ensure that practitioners stay up-to-date with the latest developments in the field (Bradley & Wang, 2018).

Call to Action : Stakeholders in the construction, design, and urban planning sectors must prioritize building acoustics as a key component of sustainable development. This involves:

- ***Incorporating Acoustic Design Early:*** Acoustic considerations should be integrated into the design process from the outset, rather than being treated as an afterthought. Early integration allows for more effective and cost-efficient solutions, resulting in better acoustic performance and occupant satisfaction (Kang, 2017).
- ***Adopting Best Practices and Standards:*** Adherence to established acoustic standards and guidelines, such as those set by ISO and ANSI, is essential for achieving consistent and high-quality acoustic environments. Stakeholders should advocate for the implementation of these standards in building codes and regulations (ISO 3382-1:2009; ANSI / ASA S12.2-2019).
- ***Investing in Research and Innovation:*** Public and private investment in research and innovation is crucial for advancing the field of building acoustics. Funding for research projects, innovation hubs, and pilot programs can drive the development of new acoustic technologies and solutions (Cai *et al.*, 2021; Picinali *et al.*, 2018).

By prioritizing building acoustics, we can create healthier, more sustainable, and more liveable urban environments for future generations.

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Acoustical SODAR Systems: An India and International Perspective

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ABSTRACT

This article presents information on SOnic Detection And Ranging (SODAR) Systems from both an Indian and international perspective. This article covers the fundamentals of the SODAR system, its operating principles, the many kinds of SODARs, various monitoring approaches for measuring the height of the atmospheric boundary layer, applications in air quality management with a case study. Additionally, it addresses the current developments in the SODAR technology, as well as challenges and barriers associated with the SODAR technique.

1. INTRODUCTION

1.1 *The Atmospheric Boundary Layer (ABL)*

The troposphere is the lowest portion of the atmosphere where weather, cyclones, and anticyclones occur. It extends from the Earth's surface to about 15 x 10^3 m, with its height varying by region[1]. One of the main parts of the troposphere is the Atmospheric Boundary Layer (ABL) which is the lowest tropospheric region directly affected by surface heating and cooling[2]. This layer hosts all biological and human activities. The ABL extends from meters to kilometers and is affected by the heat-driven convective mixing during day time and surface-based inversions during night. Turbulence in the ABL transfers water vapor, heat, momentum, and pollutants[3]. Wind speed, pressure, temperature, and humidity varies irregularly with varying height in the ABL. As a result, the study of the ABL is prudent as it directly or indirectly influences the meteorological parameters.

1.2 *Sensor for probing the ABL*

Numerous monitoring methods have been devised to investigate the ABL, offering insights into atmospheric structures and the dynamic processes occurring at local scales. These methods are generally categorized based on their operational approach into *in-situ* and remote sensing techniques. *In-situ* techniques involve elevating sensors or instruments to the desired altitude range. Although *in-situ* methods, such as radiosondes and microwave refractometers, can deliver detailed vertical and spatial profiles, they fall short in providing continuous data, which is crucial for certain applications[4]. Whereas remote sensors can provide data on meteorological variables remotely and consistently in both space and time. Aside from providing continuous data in time and/or space, remote sensing techniques have several other advantages too. SOnic Detection And Ranging (SODAR) is one of the best remote sensing techniques which is internationally recognized and proven cost effective to provide continuous real-time data of air pollution meteorological parameters. It is internationally recognized and recommended by Environmental Protection Agency (EPA) for air quality dispersion modelling in Environmental Impact Assessment (EIA) as is used to determine the ABL height and its varying structures diurnally[5].

2. SODAR FOR PROBING THE ABL

In 1946, Gilman *et al.*[6] developed the first SODAR system, designed to measure the intensity of backscattered sound for vertical analysis of the lower atmosphere. Their study highlighted the superiority of acoustic methods like SODAR for examining the lower atmosphere over other remote sensing techniques. This is because sound waves experience much stronger refractive index fluctuations - about a thousand times greater than electromagnetic waves in the boundary layer-leading to a scattering efficiency that is a million times higher. SODAR, as an active remote sensor, provides real-time visual representations, or echograms, depicting atmospheric dynamics up to several kilometers. It consistently offers accurate ABL height measurements across various weather and site conditions[7-8].

2.1 *Working principle of SODAR*

SODAR operates by emitting sound pulses and analyzing the intensity and frequency of the backscattered signals. This analysis, based on the time it takes for the signals to return, helps assess the radial velocity and thermal structure of the atmosphere. Researchers used an integral equation approach to investigate whether the dispersion of SODAR signals depends on the statistical properties of circular entities[3, 9]. The basic equation onto which SODAR principle relies is

$$P_r = P_t \cdot \sigma \cdot \frac{c\tau}{2} \frac{A.L}{R^2}$$

$$\sigma(\theta) = 0.03\text{k}^{1/3} \cos^2\theta \left(\frac{C_v^2}{C^2} \cos^2\frac{\theta}{2} + 0.13 \frac{C_T^2}{T^2} \right) \text{ x } \left(\sin\frac{\theta}{2} \right)^{-11/3}$$

σ denotes the scattering cross section, C for the speed of sound,   is the pulse width, R is the range, A is the antenna area, L is a factor containing the equipment efficiencies, antenna gain and the atmospheric absorption, P_r is receiving power, P_t is the transmitting power, C_v is wind structure constant, C_T is Temp. structure constant, θ is scattering angle (from the initial propagation direction), k is the angular wave number, T is the temp[3].

A monostatic SODAR system, utilizing a single antenna for both transmitting and receiving signals, emits highly directed, high-power sound bursts (10-20 Watts) at a fixed audio frequency between 1-4 KHz. These sound bursts, lasting around 100 ms and repeated every 4s, can probe the atmospheric layers up to 1 km. The same antenna then detects the backscattered acoustic signals caused by atmospheric turbulence, capturing eddy sizes ranging from 0.1 to 1 m within the inertial subrange. These signals are first conditioned by a pre-amplifier and then transmitted as an analog input to the computer's microphone input terminal[9-10]. The data is subsequently processed and enhanced to provide a visual representation of the turbulent region in real time. Each data point is recorded with an 8-bit resolution and saved in a file named based on the date and time of collection. Figure 1 illustrates the working of the SODAR system.

The online logging SODAR software is presented in Fig. 2 showing the different eight color coded data points generated as per the variation in backscattered sound intensity.

Varied colour codes are assigned to the data points based on the received signal intensity. The captured signal's dynamic range 0-5 V is divided into eight phases, each with its own colour code. Based on the

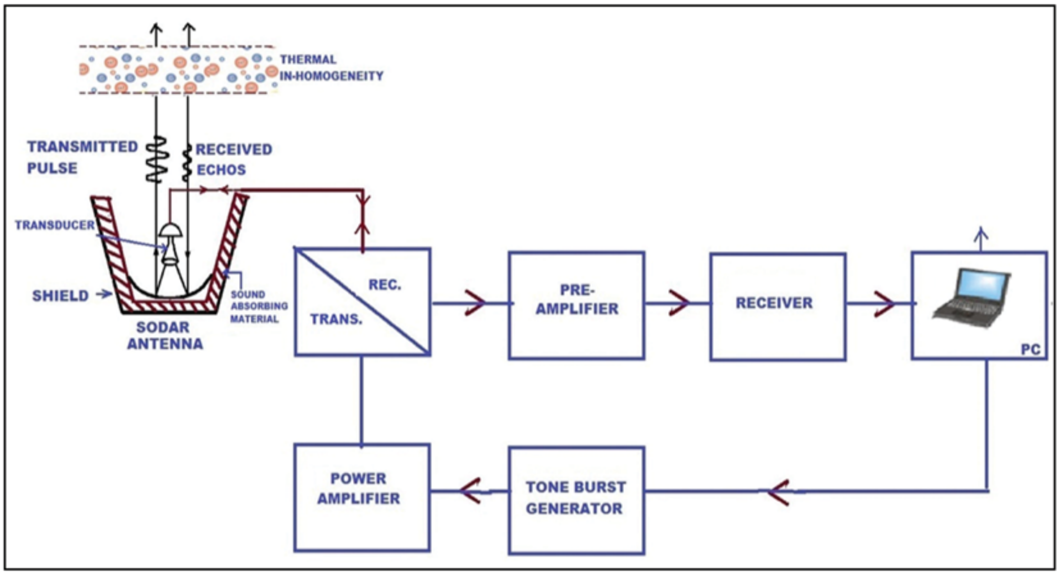

Fig. 1. Flowchart depicting the working of Monostatic SODAR

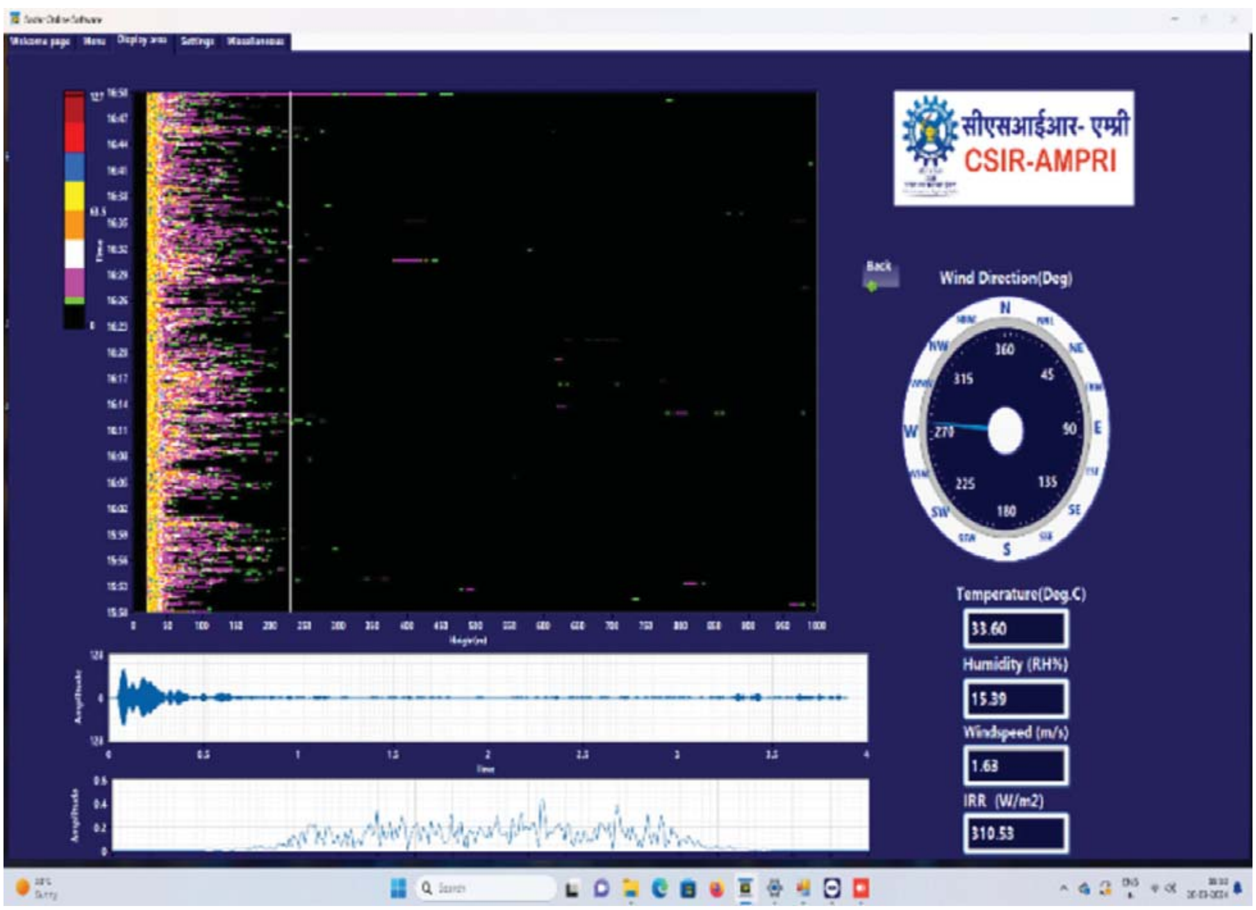

Fig. 2. Online SODAR data logging software

time t elapsed between the transmission of the tone burst and the digitalization of individual data points, the collected data point is assigned a height value of

$$h = {ct}/{2}$$

where c is the speed of sound in air and t is the time lapsed measured in seconds. Every data point with an assigned color is displayed in a 2-D picture in time versus height graphics on the computer screen in real time. Depending on the data sampling rate and tone burst repetition rate, the number of data points captured each scan is shown on the monitor as a horizontal line of coloured dots. By combining numerous scans line by line, a pictorial depiction of the SODAR echograms is developed[10]. Figure 3 shows the SODAR echograms with the CBL and SBL distinguishingly highlighted. Figure 4 shows the entire online SODAR echogram along with the ABLH (shown at the right corner) generated picture along with the

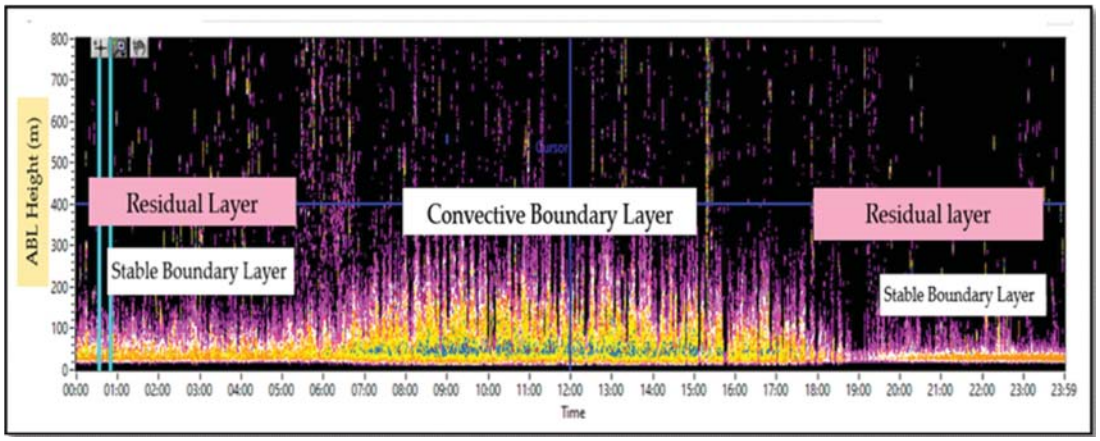

Fig. 3. SODAR echogram showing the diurnal cycle of ABL

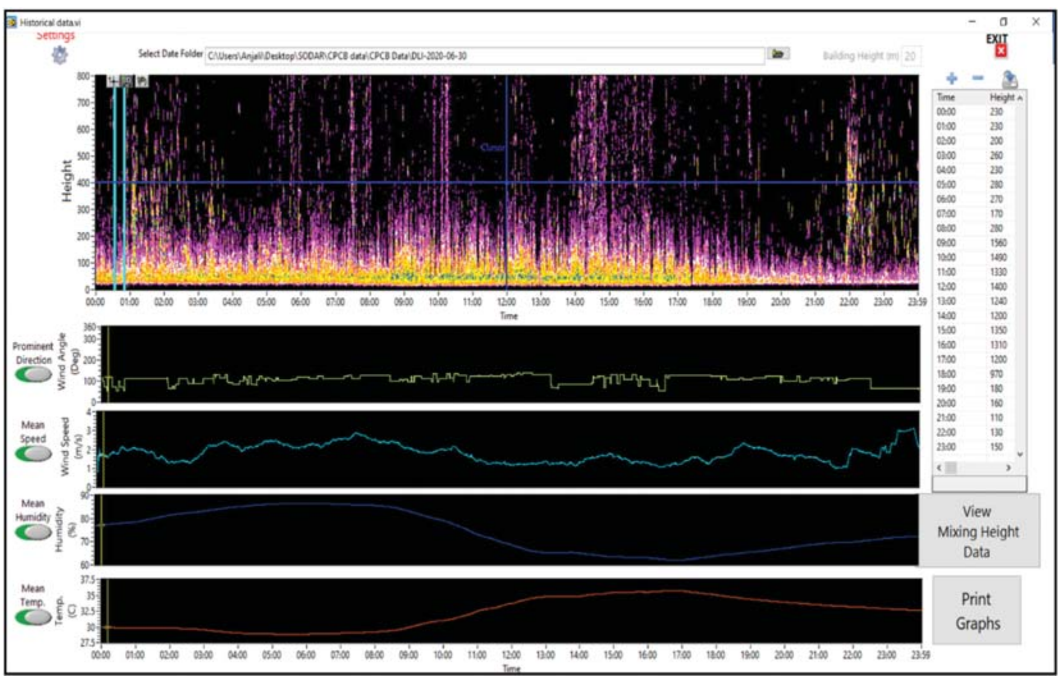

Fig. 4. Offline software for SODAR data analysis with echogram representation

changes in the meteorological parameters (WS, RH, Temp. and wind direction) generated using meteorological sensors.

In hardware and electronics, a narrow band filter reduces noise at unwanted frequencies, enhancing the signal-to-noise ratio. The signals are analyzed to provide a real-time facsimile of the thermal structural dynamics of the ABL[10]. SODAR data is depending on the stability of the lower atmospheric layer, reveals two distinct types of echoes: thermal echoes and shear echoes. Thermal echoes appear as vertical lines, resembling stalagmites, in the facsimile record. In contrast, shear echoes are depicted as horizontal lines, representing the turbulent interface between different air layers[11].

2.2 *Method of determining ABL Height using SODAR Echogram*

SODAR echograms offer insights into lower atmospheric turbulence and contaminant distribution. Due to its reliance on sonic principles, SODAR's effective range is limited to a few 100 m, extending up to 1000 m depending on the power and frequency of the emitted pulse. Data from SODAR needs to be broadly classified into two categories: inversion-time and convection-time. Methods and algorithms for calculating ABL height from SODAR data have been compiled[12-14]. Other classifications of ABL structure include fog-layer, rising-layer, and multi-layer, each requiring a different approach for height estimation. The ABL height is generally derived directly from the echogram, except during the convection period, when thermal plumes may lead to an underestimated value unless they are obscured by a low-level elevated shear echo layer. In such cases, the actual ABL height is determined using an empirical formula[15].

$$y = 4.24\,x + 95$$

where y is the calculated height of the ABL and x corresponds to the observed height of thermal plumes in the echogram. This formula was derived by correlating Sodar data with Radiosonde data.

Figure 5 illustrates the atmospheric conditions depicted on the echogram, showing both stable and unstable states. These conditions reflect the thermal inhomogeneities in the lower atmosphere, driven by various meteorological phenomena.

The Monostatic SODAR system has been operational in Delhi for several months, collecting data both day and night under varying atmospheric conditions. The echograms have clearly distinguished and classified stable and unstable conditions, along with various perturbations and Kelvin-Helmholtz instabilities. Detailed analysis of these echograms, enhanced by software resolution, reveals structures caused by meteorological phenomena, which manifest as thermal inhomogeneities in the lower atmosphere. Figure 7 presents the diurnal variation and structural diversity of the ABL, influenced by changes in wind direction, wind speed, relative humidity, and temperature, for October 17, 2019, covering the period from 0000 to 2359 IST[4].

The primary pattern observed is a "classical" 24-hour cycle with two transition phases occurring between 0700 - 1000 IST and 1600 - 1800 IST. These phases alternate between stable stratification, characterized by evening and nighttime inversion (1900 - 0900 IST), and unstable stratification, driven by daytime convection (0900 - 1700 IST). Local circulation patterns are unclear in this instance, with wind patterns indicating a land breeze from 150 - 250 degrees. Temperature and relative humidity exhibit typical diurnal patterns associated with fair-weather conditions. Within the inversion layer, wind speed increases steadily with altitude, reaching a peak at the layer's upper boundary. Between 0430 - 0630 IST, the wind speed and direction shift as the stratified echo layer begins to dissipate. The ABL's continuous variation throughout the day is evident from these structures[4].

2.3 *Recent advancements and innovations in SODAR*

SODAR's development and experimentation have been documented by numerous experts. In the late 1960s and early 1970s, scientists at the National Oceanic and Atmospheric Administration (NOAA) in the USA established the practical viability of using acoustic sounders to detect winds and monitor temperature inversions by measuring Doppler shifts in the received signals. This led to significant advancements in the engineering design of SODAR systems in the 1970s, and a rise in commercial interest

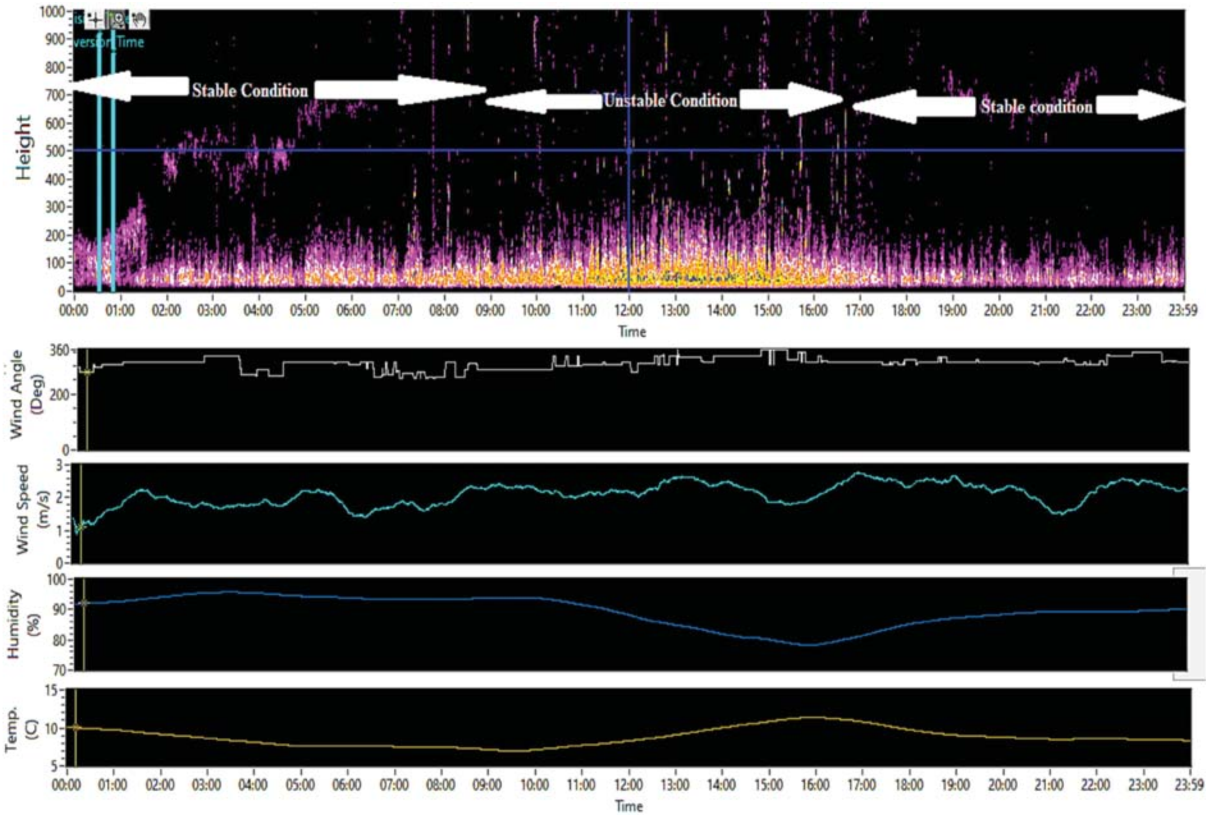

Fig. 5. Stability conditions observation at Delhi

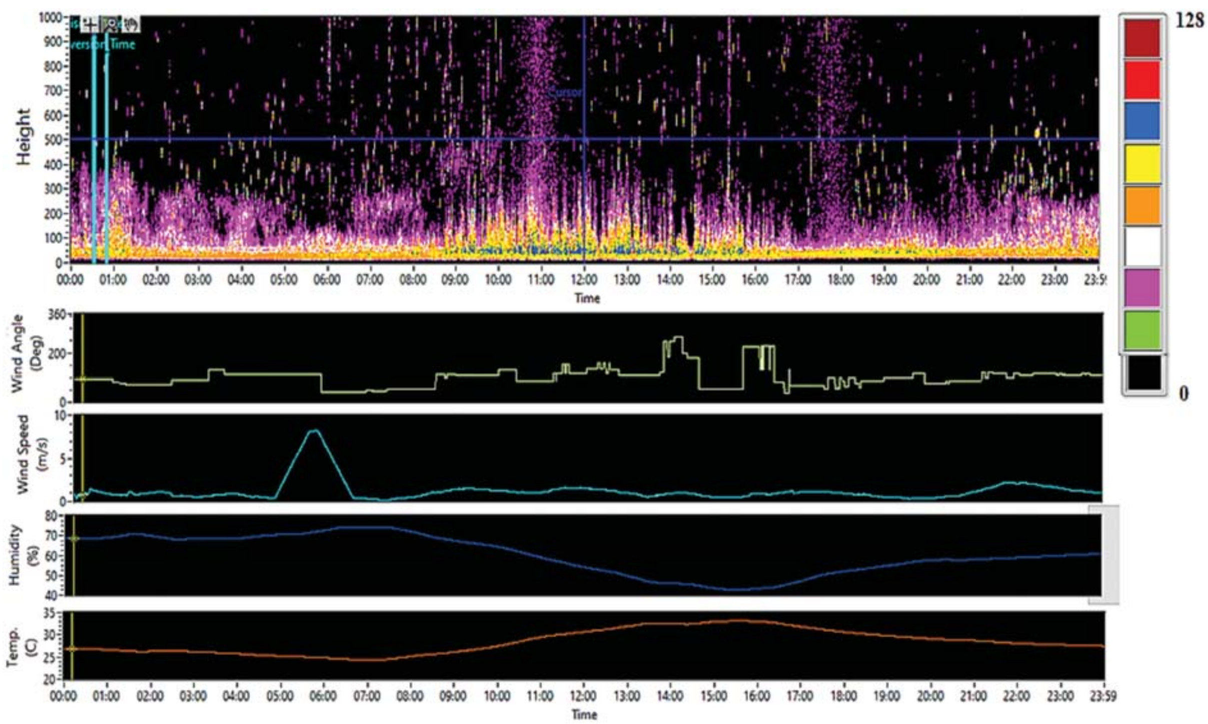

Fig. 6. SODAR echogram observation at Delhi

due to increased academic focus, technological developments, and application potential. Since then, several commercial SODAR systems have been developed by various companies. Simultaneously, commercial SODAR interest arose in response to increased academic interest, technology development initiatives, and anticipated application potential. Bucket antennas were used in the commercial systems. The several commercial SODAR systems and their companies had below since 1970[3, 16-20].

These companies and their SODAR were mostly based on monostatic antenna setups and were primarily used for remote wind profile measurement. Signals from temperature fluctuations were captured by the monostatic configuration. As a result, determining wind speed (through Doppler shift measurement) was solely dependent on backscatter induced by linked temperature changes. During gloomy and strong wind circumstances, however, the atmosphere was primarily neutrally stratified, and signal intensity frequently drops below essential levels for accurate wind speed detection. As a result, Mikkelsen *et al.*[21]

Table 1. Commercial SODAR and their company name with a country.

S. No.	Country	Model and Company/ institute	Remarks
1.	USA	Model 300 AeroVironment Inc.	One of the first commercial devices, designed to measure turbulent structures up to a height of several 100 m.
2.	USA	Mark VII NOAA	The acoustic echo sounder is a portable system that provides an analogue record of backscatter data.
3.	Germany	Scientific Engineering System Inc. (SES)	By adding a microcomputer to the device, the first digital-based acoustic sounder was created.
4.	Germany and USA	SES and NOAA	A three-axis digital-based acoustic sounder is being developed. This device can calculate vertical and horizontal wind speed and direction by detecting both the Doppler shift and backscatter intensities in real-time.
5.	USA	Radian Corporation	SODAR system with three axes based on a microcomputer
6.	USA,	Xonder SODAR system Xonics Inc.	Wind profile and turbulence measurements are possible.
7.	USA	Invisible Tower (AVIT) Aero Vironment Inc.	Three neighboring parabolic dishes are operated consecutively with a three-axis arrangement.
8.	France	REMTECH	Up to 1000 m, a phased array SODAR system capable of sensing Doppler shifts and turbulence parameters, as well as being the first to use multiple-frequency coding.
9.	Germany	Doppler SODAR PCS.2000, Metek	Mobile stand-alone profiling at off-the-beaten-path locations
10.	Germany	Flat Array Sodar SFAS Scintec	The Scintec SFAS is a small acoustic profiler that can monitor wind and turbulence up to 500 m above ground level.
11.	Japan	Kaijo Corporation	The Doppler SODAR is developed.
12.	Australia	Atmospheric Research Pty Ltd	The Doppler SODAR is developed.
13.	USA	Model VT-1 Atmospheric Research & Technology	The Model VT-1 is a monostatic phased-array Doppler SODAR system with a monostatic antenna

created a new SODAR that was based on a Bi-static antenna design. A Bistatic SODAR configuration received and sound scatters from wind turbulence . Therefore, it continues to receive adequate backscatter signals even during high wind speed induced neutrally stratified conditions.

The integrated product of SODAR and RADAR termed RASS for measuring both wind and temperature profiles resulted from continuing R& D advances in technology as well as signal processing approaches[1]. The RASS operated at frequencies about 1 GHz, was rapidly becoming a common profiling tool for monitoring both temperature and wind profiles in the ABL[22]. SODAR technology had progressed quickly, and a variety of commercial versions are now available.

Singal and Pancholy[23] also experimented with sound waves to investigate the atmosphere in India. The classic monostatic SODAR was created at the Council of Scientific and Industrial Research - National Physical Laboratory (CSIR-NPL), New Delhi[24, 25]. The SODAR equipment and software were upgraded using the virtual LabVIEW platform as technological development tools improved[26-27]. In India, the SODAR system was used for ABL monitoring over the past five decades, with ongoing research and development efforts in SODAR technology application. The technology and software were deployed in industrial and institutional areas to determine the carrying capacity of air pollution, as well as the stability class for dispersion modelling. SODAR encountered issues like inherent noise and time utilising image-processing. An alternative way using Kalman filters was developed in 2002 to extract the ABL. As a result, time-consuming picture processing steps are skipped, allowing for speedier real-time interpretation of atmospheric conditions from ABL. Mukherjee *et al.*[28] used adaptive filtering technique with the use of Kalman filter to filter the noise from SODAR thereby enabling accurate estimation of mixing height. Later, the limitations encountered in the Kalman filter was removed by designing fuzzy logic based adaptive scheme. Kumar *et al.*[29] assessed and compared various structures of ABL using four feature selection approaches and eight classification methods, which could lead to an automated structure classification system for atmospheric and pollutant studies. In order to extract 133 statistical features from these echograms, 1698 SODAR echogram images were screened and evaluated.

2.4 *Applications of SODAR in atmospheric studies, including wind profiling and boundary layer analysis*

The SODAR technology has a diverse array of applications within the field of atmospheric research, with a particular emphasis on the examination of wind profiles and the investigation of the ABL.

a. ***Prediction of air pollution and civil aviation via weather surveillance :*** Advancements in SODAR technology have enabled its use in predicting severe air pollution and assessing civil aviation conditions by analyzing anomalies in echogram structures. A notable study involved examining fog conditions and related anomalies over Delhi in December[30].

b. ***Predicting natural calamities :*** SODAR is utilized to study and predict natural calamities. It was deployed to investigate an unprecedented tornado over Delhi and surface undulations observed in March 1978. The observations revealed atmospheric turbulence caused by the tornado occurring both randomly and periodically[30]. Gera *et al.*[7] reported a unique atmospheric wave using a monostatic SODAR installed at Vapi on January 25, 2001, a day before the Bhuj earthquake on January 26, 2001. At Gauhati University, SODAR echograms were used to predict earthquakes, where earthquake-induced gravity waves were observed. Additionally, a monostatic SODAR was employed to study the effects of thunderstorms on VHF signal propagation over the coastal areas of the Bay of Bengal, enabling the prediction of thunderstorm onset[32].

c. ***Associating Meteorological parameters with SODAR derived ABL height :*** In a study conducted in Delhi, SODAR-derived intensity information was used to examine the temperature structure parameter of the area by applying moisture correction and the refractive index structure parameter[33]. It was discovered that during moist weather with light wind and steady stratified layer conditions, SODAR echograms revealed unique dot-shaped echoes. These echoes indicated that the back-scattered acoustic energy resulted from correlated changes in temperature and humidity due to turbulent mixing in the inertial subrange. These dot-shaped echoes, representing clusters of water vapor transported by the wind in the boundary layer[25, 34]. In 1986, a study on the effects of wind speed on the formation of these structures found that surface wind speeds of 2.5 m/s or less (under stable conditions) were the dominant factor in forming most shear echoes. Additionally, the influence of meteorological parameters on ABL height was studied at Kolar Gold Fields, along with the estimation of the dispersion coefficient[35].

d. ***SODAR as tool for air quality management :*** Studies began to get diverted towards establishing a correlation between pollutant concentration and ABL stability aiding as a key factor for air quality management. In 1986, Singal[15] figured a correlation between surface level concentration of CO to the stability of ABL, where SODAR was used as a powerful tool to map the dispersive condition of lower atmosphere. SODAR determined stability in the atmosphere and mixing height were considered as two basic parameters to study the distribution and concentration of particulate matter at Delhi. Prominence of ABL height in air quality improvement expedited numerous experiments to indulge ABL height for air quality studies. During an experiment to predict the monthly average Suspended Particulate Matter (SPM) concentration using two separate models, IITST and ISI (ASME), SODAR was employed to assess the ABL height. At the Kaiga Nuclear Power Project site, a SODAR system was built to investigate the dispersion properties of air effluents and the effects of local topography on dispersion patterns. Soni *et al.*[36] studied ABL's influence of on ground concentrations of air pollutants (SO_2, NO_2, Suspended Particulate Matter (SPM), Respiratory SPM(RSPM)) as well as on meteorological parameters (Temp., Wind speed and Relative Humidity) over Delhi during two (Spring and Summer) seasons. SODAR retrieved ABL height was used to study the change in pollutant concentration in the ambient air during Diwali festival in India. The temporal variation in the concentration of various pollutants (TSP, PM_{10}, SO_2 and NO_2) during pre-Diwali, Diwali, post Diwali and foggy days are studied from 2002-2007 by establishing a correlation between ABL height, meteorological parameters, and Pollutant concentration[37]. Goyal *et al.*[38] used SODAR derived mixing height as one of the methods for determination of ventilation coefficient (VC) to determine the assimilative capacity of Gangtok city. SODAR was used in a case study to investigate pollutant dispersion modeling.

SODAR was used at open cast coal mining site as a part of Dudhichua project and Bharatpur opencast project to determine the dust emission factors over four different seasons. SODAR was used to determine the stability class at four different seasons (post-monsoon, winter, summer and monsoon) pertaining to both the projects. A Doppler and monostatic SODAR was used to analyse different parameters (wind speed, wind direction, mixing height and VC) over different coal mines of Jharia namely Indian Reserve of coking coal, Bharat coking coal Ltd. open cast coal project for coking coal, Jharia, Jharia coal field, and Dhanbad[39]. At the Rajpura mine, a Doppler SODAR (sound detection and ranging) was placed to gather detailed micro-meteorological data, including mixing height for air quality modelling. SODAR was utilized to calculate the micro-meteorological data, including the mixing height, in a similar study conducted in Rajpura to build empirical equations for determining emission rate from various open cast mining operations.

In a study on aerosol optical depth measurements over different wavelengths over different locations of central India region ranging from Delhi to Hyderabad as a part of ISRO-GBP, the mixing height over these regions were also extracted using SODAR. Doppler SODAR was used to determine the ABL height during a campaign conducted for Aerosols, gases and radiation Budget over India under ISRO's Geosphere Biosphere Programme.

e. ***Wind Profiling studies and Engagement of Doppler SODAR :*** The use of SODAR on wind profiling and its related studies in India started early at 1983[15]. Singal *et al.*[25] carried studies on wind shear using monostatic SODAR where 2 years (May 1977 to April 1979) of prolonged SODAR data were analysed. One of the finest modifications in SODAR was achieved when CSIR-NPL in New Delhi, India built a three-axis Doppler SODAR based on a personal computer that worked in Doppler mini SODAR mode. The frequency shift in the signal received after scattering was extracted using the rapid Fourier transform approach[31]. Doppler SODAR are meant for wind speed and wind direction relation studies. Goyal *et al.*[38] mentioned Doppler SODAR to study the diurnal variation of horizontal wind speed and direction for the onset of sea breeze. At Gadakani, for the first time, the variations in vertical structure of the mean wind and its diurnal fluctuation from the surface to the lower stratosphere between the dry and wet spells of monsoon were documented using SODAR along with a set of other unique measurements derived from automated weather stations, Lower atmospheric Wind profiler, Indian Mesosphere Stratosphere Troposphere (MST) Radar (AWS, SODAR, LAWP, and IMSTR). Doppler SODAR was subsequently used to investigate dominant mechanisms that results in the occurrence of Jets in the lee side of Western Ghats of India. Using wind speed data gathered using the SODAR technology, wind characteristics in Kayathar, Tamil Nadu, India was analyzed. Pithani *et al.*[40] used mini SODAR for obtaining wind profiles in the surface layer at a vertical resolution of 5 m, to evaluate the performance of four Planetary Boundary layer (PBL) parametrization and five cloud microphysics schemes in Weather Research Forecasting for a detailed analysis on fog event occurred at Barkachha, a rural area over Indo Gangetic Plain (IGP) on 4-6 December 2014. Babu *et al.*[41] intended to design a phased array antenna for Doppler SODARs for effective wind profiling. Antenna has been designed in such a way that it had 8 x 8 array tweeters and the mathematical algorithms used for designing has been computer using MATLAB.

National Atmospheric Research Laboratory (NARL) installed a multifrequency phased-array Doppler SODAR for monitoring the lower atmosphere. The SODAR was developed in collaboration with the Society of Applied Electronics Engineering and Research (SAMEER), that generated 100 W acoustic power and provides wind profiles up to 1 km under favourable atmospheric conditions.

Doppler SODAR was also used to study the structure of Nocturnal Boundary Layer (NBL) as well, its seasonal variation, characteristics of different types of NBL. Shravan and Anandan[42] investigated the NCEP/NCAR Reanalysis wind components at 1000 mb level in a complex terrain environment of an Indian Tropical Latitude station, Gadanki in comparison with National Atmospheric Research Laboratory (NARL) Doppler SODAR data for a period of one year (2007). During stable and unstable situations, the influence of complex terrain effect on wind flow patterns were estimated by NCEP/NCAR reanalysis II in comparison to remote sensor (NARL Doppler SODAR). Kytoon and Doppler SODAR observations were obtained in Kharagpur as part of the MONTBLEX-90 (Monsoon Trough Boundary Layer Experiment-1990) observational program. The stability, temperature structure function (C^2_T), and velocity structure function (C^2_v) of the atmospheric boundary layer are studied using these data. It was found that on most days, C^2_T follows a $Z^{-4/3}$ law, whereas C^2_v does not follow a systematic pattern. The inconstancy in the ABL over the coastal station of Thumba, with special attention towards the changes brought about during low level jets were studied using Doppler SODAR inclusive of tethersonde and low based micro-meteorological instrument. The seasonal change of vertical and horizontal wind speed over the coastal boundary layer is studied using a Doppler SODAR deployed at IGCAR Kalpakkam. During the study, vertical profiles were used to investigate the variation in mean horizontal wind speed with height over different seasons.

3. CHALLENGES AND BARRIERS TO SODAR TECHNIQUE

Despite numerous applications offered by SODAR, it encounters specific challenges. One significant limitation of SODAR is its limited vertical range, which is below the typical normal midday mixing heights and of poorer quality in measuring wind variance (standard deviation of crosswind component). Accurately determining surface fluxes of momentum and heat using SODAR data remains challenging. Reflectivity calibration for received power information requires humidity and temperature profiles, acoustic calibration of the transducer efficiency, and precise acoustic attenuation knowledge, leading to inherent errors in SODAR measurements of temperature structure parameter *C*. Additionally, due to lower sensitivity during the day caused by ambient noise, SODAR's range is restricted, resulting in underestimated measurements of thermal plume heights unless capped by a low-level elevated shear echo layer. Selecting an appropriate site for Doppler SODAR installation to ensure reliable wind profile acquisition also remains a challenge.

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'Sacred Sound' on 'Sacred Grounds': Acoustical, soundscaping and metaphysical perspective

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ABSTRACT

'Sacred Sound' is an essential element of 'Sacredness' of 'Sacred Grounds'. The pursuit of acoustically characterizing, the experience of the 'Sacred', that a devotee yearns for in a worship space, involves dynamic research on how the acoustic environment and the liturgy of worship in a worship space is optimized, through an interplay between architectural design, sound decay behaviour (in accordance with ISO 3382 set of standards), binaural reception and aural-affective-metaphysical perceptions (applying and extrapolating the soundscaping methods outlined in ISO / TS 129133-1 / 2 / 3). This study presents a relevant methodology (to comprehensively investigate the revitalising character of a worship space) and few significant investigations, from cross-cultural case studies of 16th - 18th century churches in India, Europe, and America; 20th century Buddhist monastery of Bomdila, Arunachal Pradesh; Ancient Sacred Grove of Holy Cross Baradi, Goa; and Sacred Grounds of 3rd century BC, Sanche Stupa, India. This cross-cultural multi-disciplinary research built on trained sonological competence to comprehend 'Sacred Sound' on 'Sacred Grounds', offers a scope of an adventurous domain for dialogue between Science (Reason) and Spirituality (Faith) with a rewarding prospect of identifying, preserving, and designing sacred spaces which revitalise and harmonise a human soul and humankind.

1. INTRODUCTION

'Sacred Grounds' or 'Worship spaces' is a space meant to facilitate effective liturgical activities for the spiritual nourishment of the participating devotee or congregation. This mystical nature of a worship space makes, building a house of worship or marking the ground as 'sacred', an occasion of worship for the architect, builder, priest and the community. Richer the liturgy of worship, brighter will be the acoustical heritage at a given worship space; and richer the acoustics, deeper will be the soul-quenching experience of the 'Sacred'. 'Sacred Sound' is an essential element of 'Sacredness' of 'Sacred Grounds'.

In 2001, I was stationed as Parochial Vicar at All Saints Church, Doranda, Ranchi, when one young engineer, Ravi Baxla asked me: "Why is it that some worship spaces revitalise a devotee, while some do not?". This questioned triggered my pursuit. I shared my interest with my mentors, Prof. S. Rajagopalan, Prof. S. Sharma and Prof. A. O. Carvalho. Consequently, I chose to study acoustical characterisation of worship ambience[1].

A good number of research studies have tried to characterize acoustics in different types of worship spaces[2-10]. Most of these studies have tried to analyse the physical impulse response in a worship space. A few studies have tried to relate the impulse response with the architectural dimensions and with the subjective acoustical qualities of the worship space. A sublime experience of the Divine in a revitalising worship space, to be acoustically understood, requires extrapolation of acoustical standards to encompass aesthetics of worship. A relevant question to answer would be: *How do acoustics of a worship space revitalise the soul of a devotee to experience the 'Divine'? How should it 'sound' like in each worship space for it to be truly considered as 'sacred ground'?*

The pursuit of acoustically understanding and characterizing the experience of the 'Sacred' that a devotee yearns for in a worship space, involves dynamic research on how the liturgical acoustical functionality of a worship space is optimized through an interplay between architectural dimensions, sound decay behaviour, binaural reception and aural-affective-metaphysical perceptions.

2. ACOUSTICAL CHARACTERISATION & SOUNDSCAPING OF 'REVITALISING WORSHIP AMBIENCE': METHODOLOGY & SIGNIFICANT INVESTIGATIONS

The methodology and a few significant cues, from case studies of cross-cultural research, presented here involve 16th - 18th century churches in India, Europe, and America; 'Koothambalams' of 12th century classical Kerala temples; 20th century Buddhist monastery of Bomdila, Arunachal Pradesh (built as a replica of a much older Tibetan monastery called Tsona Gontse Monastery located in Tsona, Southern Tibet); Sacred Grove of Holy Cross Baradi, Goa; and Sacred Grounds of Sanche Stupa, India[11-22, 28-30].

2.1 *Methodology*

A thorough acoustical investigation unearths important descriptors and predictors to understand the relationship between monaural acoustic measures, binaural psycho-acoustic measures and aural-affective-metaphysical perceptions which define the revitalising 'Sacred Experience' in a worship space.

A methodology to comprehensively investigate the revitalising character of a worship space involves the following tasks:

i. *Examine the architectural and building character defining elements, to assess the architectural impact on the acoustical functionality of the enclosed worship space.*

In case studies presented here, the important architectural dimensions that were considered are shown in Table 1.

ii. *Monaural measurements of the acoustical impulse response carried out in the empty enclosed space, to assess the natural noise ambience and the behaviour of sound under variations of source and recording locations, in accordance with ISO 3382 set of standards[23].*

In the case studies presented here, the acoustical impulse was released from laptop-based acoustical software ARTA version 1.9.2 (ARTALABS, Croatia and ASIO Interface Technology by Steinberg Media Technologies GmBH) through a

Table 1. Architectural dimensions.

ABS_{TOT}	-	Total Absorption
C_{ABS}	-	Average Coefficient of Absorption
A_{TOT}	-	Surface Area
A_{NV}	-	Surface Area of Church Nave
H_{MAX}	-	Maximum Height
H_{NV}	-	Maximum Height of Church Nave
L_{MAX}	-	Maximum Length
L_{NV}	-	Length of Church Nave
V_{TOT}	-	Volume
V_{NV}	-	Volume of Church Nave
H_{AVG}	-	Average Height
W_{NV}	-	Maximum Church Nave Width
W_{AVG}	-	Average Width
W_{MIN_NV}	-	Minimum Church Nave Width
$W_{AVG\ NV}$	-	Average Church Nave Width
$H_{MIN\ NV}$	-	Minimum Church Nave Height
$H_{AVG\ NV}$	-	Average Church Nave Height
$L_{NV:\ HNV}$	-	Church Nave proportions (Length / Height)
$L_{NV:\ WNV}$	-	Church Nave proportions (Length / Width)
$W_{NV:\ HNV}$	-	Church Nave proportions (Width / Height)
R_{CURVE}	-	Radius of curvature

passive speaker powered by a built-in mixer with an M-AUDIO 2 audio interface (M-Audio USA) at different source locations (under investigation). The acoustical room response was plotted at different recording locations (under investigation) using the same software through an omni-directional Behringer ECM8000 measurement microphone (Behringer, Willichm Germany).

iii. *Soundscaping of the worship space (enclosed or open), as a space, revitalising the devotee with a 'Sacred' experience, applying, and extrapolating the soundscaping methods outlined in ISO/TS 129133-1/2/3, to characterize the divine 'transcendence' experience of trained listeners as a binaural impact of the acoustic stimuli of the environment*[24-30].

In the case studies presented here, a binaural sensor unit, SQobold front-end (Head acoustics, Germany) was used to make aurally accurate recordings of the 'incidental' and 'intentional' acoustic environment during the time of 'listening' by the participants, through binaural microphones of BHS II headset (microphones and headphones) (Head acoustics, Germany), simulating the way human beings perceive the acoustic environment. These measurements were analysed and classified according to ISO 12913-2, using softwares HEADSPACE-5600 (Head acoustics, Germany). These recordings allowed auralisation and assessment of psycho-acoustic indicators.

2.2 *Character defining investigations: Based on significant case studies*

Research on Acoustical Characterisation of Worship Ambience and on Soundscaping of Revitalising Spaces (indoor and outdoor) involves several significant investigations which enable identification of Character Defining Elements of the Acoustical Heritage of a given Revitalising Worship space. Some of these characters defining impacts, that these investigations unearthed, are listed below.

2.2.1 Revitalising Impact of Architectural Elements

The architectural elements of a given space impact the space to be acoustically revitalising. To illustrate the same, the impact of domes and barrel-vaulted ceilings on the functionality of the enclosed worship space is discussed below:

The aerial 3D view of Mission Concepcion Church, San Antonio - Texas, shown in Figure 1 reveals the dome at the nave-transepts-sanctuary junction of the church.

The Latin cross style floor plan of the church is shown in Figure 2.

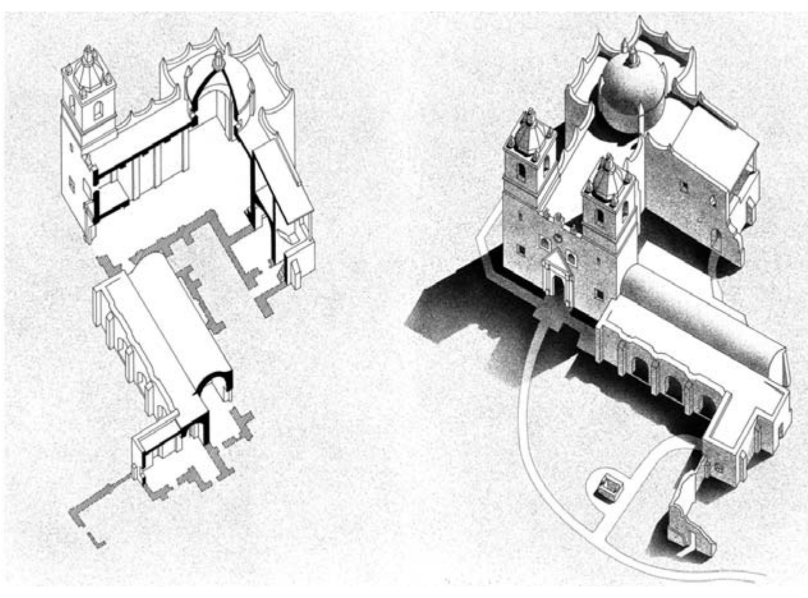

Fig. 1. Aerial 3D view of 'Mission Concepcion church', San Antonio, Texas - USA (Photo courtesy: https://www.loc.gov/pictures/collection/hh/item/tx0038/)

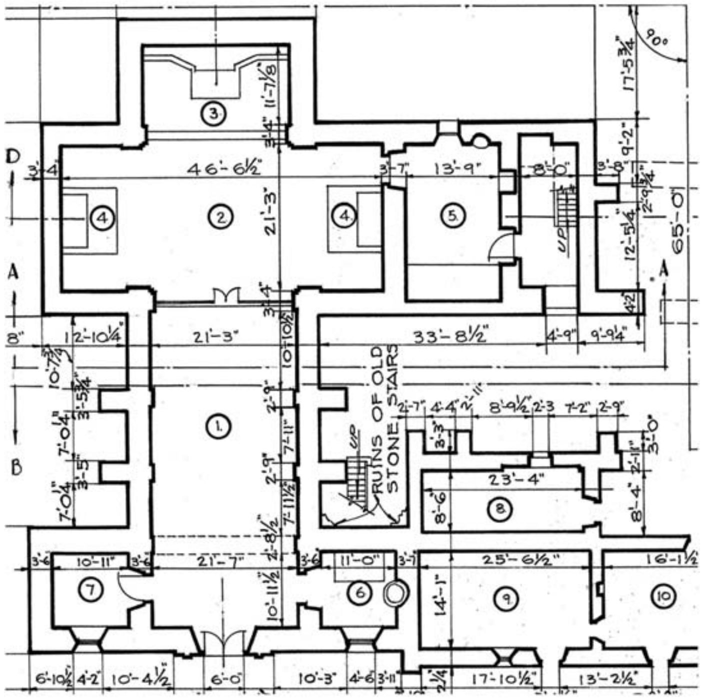

Fig. 2. Floor plan of 'Mission Concepcion church' (Photo courtesy: https: / / www.loc.gov / pictures / collection / hh / item / tx0038 /)

The Western elevation cross-section of the church shown in Figure 3, reveals the barrel-vaulted ceilings of the church and of its lateral chapels.

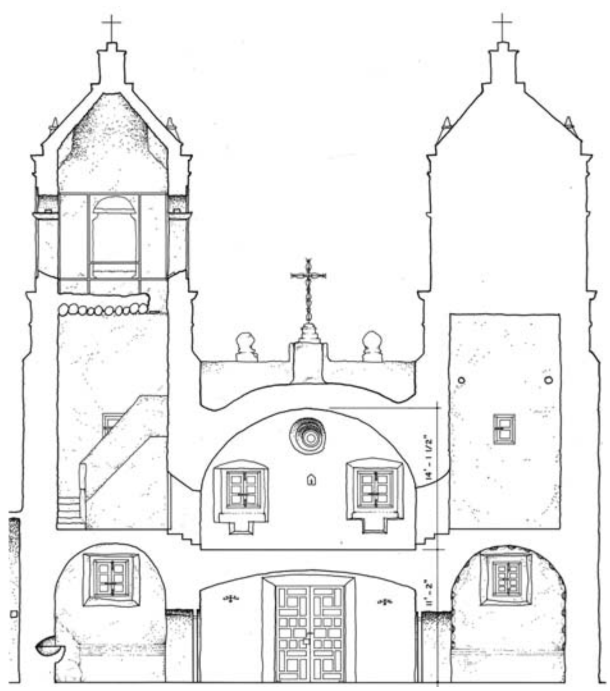

Fig. 3. Western Elevation cross-section of 'Mission Concepcion church' (Photo courtesy: https: / / www.loc.gov / pictures / collection / hh / item / tx0038 /)

The architectural details of the different arched ceilings in 'Mission Concepcion church' are listed in Table 2.

A thumb rule for a good design of a vault requires the radius of curvature of the arc to be less than half or greater than twice the height of the arc from the floor[2]. Inspection of the values of radius of curvature of the different ceilings, as listed in Table 2, shows that the Dome and the Narthex vault has optimal design. Therefore, the space beneath the dome and the narthex, being devoid of any detrimental concave effects, become ideal listening spaces. The vaulted ceiling above the Choir loft therefore, though not of an ideal value, becomes a functional good feedback reflector for the singers and musicians in the choir loft. Similarly, the spaces beneath the vaulted ceiling of the lateral chapels, with the reverberant concave effects, exhibit good conditions for meditation.

The Indian Subcontinent boasts of many worship spaces and meditation spaces with domed and vaulted ceilings. One such instance known for its captivating acoustics is the Gol Gumbaz in Bijapur[31]. There is a growing interest in studying the impact of these curvilinear surfaces using computer simulation techniques. One such study is the impact of the domes on the performance inside the mosques[32]. These simulations, effectively used can help in discovering the intended revitalising ambience that was designed into these intricate and intimate spaces by the original designers.

Table 2. Architectural details of arched ceilings in 'Mission Concepcion Church', San Antonio, Texas.

Architectural parameters	Values
Radius of curvature of Dome (ft)	12.0
$Height_{maximum}$ (Dome) (ft)	43.0
Radius of curvature of Nave/Sanctuary/Transepts Barrel vaults (ft)	16.0
$Height_{maximum}$ (Nave/Sanctuary/Transepts Barrel Vault) (ft)	26.0
Radius of curvature of Narthex barrel vault (ft)	16.0
$Height_{maximum}$ (Narthex Barrel Vault) (ft)	51.0
Radius of curvature of Choir loft barrel vault (ft)	16.0
$Height_{maximum}$ (Choir loft barrel vault) (ft)	12.0
Radius of curvature of lateral chapels' barrel vault (ft)	12.0
$Height_{maximum}$ (lateral chapels' barrel vault) (ft)	11.0

2.2.2 Revitalising Impact of Acoustical Resonance between Materials and Liturgical function

The materials adorning a worship space can be so chosen, to absorb, reflect, diffuse, or transmit sound waves and to resonate with the 'live' acoustical signal in that space to create a 'sacred experience.' This acoustical resonance between the physical elements to create a meta-acoustical effect was studied in a prayer hall of a Buddhist Monastery, Bomdila - Arunachal Pradesh (India)[18].

This study revealed how an ancient practice of Tibetan chanting like "Gyuke" or "Dzoke", could be rendered to match the resonant frequency of the timber constituting the ensemble. This acoustical resonance between the throat chant frequency and the timber resonant frequency would create a transcendental experience of meta-acoustical elevation. In this experimental layout shown in Figure 4, the flooring and the wainscot were wood-panelled.

The flooring with its typical wooden planks on joists structure and with an air gap between the ground and the floor level, allowed for free vibration of the planks at its resonating frequency as described in Figure 5. It was discovered that the floor was vibrating in the frequency range of 100 - 120 Hz. The two monks who were requested to perform the harmonic chants in front of the test equipment were also found to be singing in frequencies between 100 Hz. and 125 Hz. This possibly explains why many devotees or tourists who have witnessed a chanting of these Monks in a proper monastery have experienced the sensations of being elated and elevated from the ground.

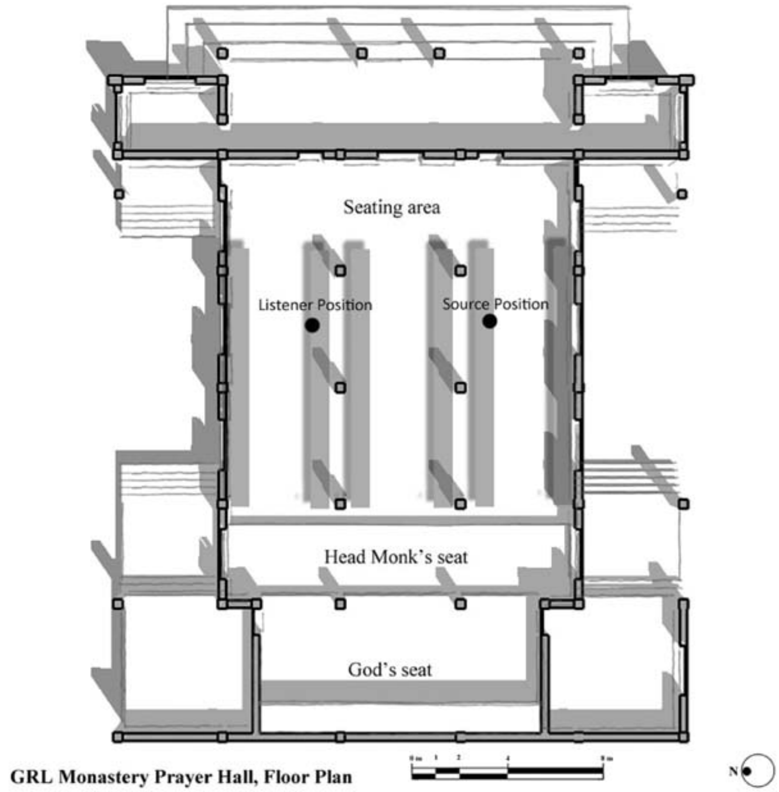

Fig. 4. Plan showing test positions prayer hall of a Buddhist Monastery, Bomdila (courtesy: Arch. Buland Shukla)

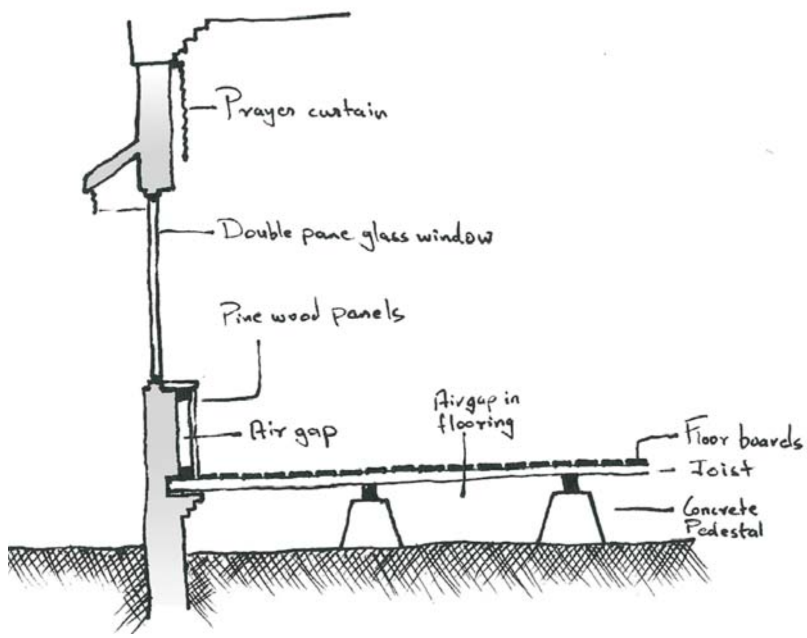

Fig. 5. Schematic section showing the flooring detail - prayer hall of a Buddhist Monastery, Bomdila, Arunachal Pradesh - India (courtesy: Arch. Buland Shukla)

2.2.3 Revitalising Impact of conserving Acoustical Heritage of Worship Spaces

Acoustical investigation becomes a useful reference tool in the conservation of a heritage worship space, to ensure that the revitalising elements of worship ambience are either preserved, restored or rehabilitated in a renovated heritage worship space, as illustrated in the acoustical conservation of the worship heritage of Nossa Senhora de Penha de Franca church, Goa[20] (shown in Figure 6).

The pre-restoration and post-restoration variance of the different monaural acoustic measures is shown in Figure 7.

None of the objective acoustical parameters showed significant differences between the pre-restoration and post-restoration measured values at the benchmark significance level of $p < 0.05$. The subjective and objective acoustical tests in the church verified the credibility of the restorative exercise undertaken in the church. Although not 95% significantly better, the considerable improvement in Definition for Speech(D_{50}), Clarity for Music(C_{80}) and L_{Aeq} post restoration makes the increase in Reverberation Time (RT) (from 2.2 s to 2.8 s) more effective thus creating an optimal "loud and intelligible liveness" in the church. Although statistically insignificant, the mean values of the subjective acoustical impressions indicate an overall perception of good subjective acoustics in the church.

This joyful subjective perception of the worship space confirms the fact that this restored "intelligibly loud and live and yet silent" worship space now elicits a heightened experience of the Divine as expressed by the clergy, the choir and the congregation that gathers for worship in the restored church.

The acoustically characterized worship experience thus works as a reference tool for future conservative interventions.

Fig. 6. Nossa Senhora de Penha de França church, Goa - India (pre- and post-restoration).

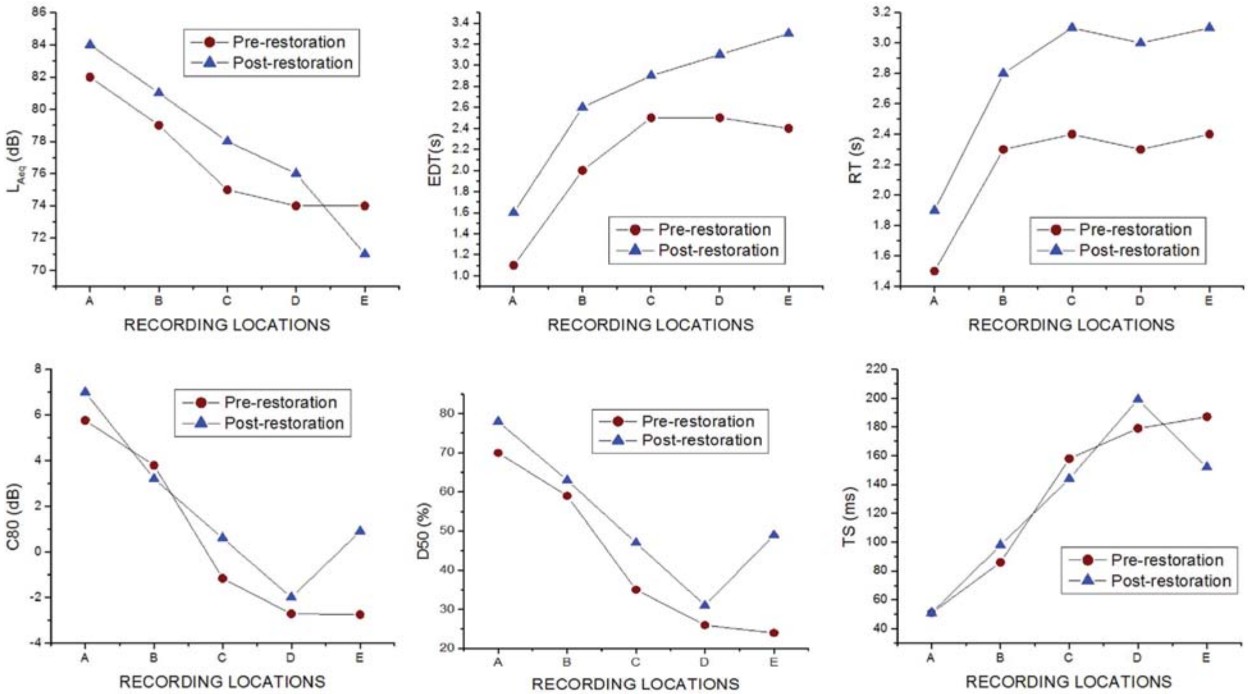

Fig. 7. Pre-restoration and post-restoration comparison of objective acoustical measures in Nossa Senhora de Penha de França church.

2.2.4 Revitalising Impact on congregation by signals from different Source Locations

Signals from different source locations in a worship space elicit distinct response. It is important to understand as to what acoustical functionality (speech / music / singing) was intended at each source location. This critical knowledge helps in optimizing the liturgical impact of the acoustical renditions on the congregation in a worship space. The following study on the Acoustical Worship Heritage in Schmerzhaften Mutter Gottes, Vilgertshofen - Germany,[21] shown in Figure 8, illustrates this impact.

Spectral variance of Reverberation Time (RT_{60}) and definition for Speech (D_{50}) at four recording locations ('B', 'C', 'D', 'E') between the two sources 'S1' (Altar location in sanctuary) and 'M1' (Pipe organ location on choir loft) in Schmerzhaften Mutter Gottes, Vilgertshofen, is shown in Figure 9.

Fig. 8. Schmerzhaften Mutter Gottes, Vilgertshofen - Germany

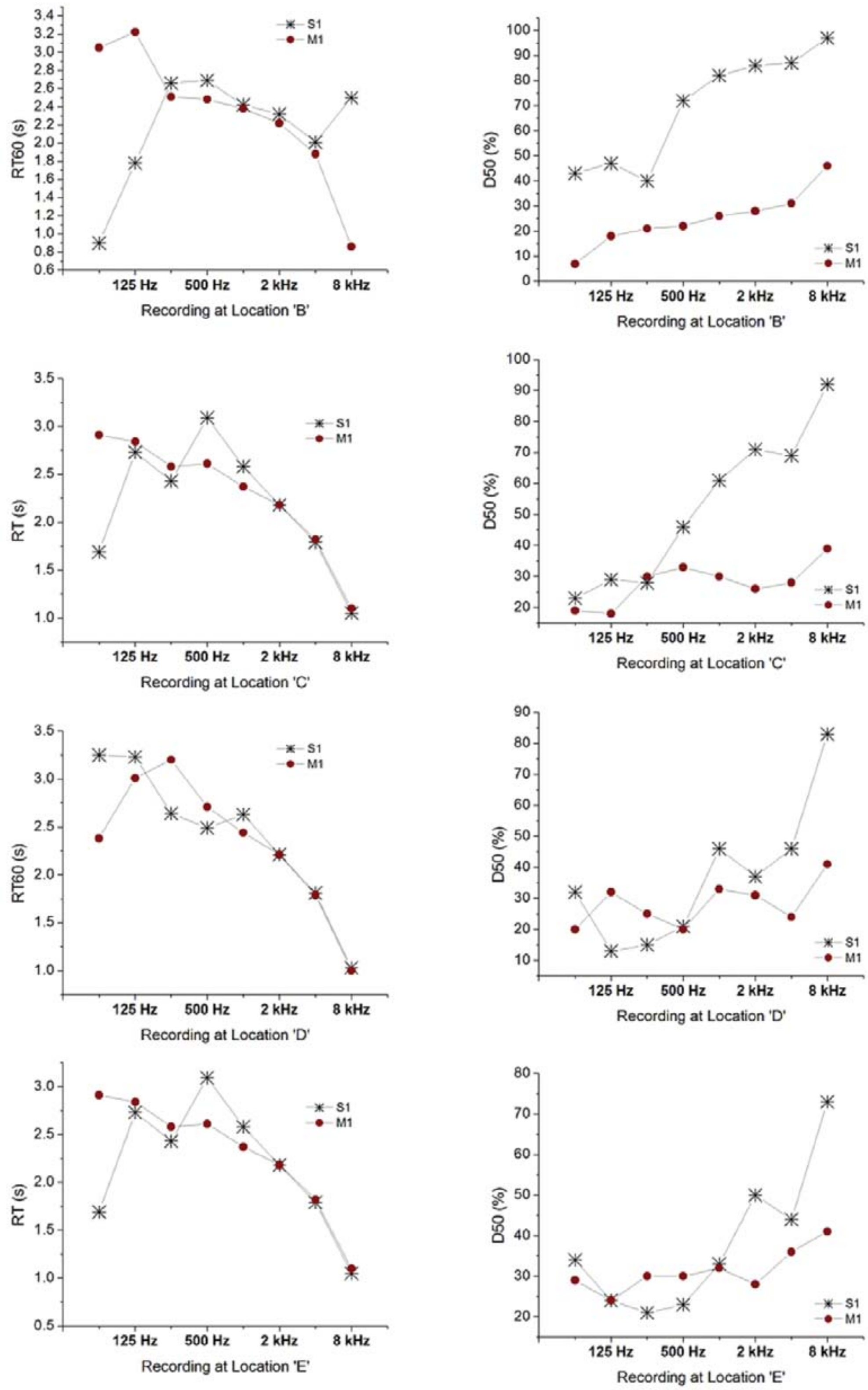

Fig. 9. Spectral Variance of RT_{60} and D_{50}.

Cumulative spectral decay for the sources 'S1' and 'M1' at a central recording location in the church (recording location 'C') for the first 80 ms window is shown in Figure 10.

Positional variance of Rapid Speech Transmission Index (RASTI) and Loudness (L_{eq}) at five recording locations ('A', 'B', 'C', 'D', 'E') comparing two sources ('S1' & 'M1) is shown in Figure 11.

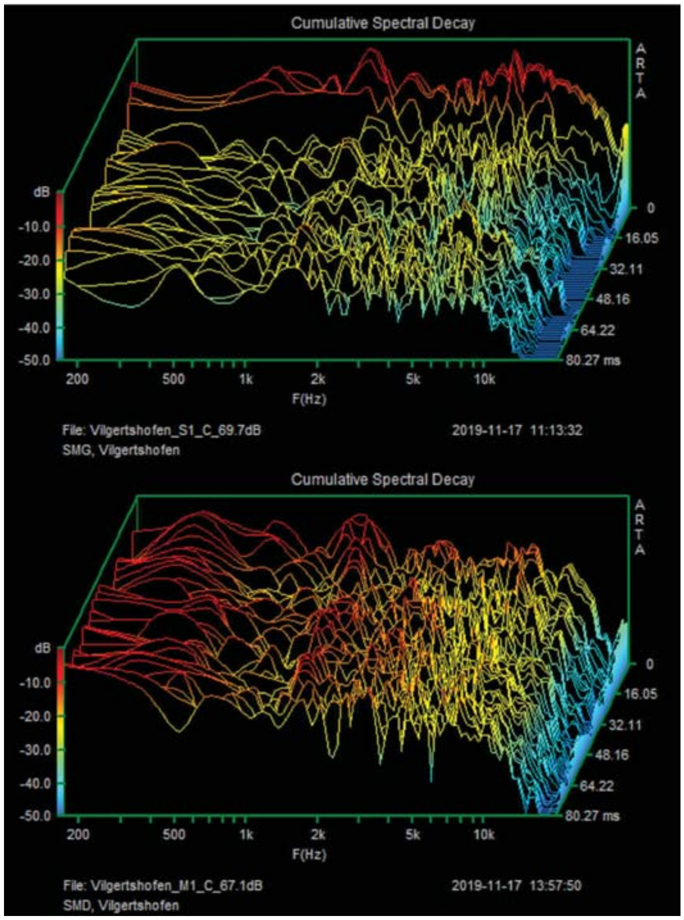

Fig. 10. Cumulative Spectral Decay for source 'S1' (Altar location in sanctuary) and for source 'M1' (Pipe-organ location in choir-loft) at the center of the church (Recording location 'C')

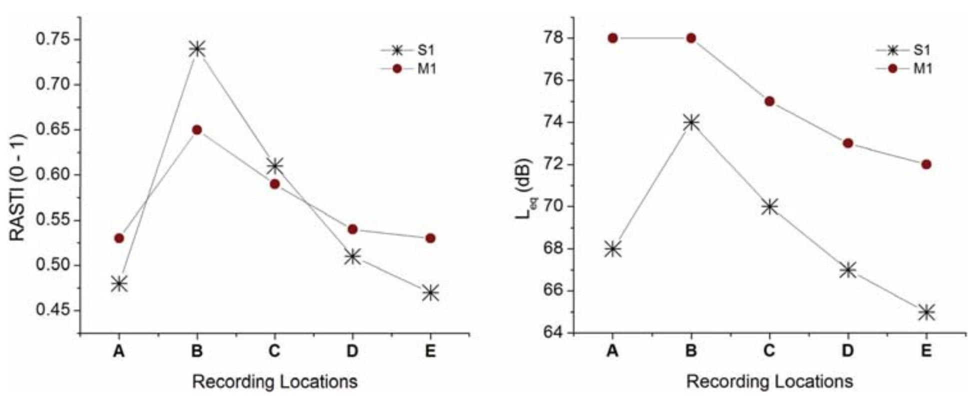

Fig. 11. Variance of RASTI and Leq at different recording locations for source 'S1' (Altar location in sanctuary) and for source 'M1' (Pipe organ location on choir loft)

A mean value of RT_{60} = 1.44 seconds and L_{eq} = 74.5 dB was recorded in the intermittent space between the two tested sources, for the impulse response from the pipe-organ location on the choir loft (M1) which implies that the worship space provides good conditions of Reverberation Time and Loudness that optimize the listening experience in the nave of the church to renditions played on the pipe-organ from the choir-loft.

Although the worship space is comparatively more reverberant (mean value of RT_{60} = 2.12 seconds) and less loud (mean value of L_{eq} = 69dB) for the impulse response from the altar location on the sanctuary floor (S1), the D_{50} spectral analysis and the positional RASTI analysis shows better intelligibility for the altar location in the central nave listening positions and in the effective intelligibility range (500 Hz - 4kHz). Thus, the present altar location (S1) provides the celebrant of the liturgy with a combination of liveness and intelligibility for speech, singing or renditions of music.

2.2.5 Revitalising Impact of acoustic environment of open Sacred Space on aural-affective-metaphysical perceptions

The acoustic environment of a Revitalising Space impacts the aural-affective-metaphysical realms of a listener as explored in the study on the "Revitalising soundscape of 'Holy Cross' sacred grove - Baradi, Goa - acoustic environment's affective and meta-physical heritage"[29]. Pilgrims throng to the sacred grove of Holy Cross Baradi, shown in Figure 12, to be revitalised by the 'metaphysical' experience of this hill-top space. This study soundscapes 'Holy Cross' sacred grove as a 'Revitalising space' extrapolating and complementing ISO/TS 12913-1/2/3 methods to connect the auditory, affective, and meta-physical perceptions of the acoustic (natural/human/machine/live-performance) environment.

Fig. 12. Sacred Grove of 'Holy Cross' Baradi - Goa.

Table 3. ANNOVA Tests on means of 'natural' and 'performance' sound populations for Acoustical 'Pleasantness' & 'Eventfulness'.

Affective Type	Sound Type	Mean	Variance	N	F-value	p-value
Pleasantness	Natural	0.75	0.03	13	0.15	0.7
	Performance	0.77	0.03	13		
Eventfulness	Natural	0.77	0.02	13	0.06	0.81
	Performance	0.79	0.02	13		

The assessed difference in impact between 'natural' and 'performance' sounds on acoustical 'Pleasantness' and 'Eventfulness' is shown in Table 3.

There was no significant difference found in 'pleasantness' or 'eventfulness' between 'natural' and 'live performance' sounds (cf. Table 3).

The difference in impact between 'natural' and 'performance' sounds on metaphysical perceptions was similarly assessed as shown in Table 4.

Though perception of 'harmony' was found to be 78% better for 'natural sounds' as compared to live performance, however, there was no significant difference between 'natural sounds' and 'live performance' in the perception of 'heightened awareness', 'stillness', 'harmony' and 'inspiration' (cf. Table 4).

Table 4. ANNOVA Tests on means of Acoustical 'Metaphysical' populations of 'natural' and 'performance' sounds for each metaphysical impact.

Metaphysical Type	Sound Type	Mean	Variance	N	F-value	p-value
Heightened	Natural	0.74	0.03	13	1.26 x 10-4	0.99
Awareness	Performance	0.74	0.03	13		
Stillness	Natural	0.66	0.05	13	0.01	0.91
	Performance	0.67	0.04	13		
Harmony	Natural	0.77	0.02	13	1.56	0.22
	Performance	0.69	0.03	13		
Inspiration	Natural	0.63	0.08	13	0.73	0.40
	Performance	0.70	0.03	13		

Analysis of the derived acoustical parameters showed that 'Acoustic pleasantness' and 'Acoustic eventfulness' of 'live performance sounds' and 'Acoustic transcendent awareness' of 'natural sounds' in a multiregression with subjective acoustic qualities showed a positive correlation with loudness, clarity, tonality and negative correlation with intimacy (at $p \leq 0.05$), while 'Acoustic transcendent harmony' of 'natural sounds' in a multiregression with subjective acoustic qualities showed positive correlation with all the tested subjective acoustical qualities (at $p \leq 0.05$). 'Acoustic transcendent inspiration' for 'live performance sounds' in a multiregression with subjective acoustic qualities showed a positive correlation with loudness, clarity, intimacy, and negative correlation with tonality (at $p \leq 0.05$).

Holy Cross sacred grove, Baradi - Goa (as a 'context' of this soundscaping exercise) was perceived as optimally 'Revitalising' (mean=4.71 on a scale of '+1 to '+5'). Conservation proposals made by the soundscaping participants indicated that Holy Cross sacred grove, Baradi - Goa impinged a strong impression on the participants as a 'naturally Revitalising space'. This identification and characterization of character defining elements of the soundscape of Holy Cross sacred grove, Baradi - Goa as a 'Revitalising space' thus enables conservation of this sacred space for posterity as living heritage of the neighbourhood.

2.2.6 Revitalising binaural impact at Sacred Grounds of a World Heritage site

A soundscaping exercise in the acoustic environment of an unenclosed World Heritage Space, analyses the binaural psycho-acoustic parameters in relation with the aural-affective-metaphysical perceptions of the listeners / participants as illustrated in this study at the world heritage site of the Buddhist Stupa in Sanche, Madhya Pradesh (India), shown in Figure 13.

The 'incidental' natural 'acoustic environment' of the 'context' was supplemented with rendition of a Buddhist chant 'Mangala' by a group of singers.

Binaural recordings of the 'incidental' and 'intentional' acoustic environment during the time of 'listening' by the participants, were done in accordance with ISO / TS 12913-2, simulating the way human beings perceive the acoustic environment.

Fig. 13. World Heritage Site of Sanche Stupa, Madhya Pradesh - India and the Soundscaping team conducting binaural recordings

Listeners were instructed about nomenclature and methodology of soundscaping 'revitalising spaces' and trained to perceive and record their affective and metaphysical perceptions of the acoustic environment. Statistical analysis of the data was done using Microsoft Excel 2007 and Origin 6.1.

The variations in the psycho-acoustical parameters: 'sharpness (acum)', 'tonality (tuHMS)' and 'loudness (sone)', 'fluctuation strength (vacil)' and 'roughness (asper)' for the natural and animated acoustic environment is shown in Figure 14.

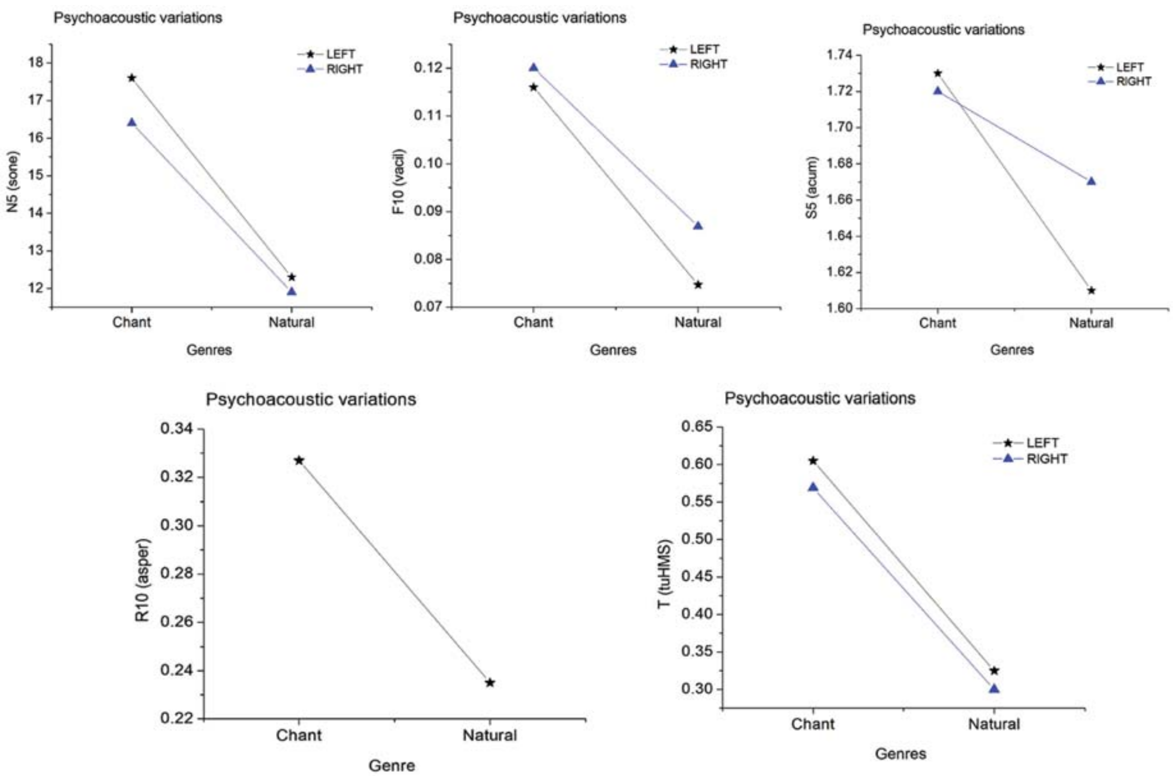

Fig. 14. Variance in Loudness (N5); Fluctuation Strength (F10); Sharpness (S5); Roughness (R10) and Tonality (T) at (left ear) and (right ear) for 'rendition of chant' and 'natural' acoustic environment on the Sacred Grounds of Sanche Stupa

It is observed that the psychoacoustic parameters of loudness (sone), sharpness (acum), tonality (tuHMS), fluctuation strength (vacil) and roughness (asper) show higher values for the rendition of the chant as compared with the natural ambient acoustic environment. This observation when correlated with the aural-affective-metaphysical perceptions of listeners decodes nuances of 'revitalising experience' of the 'Sacred' on such historic 'sacred' grounds.

2.2.7 Revitalising impact of acoustical worship ambience: Cross-cultural comparison

A cross-cultural investigation of the acoustical heritage of worship spaces, helps gain appreciation for the uniformity and uniqueness of revitalising acoustical aesthetics of worship spaces across different continents. Comparison of the "Acoustical worship ambience of Spanish Franciscans built churches: Nossa Senhora do Pilar (Goa) and Mission Concepcion (Texas)" [30], illustrates this procedure.

Spatial variance of monoaural measures in accordance with ISO 3382 set of standards for impulse responses recorded in different locations of each church is shown in Figure 15.

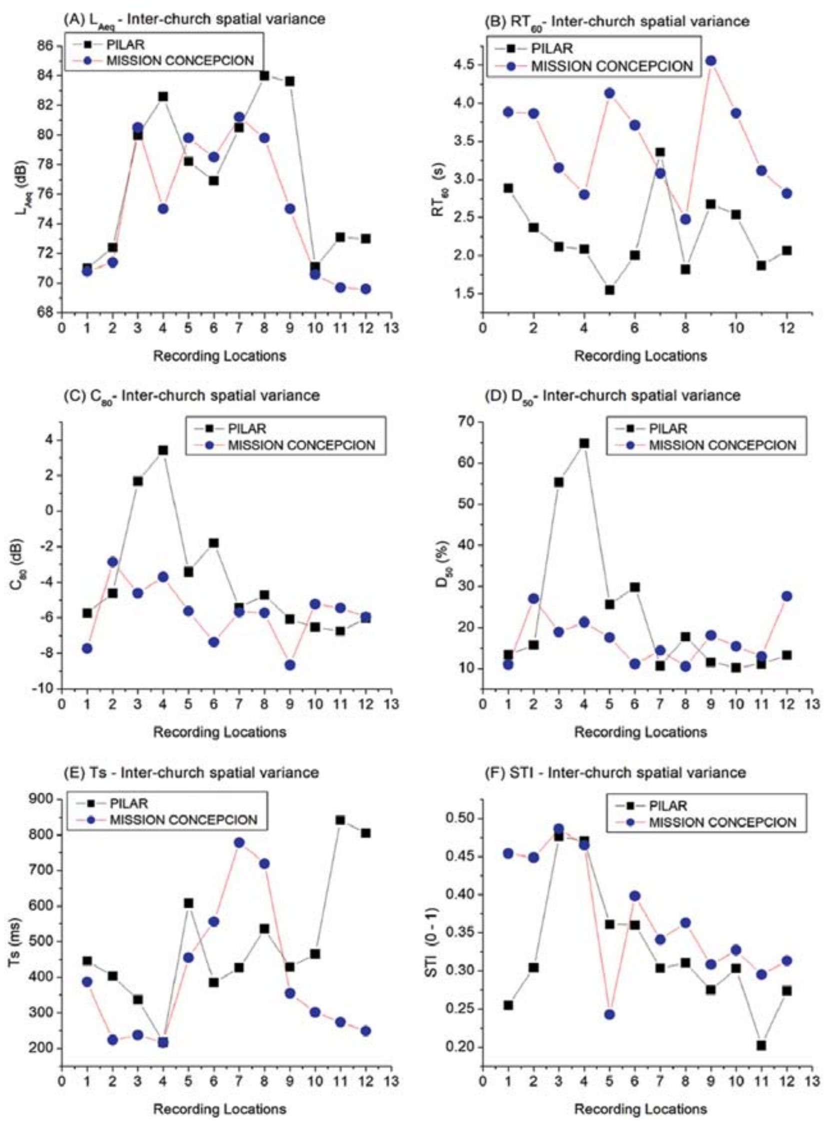

Fig. 15. Inter-church spatial variance of acoustical measures in Nossa Senhora do Pilar church, Goa - India and Mission Concepción church, San Antonio, Texas - USA

The detailed comparative study of connecting sound decay information (ISO 3382) with auditory perception of 'live performance', 'affective' and 'metaphysical (transcendence) impressions' (adapting / extrapolating ISO / TS 12913-2 soundscaping methods) in 17th century Nossa Senhora do Pilar church and 18th century Mission Concepción church presented some significant insights:

i. Mission Concepción was found to be significantly more reverberant and yet showed better speech intelligibility than Pilar. Music rendition from the choir-loft of Mission Concepción was perceived as significantly 'louder' and 'clearer' than from its nave floor ($P \leq 0.05$); whereas the music in Pilar was perceived as significantly 'louder' when rendered from its nave than from its choir-loft (at $p=0.04$).

ii. Music rendition from the choir-loft of Mission Concepción acoustically induced better perception of 'heightened awareness', 'stillness' and 'inspiration' than the music rendered from the nave floor. while music rendered from the nave floor of Pilar induced better 'heightened awareness' (at $p=0.06$) and 'inspiration' (at $p=0.14$).

iii. In Nossa Senhora do Pilar church, subjective acoustical quality of loudness (SAQ_{LOUD}) showed significant positive correlation with RT_{60}, D_{50}, TS, STI and negative correlation with C_{80}; acoustical transcendent inspiration ($aT_{INSPIRE}$) was found to positively correlate with RT_{60}, TS, STI and found to negatively correlate with C_{80} & D_{50}. Whereas, in Mission Concepción church there was no significant regression found between objective acoustical measures and subjective acoustical perceptions.

3. CONCLUSIONS

Acoustical research to comprehend 'Divine Experience' at 'Revitalising Worship Spaces' is a promising dialogue between Science and Religion, Faith, and Reason, for the restoration of aesthetic balance in the human-divine dynamics. This dialogue expounds the capacity of a worship space to evoke a revitalising meta-physical experience of the 'Sacred'.

- A further comprehensive extension of this research unearths the original intentions of the builders and enables exploration of the connection between the architectural style, material content of the sacred ground / edifices and the concurrent liturgical practices prevalent during the time in which they were built.
- This research will bring alive the 'living heritage' of historic 'revitalising worship spaces' as credible destinations for pilgrimage and as valuable experience for tourists, researchers, and conservationists.
- This approach will encourage custodians, citizens, and experts (from diverse fields) to rekindle a collective responsibility to preserve or restore the unique revitalising experience around historic sacred grounds.

This research actualizes 'Acoustical Characterisation of the Heritage of Revitalising Worship Spaces' and simultaneously establishes 'Identification and Conservation of Acoustical Heritage' proper to each Revitalising Worship Space. This research boosts our sonological, affective and metaphysical competencies to perceive 'Sacred Sound' on each 'Sacred Grounds'.

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Miscellany of Underwater Acoustics (UA)

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ABSTRACT

In this article on Underwater Acoustics, the topics namely design of underwater transducers and arrays, acoustic characteristics in water and sea floor backscattering have been briefly reviewed. The review on acoustic scattering from the sea floor is limited to the studies carried out using hull-mounted sonar and the application of composite roughness theory to estimate bottom roughness and textural parameters.

1. INTRODUCTION

With a rich history, underwater acoustics has been pivotal in advancing science and engineering. Greek philosopher Aristotle (384 - 322 BC) was the first to note that sound could be heard in water and air. In 1490, the Italian scientist and artist Leonardo da Vinci (1452 - 1519) wrote in his notebook, 'If you cause your ship to stop and place the head of a long tube in the water and place the other extremity to your ear, you will hear ships at great distances (Bjorno and Buckingham, 2017). About 100 years later, according to the English philosopher Francis Bacon (1551 - 1626), the water is the medium by which sounds originating therein reach a human observer standing nearby. This idea was published in Historia Naturalis et Experimentalis. Underwater Acoustics (UA) is the science of sound waves in the water that has become an essential tool for underwater remote sensing (https://www.heraldgoa.in/review). As a remote sensing technique Underwater acoustics is employed to investigate the ocean's physical, biological, and geological processes. Sound waves are helpful in understanding underwater scenarios despite formidable difficulties in their propagation through a highly variable medium in noisy and reverberation backgrounds. Sonar (sound navigation and ranging), an underwater equivalent of radar, uses sound waves for hydrospace applications. Sonar is an eye and ear of the underwater medium and is considered a branch of applied science known as UA. Both radar and sonars are echo-ranging systems, and many radar techniques apply to sonar. Still, the form of energy source, operating frequency, and operation medium are different. In radar, EM waves are transverse waves, i.e., having mutually perpendicular electric and magnetic wave components. The direction of EM wave propagation is perpendicular to both the electric and magnetic waves. With its practical applications, UA profoundly impacts our understanding of the ocean and its role in our lives. The sound waves employed in sonars are longitudinal waves due to compression and rarefaction in the medium, and their propagation direction is in the same direction as compression and rarefaction. The frequencies used in sonar are generally in the sonic frequency range, i.e., 20 Hz to 20 kHz. However, higher operating frequencies are generally used in high-resolution sonar systems. Radars use frequencies in hundreds of MHz or higher. Similarly, the propagation velocity of an EM wave is 3.0 x 10^8m/s, and for a sound wave in water, it is approximately 1500 m/s. Because of this, the data rate is much lower for a given range in sonar than the radar. This practical application of sound in the ocean has been motivated mainly by navigational hazards, catastrophes, and world events, including shipwrecks and problem areas associated with naval warfare. Inventors addressed the problem of navigational hazards using underwater bells to create warning signals around the twentieth century. Naval warfare and its disturbing effects have inspired UA researchers in World War I (WWI). Interestingly, the level of accomplishment during and after World War II (WWII) was noteworthy (Muir and Bradley, 2016). These complex works led to oceanography, acoustic science, and engineering discoveries, including sonar and geophysical exploration. The history of UA over the first half of the 20th century involves its initial development, followed by numerous achievements during two world wars. UA is an extensive topic, and they were covered in the 169th Acoustical Society of America (ASA) meeting held in Pittsburgh, USA. The sessions on UA development covered in the ASA meetings were restricted to the United States and its allies, France, and the United Kingdom. In contrast, the history of the topic in the erstwhile Union of Soviet Socialist Republics (USSR) developments covered in Godin and Palmer (2008).

UA operations can broadly be classified into two disciplines: i) active and ii) passive acoustics. In an active acoustic system, acoustic pulses are transmitted into the water to produce backscatter echoes. By examining the received echoes, it is possible to estimate the range and, in some instances, detect the presence and bearing of an underwater target (Urick, 1983). The passive acoustic technique detects and monitors acoustic signals underwater, advancing as a vital tool for ocean soundscape studies. Salinity, temperature, and pressure conditions affect sound signal propagation within the ocean media. During the summer season, with intense solar heating and a warm atmosphere, the sound speeds are higher near the surface and decrease with the depth. In the winter, the cooling of the surface reverses the temperature gradient. The sound waves will bend downward under summer conditions and upward in the winter (Lurton, 2010). Bjorno and Buckingham (2017) classified the essential actions of UA as i) Hydrography, ii) off-shore activities, iii) dredging, iv) defense and security, and v) marine research and fishery. Hydrography includes harbor and river surveys, bathymetric surveys, flood damage assessment, engineering inspection, pipeline and cable route surveys, exclusive economic zone (EEZ) mapping (including seafloor imaging), breakwater mapping, etc. Defense and security include mine countermeasures, submarine and torpedo detection, obstacle avoidance, search and recovery, underwater communication, vessel and fleet protection, waterside security, diver detection, etc. Marine research includes environmental monitoring, seafloor imaging and bottom characterization, ambient noise measurements, marine archaeology, and marine mammal and fishery research. The fishery consists of operations, fish school detection, catch monitoring and control, trawl position control, phytoplankton, and zooplankton investigations. Again, the classification of the development of UA can broadly be made in five timescales (Bjorno and Buckingham, 2017):

1. Development of the UA before 1912.
2. Within the years 1912 through 1918, i.e., during WWI.
3. Within the years 1919 through 1939.
4. The years 1940 through 1946, i.e., during WWII.
5. Post WWII, i.e., the years after 1946.

The post-WWII period witnessed a significant shift in underwater acoustics, with developments primarily focused on civilian applications. This era was characterized by a surge in advancements, particularly in sound wave propagation experiments, which played a crucial role in understanding the ocean environment.

2. UNDERWATER ACOUSTICS ASPECTS

The major constituents of the sonar are the wet end, i.e., the transducer, and the dry end, also known as the signal/data processing end. Again, the developments of the wet end, i.e., transducer technology, are partly motivated by the two world wars and the Cold War, when threats arose due to the submarines and underwater mines (Rossing, 2007). The growth of material science has also significantly contributed to developing transducer and transducer arrays for sound signal transmission and reception. Besides, two non-military commercial applications in UA research are i) geophysical prospecting and ii) fisheries. In this article, we have covered few crucial UA aspects:

1. Underwater transducer
2. Understanding the behavior of the sound velocity
3. Interaction of acoustic waves with the seafloor

As we know, the advancement of underwater technology in the twentieth century was associated with the remarkable improvement in transducer design. We also covered historical tips on transducer design here.

2.1 *Transducers and Arrays*

Elisha Grey (1890) recognized that the carbon-button microphone in a waterproof container that could be used as a "hydrophone" to receive the underwater bell signals. Fessenden built an oscillator for underwater transmission in a range of more than 30 miles (Chakraborty, 1989). Wood (1965) described in details a Langevin quartz ultrasonic transducer, which consists of a steel-quartz-steel assembly and radiates like a piston. Later, the above sandwich construction was replaced by a synthetic Rochelle salt crystal transducer assembly and a thin-walled magnetostrictive nickel tube transducer. According to Wood (1965), Pierce (1925) developed a magnetostrictive oscillator operating at 25 kHz, generating a few kilowatts of power for echo-sounding applications. Sherman (1975) mentioned that the piezo-ceramic transducer possesses a higher electro-mechanical coupling factor over the transducer designed with magnetostrictive material. Subsequenty, research, Woolett (1968) showed that piezo-ceramic materials have the highest stored electro-mechanical energy density. It means that their power-handling capability is higher. It is also reported by Berlincourt *et al.* (1964) that piezo-ceramic materials possess less dielectric losses, and a variety of shapes can be formed easily. However, obtaining the required directivity and beam width with a single transducer system is impossible for many modern applications. A practical and pressing problem in the communication field for scientists was to minimize the sound signals in unwanted directions by making them more directives in specific directions. These communication technology problems became the basis for the genesis of array systems design. One convenient method of overcoming these difficulties is forming an array of transducers with a suitable geometry. Woollett (1968) elaborated on applying arrays to obtain a significant array gain in the desired direction for piezo-ceramic materials with high efficiencies and improved power handling capability. As the generation of higher and still higher powers in a specified direction was achieved and perfected, many applications of arrays were made, and their characteristics were studied. An array of disk elements in a suitable configuration may produce a specified beam width of required directivity with low sidelobe levels. The underwater three-element transducer array was used for beam steering application) (Lasky, 1974). Sources with extensive bibliographies on various antenna arrays are listed in a paper by Southworth (1931). However, classical array theory directly determines the radiation pattern and directivity of a uniform array of elements with uniform excitations.

The development in the design of an array was significantly advanced due to Rumsey's (1957) innovative idea. This concept, which states that structures with shapes specified in terms of angles will have radiation patterns and input impedances independent of the operating frequency, has paved the way for numerous new forms of antennas. It has been noted that, in general, continuous radiative structures of different shapes do not provide sufficient directive gain. In many practical situations, higher gain and a sharp main beam in a specified direction are often required. As a result, many new two- and three-dimensional array types have been proposed, whose geometrical configurations depend on the angular parameter of a particular shape (Chakraborty, 1986). However, there are limitations in the radiated power due to the efficiency of the projector transducer in converting electrical power to acoustic power. Efficiency depends on the transducer bandwidth, varying from 0.2 to 0.7 for a tuned, narrow bandwidth projector (Waite, 2002). The radiated powers for typical sonars may range from 1 W to 40 kW, having transmitted directivity index (DIt) values between 10 and 20 dB.

In the field of underwater acoustic technology, there are significant challenges and limitations in increasing the radiated power. The necessity to generate the maximum amount of acoustic power to overcome the reverberation background limits the detection range. However, it is impossible to enhance the power level further when it is already higher. Attempts to increase the radiated power are limited due to two effects: cavitation and mutual interaction among the transducer array elements. The cavitation threshold is a crucial design issue of the transducer when increasing power beyond a specific limit. It is a parameter that predicts the start of cavitations at some point before it spreads to the total radiating face of the transducer. Higher power applied to the projector transducer array causes bubble formation over the transducer surface, ultimately reducing the radiated power to the medium by degrading the beam pattern and impedance. Power losses are due to bubbles over the transducer surface, and scattering within the bubbles is prominent, which reduce power radiation. Generally, there are three critical operational parameters to estimate the cavitation threshold: Transducer operating frequency, pulse length, and operating depth. Cavitation is a function of depth (pressure) and can be avoided by not exceeding the cavitation threshold. The cavitation threshold increases with shorter pulse length and becomes constant for higher pulse length transmissions. Similarly, there is a linear change in threshold for higher operating frequencies, whereas, for lower frequencies, there is negligible.

The acoustic interaction effect in a multi-element transducer array may create a severe problem with the individual element of the transducer. The result of such an effect leads to different acoustic loading on each transducer element depending on its position in the array. Thus, the effect of the other load impedances of the radiators will modify the distant radiation pattern. Sometimes, the interaction effects in the transducer element may cause negative radiation resistance, i.e., absorption of power from the nearby elements. A transducer array of higher directivity is standard. Limited power transmission, e.g., the power handling capability of a few transducer elements, is reduced even when all the elements are driven uniformly. The reaction force of the medium varies from piston to piston, i.e., among the radiators, and the achievement of uniform velocity motion at each face of the transducer becomes difficult. Developing a compensation technique for the designed system is essential to reduce such effect effort. There are three ways to control the mutual interaction effect: i) Separation between the array elements may be increased within the limit. Otherwise, the transmit beam pattern deterioration occurs with too much spacing. ii) Allowing large individual element sizes so that their self-radiation impedances are much greater than the mutual radiation impedances between elements, iii) Using individual amplifiers to drive each element at the correct amplitude and phase to yield a uniform velocity of motion across the array. Though a solution to reduce interaction effects is proposed above, it is necessary to develop a simulation work that is realized for improved prediction of the mutual interaction effect between the transducer elements (Chakraborty, 1988; Chakraborty, 1995). Generally, the array problem with directive radiators is solved by assuming a convenient distribution of velocity amplitudes along all structurally identical elements concerning their locations in the array. Greenspan and Sherman (1964) calculated the radiation resistances and reactance for the arrays of different geometries, and the necessity of a computation of such effects was emphasized. The mathematical analysis is instrumental in computing the interaction effects and providing the required velocity correction to the individual transducer elements. This correction is crucial for ensuring the uniformity of motion across the array, thereby mitigating the impact of the interaction effects. Here, we discussed initial design issues. Modern developments are far more and beyond the scope of this article. Butler and Sherman (2016) provided updated version of modern underwater transducers and array design aspects in much details. While further increasing the sound signal ranges, the application of non-linear techniques (parametric sounders) are commercially used, especially for depth sounders as well as for sub-bottom profilers. Today, much of the efficiencies of the arrays depend on the application of pre-processing of the received array signals. Besides beamforming techniques, two more techniques are well-known Interferometric and High-resolution techniques. Interferometric techniques are used, where two-spaced array receivers measure phase differences. The difference in acoustic paths helps measure the direction of arrival (DOA). This technique and beamforming technique are well used for sea bottom imaging. High-resolution techniques (HRT) require fulfilling array element spacing as required in beamforming, but the array can be shorter than for beamforming.

In India, significant research have been carried out at IITM and DRDO - NPOL on underwater transducer design (https://www.iitm.ac.in/happenings/press-releases-and-coverages/iit-madras-defence-research-and-development-organisation) where contribution of Ebenezer (Ebenezer et al, 2003) on transducer design is noteworthy. More than that, recently a Materials and Transducers-Simulated Test (MATS) Centre has been developed at DRDO-NPOL, Kochi. The center is the only one of its kind in the Asia-Pacific region and one of the few in the world. A MATS is designed for undertaking static or dynamic measurements/evaluation/calibration of any materials, sensors/ transducers for undersea use. It can be used by people researching oceanography, ocean acoustics, marine geophysics, underwater acoustic transducers or other areas dealing with undersea equipment. Static as well as dynamic calibration of transducers and other sensors can be efficiently carried out under controlled pressure and temperature conditions. MATS provide three pressure chambers of different sizes to cater to various measurements that must be simulated for the ocean environment. It is also designed for measurements at different operating frequencies (https://www.drdo.gov.in/drdo/naval-research-board/npol-kochi).

2.2 *Sound Speed Profiles of Ocean Medium*

In an ocean medium, sound is a form of energy transmitted through longitudinal or compressional pressure waves, where water molecules vibrate back and forth in parallel to the direction of the sound wave and pass on the energy to adjacent molecules to transmit sound energy. Therefore, sound travels faster and more efficiently when the molecules are closer together and transfer their energy to neighboring particles. In other words, sound travels faster through denser materials (Webb, 2019). Since water is much denser than air, the speed of sound in water (about 1500 m/s) is approximately five times faster than in air (around 330 m/s), which explains why we sometimes have difficulty localizing the source of a sound when we hear underwater. Since sound travels faster through water than air, the energy required to transmit a given sound wave is higher in air than in water, and it takes about 61 times more energy to transmit a sound through air than through water. Because of this energy difference, there is a 61 dB difference between sounds transmitted through air and water, such that a sound intensity of 120 dB in water would be equivalent to an intensity of about 60 dB in the air when comparing sounds in the ocean with sounds in the air. In perspective, a sound of 130 dB in the air is equivalent to standing 100 m from a jet engine at take-off. For comparison, a sound of 130 dB in water is equivalent to about 70 dB in air, which is the intensity of the sound of a vacuum cleaner (Webb, 2019).

Three variables influence the ocean's sound speed: temperature, salinity, and pressure. These variables change with depth and location, and so will the speed of sound in different oceanic regions. We need to consider the vertical profiles for temperature and pressure to examine how the speed of sound changes as a function of depth. The pressure is low at the surface, but the temperature is highest in the water column. The effect of temperature is dominant at the surface, so the speed of sound is fast in surface waters. Generally, sound speed profiles measured in the deep sea can be divided into the principal layers (Waite, 2002):

- ***i.*** ***Surface (duct) layer :*** The outermost layer of the sea is called the surface duct or surface isothermal layer. The sea surface is always under the influence of wind-generated wave action, which causes the mixing of seawater in the surface layer of 20-50m. It has a positive velocity gradient, where the sound wave is trapped in the layer by surface reflection and refraction at the layer boundary.
- ***ii.*** ***Thermocline layer :*** This layer, situated below the surface isothermal layer, plays a significant role in seasonal variations of the ocean's sound speed. During the strong thermocline in summer and autumn, the temperature decreases with depth, leading to a higher velocity gradient. This layer weakens during winter and spring, merging with the surface layer. The main thermocline layer exists below the seasonal surface layers, where the velocity gradient is negative and is unaffected by seasonal variations (Pillai, 2013).

The deep isothermal layer, characterized by a constant temperature of about 4°C right to the bottom, significantly impacts the speed of sound. In this layer, the speed of sound increases with increasing pressure. At high latitudes, the layer extends closer to the sea surface, and in the Arctic, it may eliminate the other layers, significantly impacting the speed of sound in these regions (Waite, 2002). This layer, known as the Deep Isothermal Layer, plays a crucial role in shaping the speed of sound in the ocean, particularly in high-latitude regions.

These different components can combine to form varied shapes of sound speed profile, which depends on the environmental conditions (Fig. 2.16 in p. 46) of Lurton (2010). At the mesoscale level (tens of kilometers), currents, thermal fronts, and eddies modify average sound speed profiles. Water mass exchange between the ocean basins causes the appearance of local maxima in sound speed profiles at different depths. Similarly, near estuaries, freshwater inputs create a slower sound speed (difference between the fresh and sea water ~ 40m/s) in shallow layers, introducing perturbations in sound speed. Other factors like internal waves and tides induce variation in water density, ultimately affecting variation in sound speed profile.

As depth increases, the temperature and the speed of sound decline. Near the bottom, extreme pressure dominates, and even though temperatures are low, the speed of sound increases with depth. At moderate depths, there is a zone where both temperature and pressure are relatively low, resulting in minimal sound speed. This zone, known as the Deep Sound Channel (DSC) or SOFAR channel (Sound Fixing and Ranging), is a region of the ocean where sound waves can travel long distances with little attenuation. The depth at which this focusing occurs is known as the deep sound channel (DSC). When the source is placed close to the minimum, and because the spreading is cylindrical, very long-range propagation is possible. The best results are achieved when the receiver is close to the axis of the channel. Sounds produced in the SOFAR channel can be propagated over long distances with little attenuation. Sound waves generated in the channel radiate out in all directions. Waves that travel into shallower or deeper water outside the sound channel enter a region of faster sound transmission. As a result, sound waves moving from the SOFAR channel into shallower water will be refracted back toward the channel. As the sound waves go deeper below the channel, they will be refracted upwards back into the channel and the region of slower speed.

Accordingly, much of the sound does not dissipate out into the water in all directions but instead is trapped within the channel and can travel very long distances with little energy loss. The SOFAR channel is not just a scientific curiosity but a concept with global significance. Baleen whales use the SOFAR channel to communicate with each other over long distances of hundreds to thousands of kilometers (Webb, 2019). The military has been able to track submarines using the SOFAR channel. During World War II, to locate downed pilots or missing ships and planes, SOFAR channels were used. Scientists used the SOFAR channel to monitor global ocean temperatures, and a helpful method was proposed in 1990, which was known as ATOC (Acoustic Thermometry of Ocean Climate), where loud, low-frequency sounds produced near Hawaii and California would travel through the SOFAR channel to receiving stations around the Pacific. Researchers monitor global ocean temperature changes by monitoring the time it takes for the sounds to reach the receivers, as sounds would move faster through a warming ocean.

The application of sound velocity in oceanography is widespread, from ocean mapping to sound propagation. To use the Multi-Beam Echosounder System (MBES), one needs sound speed data near the transducer face and the mean sound speed of the sound speed profile. Sound speed values are essential for processing of backscatter and depth data, mainly when beamforming spatial processing is employed. For sonar systems, it is to be mentioned that depth data obtained using the beamforming technique provide accurate depth values, including outer beams, in comparison with the DOA technique. High-resolution techniques (HRT) were attempted to implement for ocean mapping (Chakraborty and Schenke, 1995). HRT needs a high signal-to-noise ratio (S/N). When background noise near the sea surface becomes agitated due to bad weather, HRT becomes ineffective. In India, MBES techniques were first time introduced in 1989 at CSIR-National Institute of Oceanography (NIO), Dona Paula, Goa, which was installed in Ocean Research Vessel (ORV) Sagar Kanya under the Manganese Nodule program of Department of Ocean Development (DoD), Govt of India. Massive deep seafloor mapping was carried out at the Central Indian Ocean basin to assign the mine site for India within a year or two. The Ministry of Earth Sciences, Government of India, introduced the technique to initiate mapping programs. CSIR-NIO and ESSO

National Centre for Polar and Ocean Research (NCPOR), Goa, and ESSO National Institute of Ocean Technology (NIOT), Chennai, became partners to cover the vast Exclusive Economic Zone (EEZ) of India, having 7000 km of coastline. NCPOR, situated at Vasco da Gama, Goa, is a nodal center for the country's seafloor mapping program.

Besides, area sound speed profiles are essential to investigate the ocean environment (Jensen et al, 2011). Acoustic propagation characteristics and tomography investigations, such as acoustic mapping of ocean features, are necessary to understand the energetic and ocean dynamics. The concept of underwater remote sensing techniques such as Ocean Acoustic Tomography (Munk and Wunsch, 1979) and Acoustic Thermometry (Munk and Forbes, 1989) were proposed to monitor the ocean by acoustic means. Sequential arrivals of acoustic pulses from the fixed transmitting transducers depend mainly on the acoustic characteristics of the region. The travel time fluctuations in measured and model data could be used to reconstruct the temporally evolving oceanic (dominant component of sound speed, i.e., temperature). In India, Acoustic Tomography investigations were initiated at the CSIR-NIO during the nineteen eighties under the project "Development of Acoustic Technique for Remote Sensing of the Oceans" (Ramana Murty *et al.*, 1989). The studies were mostly confined to a numerical simulation where environmental data, mostly sound speed, was necessary. The acoustic propagation models were applied to characterize the Northern Indian Ocean, such as the Arabian Sea and the Bay of Bengal (Kumar *et al.*, 1988). The Heard Island experiment was a joint venture in which eight countries - USA, Canada, Australia, New Zealand, France, South Africa, Japan, and India had participated in January 1991 (Kumar *et al.*, 1997). This experiment was meant to conduct a feasibility test to determine the strength and stability of acoustic signals at different stations spread over the four oceans. The characterization of acoustic propagation paths from the source near the Heard Island site to the Indian receiving station was made based on the numerical simulation and processing of received signals by CSIR-NIO researchers. Currently in Indian context, Chandrayadula and his group at IIT, Madras, have employed a hybrid technique combining acoustic propagation models into signal processing methods. Their employed signal processing on long-term baleen whale call data from the central Indian Ocean shows call frequency changes (Pinto and Chandrayadula, 2021). Propagation modeling is constantly advancing. More complex models are being developed that refine three-dimensional propagation (Lin *et al.* 2019) and specialize in very long-range propagation scenarios. Other models specialize in propagation over seafloors with complex structures or ice-covered ocean surfaces.

2.3 *Seabottom Backscattering*

Several processes record seafloor backscatter energy using a platform-based hull-mounted sonar source (Jackson and Richardson, 2007). These are :

1. Transmission of acoustic signal from the transmitter
2. Propagation of acoustic signal in the water column (towards the seafloor)
3. Reflection, refraction, and scattering of acoustic energies from the water seafloor interface
4. Scattering of acoustic energies from the sediment volume inhomogeneities
5. Propagation of acoustic signal from the seafloor towards the receiver through the water column
6. Reception of the return signal by the echo sounder receiver

The transmission of the acoustic signal is mainly controlled by the characteristics of the transmitter, such as source level, pulse duration, and beam pattern. After transmission, the acoustic signal suffers various losses in the water medium during propagation towards the seafloor and back propagation towards the receiver. Spreading loss, absorption loss, scattering from the in-homogeneities (e.g., suspended particles, fishes, plankton, etc.), and bending of sound rays are essential processes during the propagation of acoustic energy in the water medium. The phenomena, namely reflection, refraction, and scattering, take place as the acoustic energy interacts with the seafloor. The factors involved in these processes are - the angle of incidence, the ratio of the speed of sound in sediment to the speed of sound in water, the ratio of density in sediments to water density, attenuation in sediments, seafloor roughness characteristics, sediment layering, sediment volume in homogeneities, and various objects (with different shapes) embedded in sediment volume. The reception of a backscatter signal also depends on the characteristics of the receiver (such as receiver sensitivity), noises from other sources, and relative movements of the receiver (such as heave, roll, and pitch). It's important to note that the literature on acoustic backscatter from the seafloor is vast and unlimited. Several books describe theoretical topics and related literature (Jackson and Richardson, 2007). However, here is an introduction to the basic concepts related to acoustic interactions with seafloor sediments.

Reflection and Transmission : When a plane acoustic wave impinges upon the seafloor (an interface between water and sediment with different acoustic impedances), a part of the energy is reflected in the water medium with an angle equal to the angle of incidence. This is called reflection, a crucial phenomenon in our research, occurring at a flat or plane interface. The incident energy is reflected in a direction symmetrical to the direction of arrival (like a mirror; hence, this is also called specular reflection). However, there is a loss of amplitude in this process. Reflection depends on the angle of incidence, density contrast, and sound speed contrast at the two mediums of the reflecting interface. Part of the energy is transmitted into the sediment volume with an angle, often called a transmitted or refracted wave. The angle is called the transmission angle, following Snell's law of refraction.

Acoustic Scattering : Scattering is an important phenomenon that describes the interaction of acoustic energy with the seafloor. The roughness of the water-seafloor interface and the inhomogeneities in sediment volume cause the acoustic energies to scatter in all directions. The scattering of energy towards the transmitter of sonar, known as backscattering, is a key concept in mono-static sonar systems. These systems, such as single-beam echo sounders, utilize backscatter energies for their operation, where the transmitter and receiver are located simultaneously (Lurton, 2010; Jackson and Richardson, 2007). Acoustic backscattering from the boundaries of propagation medium (sea surface and seafloor) is called surface and bottom reverberations.

Similarly, the backscatter of energies from various objects in a water medium, such as fish, plankton, suspended particles, or a bubble, is called volume reverberation in the water medium. The seafloor, due to its non-ideal plane surface for acoustic waves, presents a complex challenge in interpreting the backscatter data. This interpretation depends mainly on the interface roughness and the volume scattering. If the microscale roughness of an interface is comparable in magnitude with the acoustic wavelength, the interface may be considered as a local plane surface for that acoustic frequency. Interface irregularities will scatter acoustic energies in all possible directions. This scattering of energy depends on the frequency of the incident acoustic wave, incidence angle, and local characteristics of the interface relief (i.e., the ratio of the mean amplitude of interface roughness to the acoustic wavelength). The scattered energy is segregated into two parts: coherent and incoherent. The coherent part of the energy contains specular reflections, where a part of the incident wave is reflected in a specular direction without any deformations other than the loss in amplitude. The rest of the energy is scattered in the entire medium, including the backscatter energy towards the source. This scattered energy represents the incoherent part.

The acoustic roughness of the seafloor is a measure of the variability in acoustic impedance (of the interface). However, the physical roughness of the seafloor mainly depends on the surface topography. Therefore, the acoustic roughness of the seafloor may not always be identical to the physical roughness (Chakraborty, 1989; Chakraborty and Pathak, 1999). The micro-scale roughness of the seafloor depends on several aspects, such as sedimentary compositions, ripples on the seafloor (due to tide and current), the presence of gas, and living bio-organisms. The amplitude of micro-scale roughness ranges between a millimeter and a few meters depending on the sonar's operation frequency. Micro-scale roughness scales corresponding to different physical processes may coexist on the seafloor. Seafloor interface roughness is quantified by a parameter called, Rayleigh parameter. The Rayleigh parameter is expressed as $P=2ka\, h\cos\theta_i$, where ka is the acoustic wave number, θ_i is the angle of incidence, and h is the root-mean-square relief of the rough surface from its mean value. For $P << 1$, the roughness of the surface is small, and most of the sound energy propagates in a specular direction as a coherent wave. Meanwhile, $P >> 1$ corresponds to large roughness, which causes considerable energy to scatter (Brekhovskikh and Lysanov, 2003).

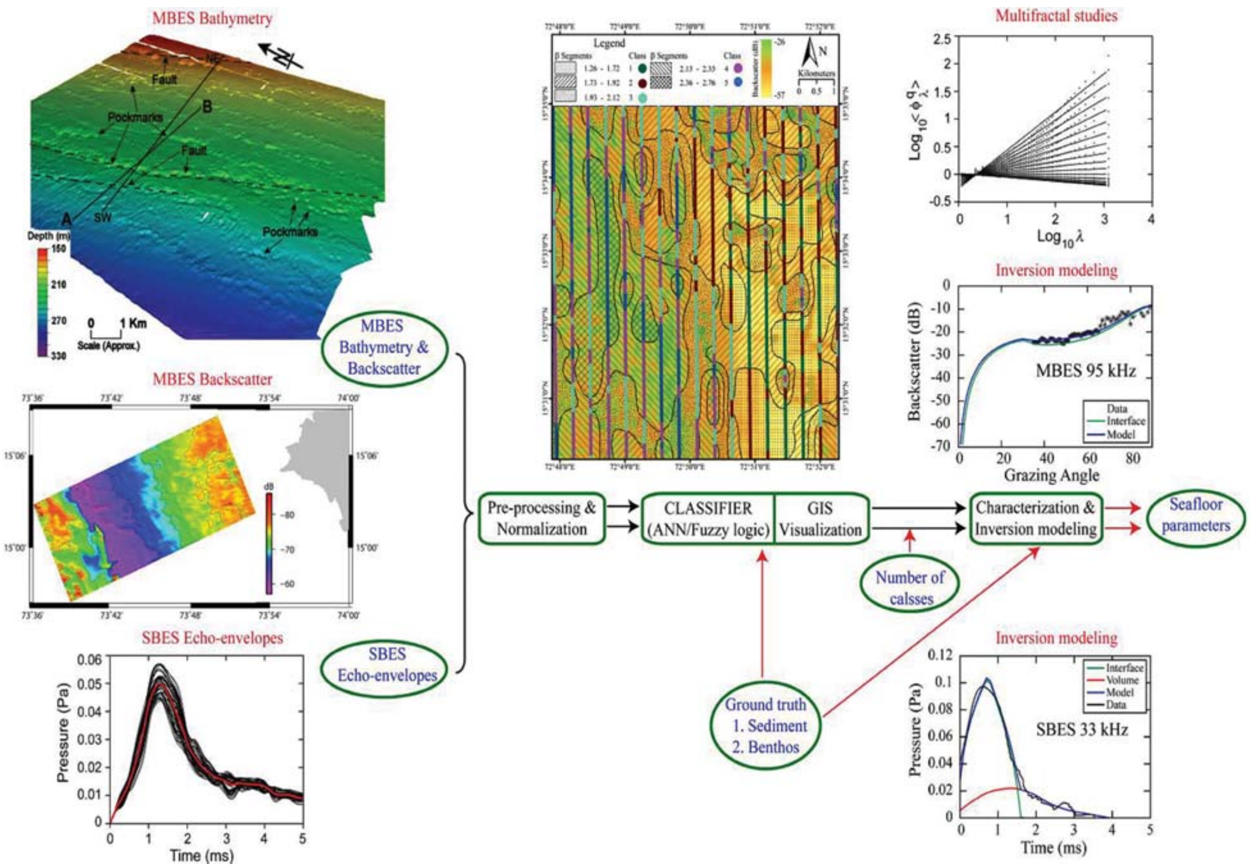

Fig. 1. The figure illustrates general procedure for acoustic based seafloor studies describing model-based techniques and empirical methods.

Interaction of Acoustic Waves with the Seafloor : The interaction of acoustic waves with the seafloor mainly depends on the frequency. At high frequency, interaction is limited within surficial sediments due to less penetration. The complications in scattering processes at high frequencies arise due to the seafloor interface irregularities and the nature of sediments. Most of the incident energy penetrates in seafloor sediments at low frequencies. The characteristics of seafloor sediments play a significant role compared to the interface relief irregularities at these low frequencies. Thus, reflection and refraction at various interface layers within the sediment volume are substantial at low frequencies. Moreover, the presence of bio-organisms in the seafloor sediments and their effects on the scattering processes complicates the situation further (Jackson *et al.*, 1986). Therefore, interpreting echo obtained from the scattering of acoustic energy from the seafloor sediments is challenging.

Transmission loss (TL) quantitatively describes the weakening of acoustic energy as wave propagates outward from a source. Transmission loss is the sum of a loss due to geometrical spreading and a loss due to attenuation (Urick, 1983). Acoustic energy spreads in all directions from a source during the propagation. The decrease in acoustic intensity is inversely proportional to the surface area of a sphere. This phenomenon is called geometric spreading loss. In addition, there is another type of loss called attenuation loss in a water medium. Since seawater is a dissipative propagation medium, part of the acoustic energy is absorbed due to various chemical processes (Medwin and Clay, 1998). The loss depends on the characteristics of a propagation medium and the frequency of operation. The model developed by Francois and Garrison (1982a, 1982b) is the most widely used attenuation model, which inputs temperature, salinity, hydrostatic pressure, and acoustic frequency. This model takes into account the total attenuation from three factors/contributors: boric acid, magnesium sulphate, and pure water. The total transmission loss (in dB) is expressed as (Lurton, 2010), $2TL = 2(20\ R + awR)$. Factor two in the equation is multiplied to account for the losses for outgoing and return signals. Here, the range R is expressed in meters, and the attenuation aw is expressed in dB/km. Therefore, the unit of either R or aw has to be converted appropriately to calculate TL.

Model based Seafloor Characterization : It was mentioned earlier that seafloor characterization is a process to differentiate or recognize different regions based on the sediments' physical, chemical, geological, and biological characteristics. This is possible by measuring the properties of seafloor sediments directly in a field or a laboratory. However, the remote acoustic characterization using backscatter models is more cost-effective and rapid. Several acoustic models have been developed to describe the interaction of acoustic waves with seafloor sediments. Initially, simple mathematical models were developed from minimal field data measurement. One such simple model is to distinguish sediment types from the reflectivity measurements (Srinivasan *et al.*, 1982). If the acoustic reflection from the seafloor at normal incidence is correlated with the ground truth, it is possible to differentiate sediment types based on the reflectivity. Such a simple model is only sometimes sufficient to describe seafloor sediments. Reflectivity could be different (for the same sediment type) due to volume heterogeneity, slope of a surface, presence of gas and bio-organisms, etc (Haris *et al.*, 2012). Thus, there is a need for a systematic and quantitative approach to develop theoretical models, which include all the possible variability. Backscatter models generally estimate the surface scattering and the volume scattering coefficients as a function of frequency, angle of incidence, seafloor acoustic parameters, surface roughness, and sediment volume inhomogeneities. The advent of increased computational capabilities gave a thrust for developing new and more realistic complex models to explain the acoustic scattering from the seafloor. Predictions of backscatter echo characteristics from the physical processes of seafloor scattering are generally called forward problems.

Meanwhile, the quantitative estimation of seafloor characteristics based on the information embedded in the scattered echo is called an inverse problem (Holliday, 2007). For an inverse problem, the first step is to decide on a forward theoretical model that describes or relates various physical processes of acoustic interaction with the seafloor sediments. Inversion approaches are commonly used for the estimation of seafloor characteristic parameters (Jackson and Richardson, 2007; Sternlicht and de Moustier, 2003a,b; Tolstoy, 2010; Ballard *et al.*, 2010; Jiang *et al.*, 2010; De and Chakraborty, 2011; Haris *et al.*, 2011). Models for seafloor characterization are broadly grouped into empirical and theoretical categories.

The use of high-frequency SBES (Single Beam Echo Sounder) and MBES (Multi-Beam Echo Sounder) operable within the frequencies 300 kHz is well established for remote acoustic seafloor characterization. The acoustic backscatter data obtained from such echo-sounding systems can be matched with theoretical scattering models to interpret the information embedded in the data (Haris, 2015). The numerical approach for extracting information from the data is called "inversion modeling." The inversion modelling primarily involves a physics based model and this model is employed for the inversion of echo-sounding data to estimate the seafloor roughness parameters, namely the sediment mean grain size, spectral parameters at the water-seafloor interface, and sediment volume parameter, that can be further used to examine fine-scale interaction between acoustic wave and the seafloor (APL Handbook, 1994). The composite roughness model developed by Jackson *et al.* (1986), using the shape of the angular backscatter data, has been extensively applied in this context (de Moustier and Alexandrou, 1991; Matsumoto *et al.*, 1993; Chakraborty *et al.*, 2000). Chakraborty *et al.*, 2002; Chakraborty *et al.*, 2003. Chakraborty *et al.*, 2004). In this section, a model-based seafloor characterization technique based on the composite-roughness theory has been developed and demonstrated utilizing the data acquired using an MBES operable at 95 kHz. The practical application of this technique is evident in the MBES angular backscatter data acquired over the substrates ranging from clayey silt to sand in the central part of the WCMI, which are subject to inversion modeling. Moving beyond the techniques that employ MBES angular backscatter data, Pouliquen and Lurton (1992) initiated a modeling method for seabed identification using the shape of the echosounder signals. Sternlicht and de Moustier (2003 a,b) also developed a robust time-dependent seafloor acoustic backscatter model within the frequency range 10-100 kHz that has been effectively demonstrated for seafloor characterization using the normal-incidence SBES (De and Chakraborty, 2011). Multiple acoustic frequencies (van Walree *et al.*, 2006) highlighted in this work improve seafloor characterization because the roughness spectrum and the sediment volume heterogeneities cause backscatter variation that can be conveniently substantiated using multi-frequency inversion results. In this chapter, the seafloor parameters computed using 95 kHz MBES data are compared with the ground-truth data as well as with the inversion results obtained using 33 and 210 kHz SBES data at the exact locations (De and Chakraborty, 2011; Haris *et al.*, 2011). Here, the composite roughness model uses the shape of the angular backscatter data developed by Jackson *et al.* (1986) and requires a few acoustic parameters as inputs to the modeled input. Without measuring geoacoustic parameters in the study area, these parameters are estimated through inversion. The equations relating geoacoustic model parameters to the mean grain size are adapted from the APL-UW High-Frequency Ocean Environmental Acoustics Models Handbook (APL Handbook, 1994).

Computation of scaling parameter to calibrate the data : Even after implementing the pre- and post-processing procedures discussed in the preceding chapter, prior to the model-data comparison, there was an unfulfillment of absolute calibration, and a depth-dependent offset (scaling parameter in dB) was required to correct each of the processed data sets. The scaling parameters (calibration offsets) were computed by comparing the model derived backscatter values with the measured data. The seabed scattering model combines the most dominant dimensionless scattering mechanism of the surface roughness coefficient and volume scattering coefficient as a superposition of the incoherent scatter to estimate the total seabed backscattering strength. The scaling difference between the APL-UW model predicted backscatter values and the processed MBES data is apparent for the fine and coarse sediment regions. These differences may be due to instrument calibration, model accuracy or erroneous TVG applied online (de Moustier and Matsumoto, 1993; Dziak *et al.*, 1993; Kloser *et al.*, 2010). Therefore, it would be convenient to treat the level of measured backscatter values for appropriate model-data comparison. The error-to-signal (E / S) ratio has been used as a merit function to evaluate the model-data matching procedure with the goal of minimizing the value. This method is independent of the backscatter angular range, and provides a convenient numerical evaluation of the model-data comparison. The resulting scaling parameter (difference between model and data), which minimizes the ratio is used as the representative scaling factor to calibrate the data. Accordingly, the scaling parameters at 12 locations from the study area have been computed. The scatter diagram among the derived scaling parameter and water depth of

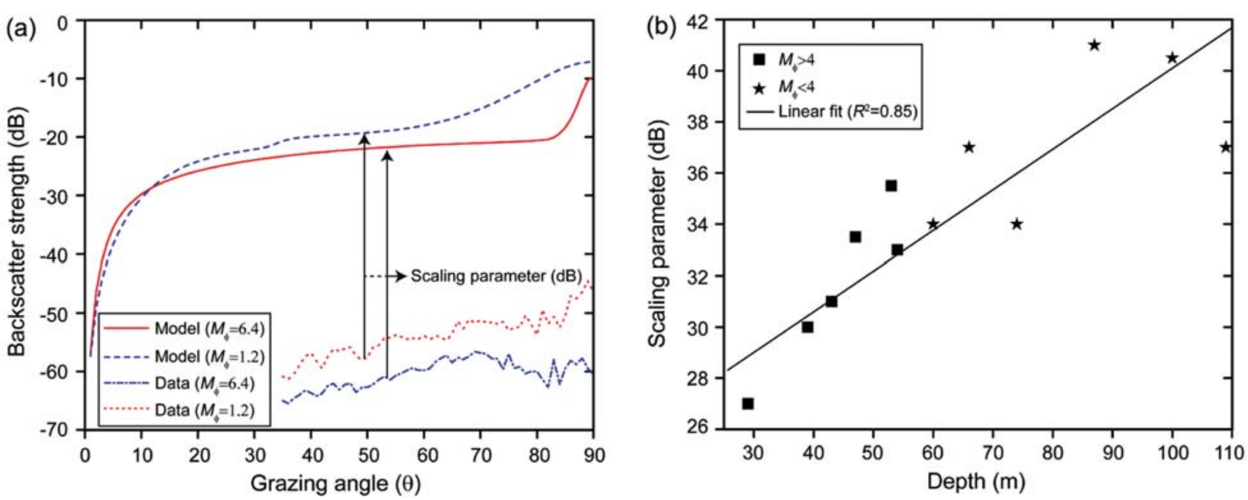

Fig. 2. (a) The differences between the model predicted backscatter values and the corresponding processed MBES data are significant for representative sediment types. Panel (b) depicts the linear relationship among the scaling parameter (in dB) and water depth (m) of the study area (adopted from Haris *et al.*, 2011).

the study depicts a linear relationship with a correlation coefficient of 0.85. For model-data comparison and subsequent inversion modeling, the processed backscatter data for all the grazing angles were calibrated with the corresponding scaling parameter obtained from the linear trend line of the scatter diagram.

Two-stage parametric optimizations : The computation of the correct set of geoacoustic parameters gets convoluted by the large number of good fits existing in the multidimensional search space. It is possible to obtain convincing model data in the search space that does not necessarily represent the correct set of seafloor parameters. Accordingly, by constraining the search space, we have parsed the problem into a two-stage parametric optimization method. Several options are available to quantify the corresponding results involving the data and model. Here, we have designated the cost function, the error-to-signal ratio *(E / S)*, as the suitable parameter to evaluate the model-data matching procedure (to minimize the value). A low value of *E / S* signifies a finer model-data comparison. In the framework of a 3D global search-based echo envelope matching procedure, Sternlicht and de Moustier (2003b) have

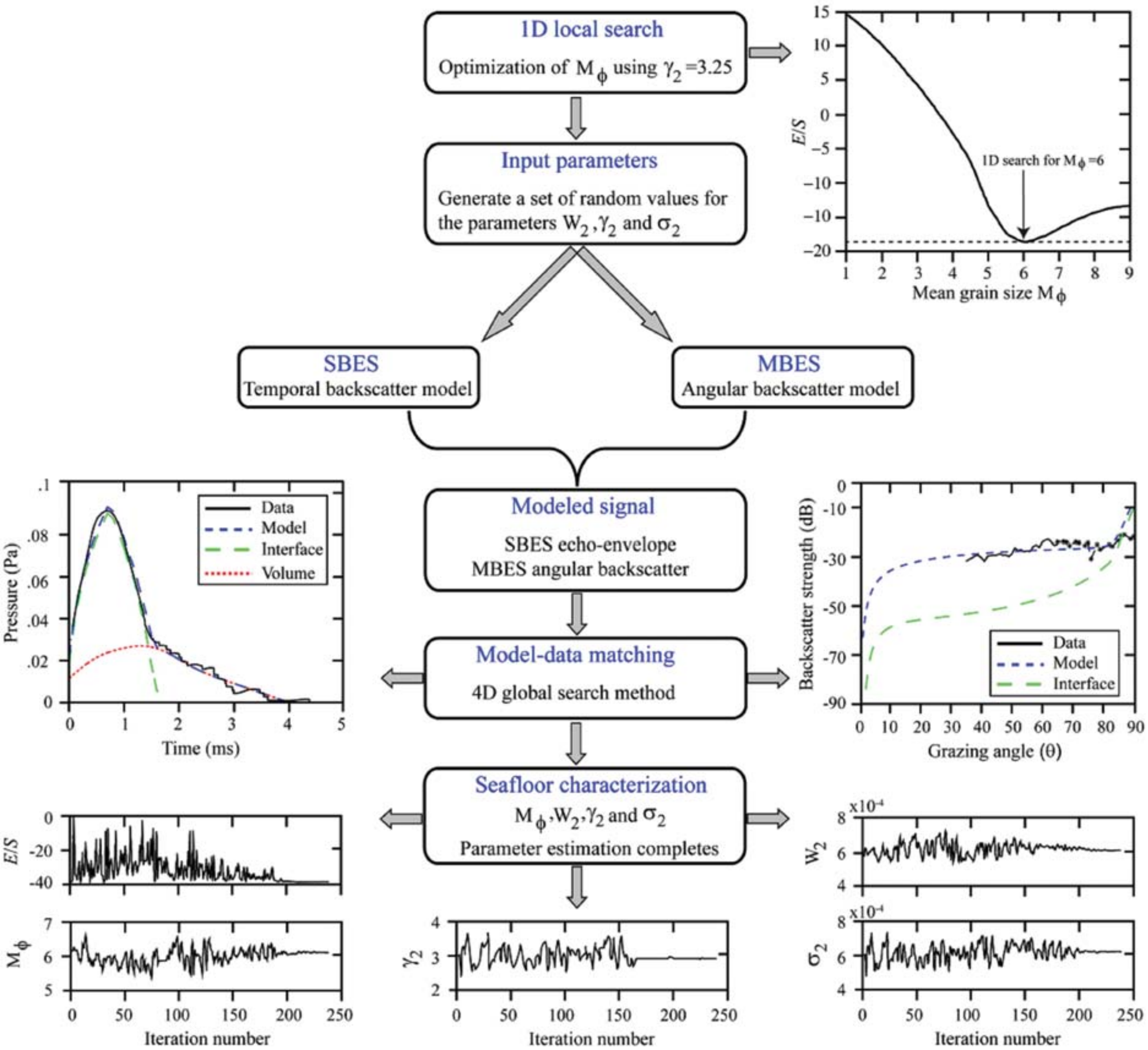

Fig. 3. Flow chart representing 4D inversion procedure for seafloor parameter computation (adopted from Haris *et al.*, 2011).

applied simulated annealing with the downhill simplex method to compute the parameters mean sediment grain size, spectral exponent, and sediment volume scattering parameters. A 4D global search technique has also been developed for estimating the seafloor characteristics parameters. The first stage of the model-data matching procedure employs a 1D search to estimate the general values of the sediment mean grain size. The output of the 1D search process provides the input mean grain size value for the subsequent 4D global search method to calculate the precise mean grain size, the roughness spectral exponent and strength, and the sediment volume parameter (Figure 3).

Mean sediment grain size ($M_{Ø}$) : The following sections describe the analyses of the computed sediment geoacoustic inversion results (at 33, 95, and 210 kHz) along with the ground truth values of the mean grain size of the seabed sediment. The analyses compare the computed seafloor parameters at three acoustic frequencies to evaluate and assess the modelling performance and bottom characterization potentialities. Figure 4 shows the model-data comparison in three geologically distinct sediment provinces. The correlation analyses include the published SBES inversion results to substantiate the estimated $M_{Ø}$ values

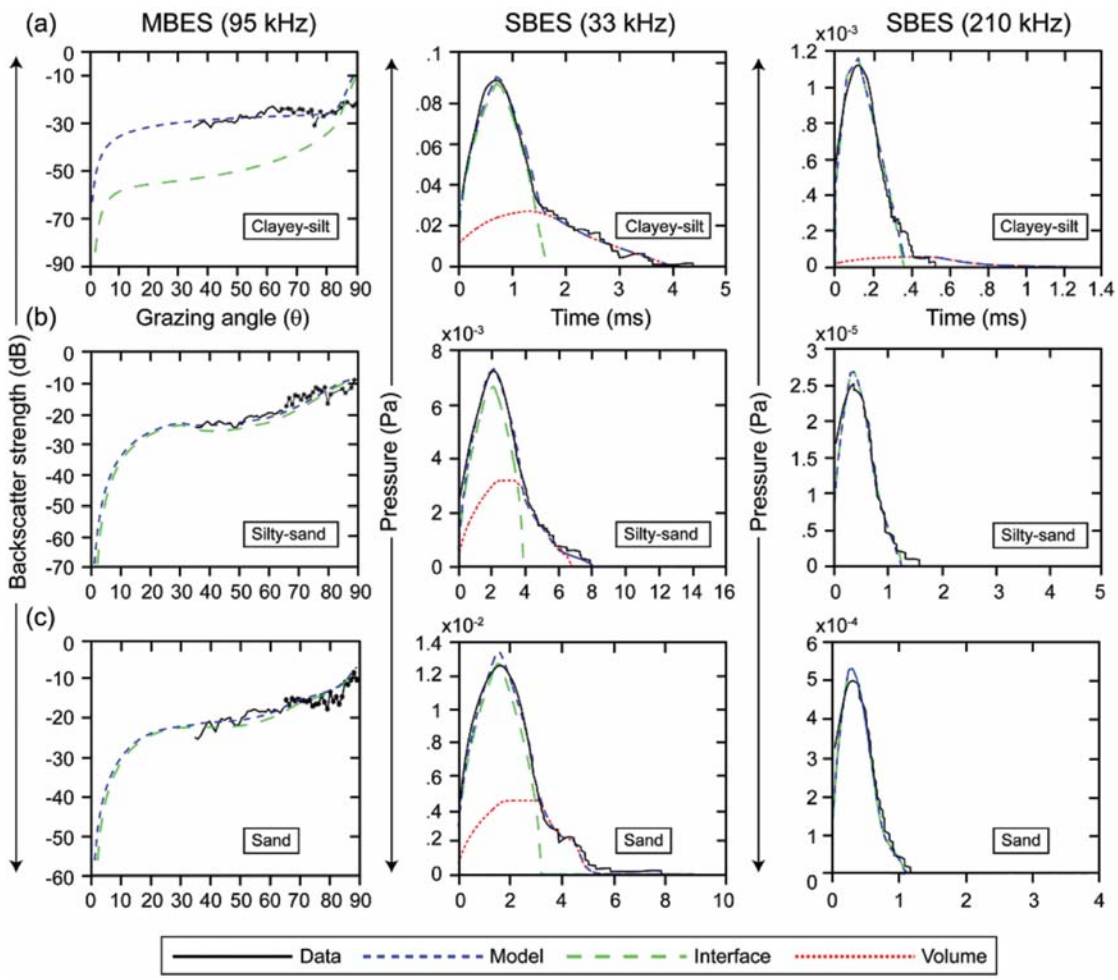

Fig. 4. Panels (a), (b) and (c) represent the model-data comparison for three geologically distinct sediment provinces: clayey-silt (location 1), silty-sand (location 10) and sand (location 8) with respective 33-, 210-(SBES) and 95-kHz (MBES) frequencies. The model data matching procedure for the 95 kHz angular MBES data was carried out within the grazing angles 35° to 65°. The excluded data (star) between 65° and 90° is also plotted to depict the relationship with the data (adopted from Haris 2015).

at 95 kHz. Statistically significant correlation coefficients of 0.97, 0.97, and 0.98 are evident among the model-derived $M_{\O}$ values at 33 and 210 kHz; 33 and 95 kHz; and 95 and 210 kHz, respectively, indicating the suitability of MBES data for inversion modelling. The model-derived $M_{\O}$ values are in good corroboration with the ground-truth measurements (laboratory-derived $M_{\O}$ values). However, variations are noticeable among the computed $M_{\O}$ values at three acoustic frequencies. The backscattering from the seabed can generally be ascribed to two contributing factors, namely interface and volume scattering. The strength of the backscatter signal is primarily controlled by the acoustic frequency, the acoustic impedance contrast between water and sediment, the contributions from seafloor interface roughness, and the sediment volume heterogeneity. In fine sediment region, a part of the transmitted acoustic energy penetrates the sediment and is scattered back by the buried inhomogeneities, including coarse sand particles and mollusk shells (De and Chakraborty, 2011; Haris *et al.*, 2011; Haris *et al.*, 2015). The buried heterogeneities can cause local impedance contrast resulting in deviation of the geoacoustic parameters (values correlated with $M_{\O}$) calculated in the model-data matching procedure (Sternlicht and de Moustier, 2003a). The input geoacoustic parameters are sensitive to the acoustic impedance contrast (the product of density and sound speed in the sediment), and the variation of density within the sediment layers can contribute to the disparity between the model derived and the ground-truth $M_{\O}$ values.

Seafloor roughness parameters (γ and w2) : The computed seafloor roughness parameters (γ and *w*2) at 95 kHz along with the SBES inversion results have been analyzed to evaluate the relationship between the backscatter and relief spectral parameters (Fig. 5). The scatter diagram between the measured $M_{\O}$ and estimated γ reveals the limits of all the estimated parameters for coarse and fine seafloor sediment. It is observed that the relatively higher γ values of are associated with fine sediments, while the lower values of γ are the characteristics of coarse sediments. The seafloor "roughness power spectrum" estimated from the SBES and MBES data characterizes the size and periodicity of the seafloor height fluctuations as a function of the spatial frequency (Briggs *et al.*, 2005).

It was observed that the computed γ values are corroborated well with the published data, but have a narrower range of values. Several studies (Jackson *et al.*, 1986; Stanic *et al.*, 1989) have concluded that the majority of measured 2D spectral strength (*w2*) values are greater than 0.002 cm^4 in coarse sediments and restricted to values around 0.003 cm^4 in fine sediments (Sternlicht and de Moustier, 2003a). The scatter diagram between the measured $M_{\O}$ and estimated *w2* (Fig. 5) reveals that the *w2* values are less than 0.001 cm^4 in fine sediments and confined within the limit 0.002-0.005 cm^4 in coarse sediments. It is observed that the relatively higher values of γ are associated with fine sediments, while the lower values of γ are the characteristics of coarse sediments. The seafloor "roughness power spectrum" estimated from the SBES and MBES data characterizes the size and periodicity of the seafloor height fluctuations as a function of the spatial frequency (Briggs *et al.*, 2005). The scatter diagram between the measured $M_{\O}$ and estimated *w2* (Fig. 5) reveals that the *w2* values are less than 0.001 cm^4 in fine sediments and confined within the limit 0.002-0.005 cm4 in coarse sediments. The *w2* values are well clustered at the three acoustic frequencies, having fewer fluctuations for the fine sediment as compared with the coarse sediment region (Fig. 5). It is also observed that the relatively higher values of *w2* and lower values of γ are associated with coarse sediments, while the lower values *w2* and higher values of γ are the characteristics of fine sediments. Briggs *et al.* (2005) and Jackson and Richardson (2007) have reported that the computed *w2* and γ values can cluster depending on the sediment type with distinct trends in coarse and fine sediment regions. Similar clustering patterns of roughness parameters are conspicuous in the present study, demarcating the coarse and fine sediment provinces.

Sediment volume scattering parameter (σ_2) : The σ_2 values are generally related to the sediment type (fine or coarse) and seafloor inhomogeneities (Jackson *et al.*, 1986). Jackson and Briggs (1992) have demonstrated dominant sediment volume backscatter in finer sediments, and used σ_2 as a variable parameter with a maximum range up to 0.004 in soft sediments. However, Stewart and Chotiros (1992) have experimentally demonstrated that the limit of σ_2 designated in soft sediment is low, and the sediment volume scattering coefficient is usually much higher than the predicted value. Nonetheless, it is convenient to use σ_2 as a variable parameter in the model-data matching procedure.

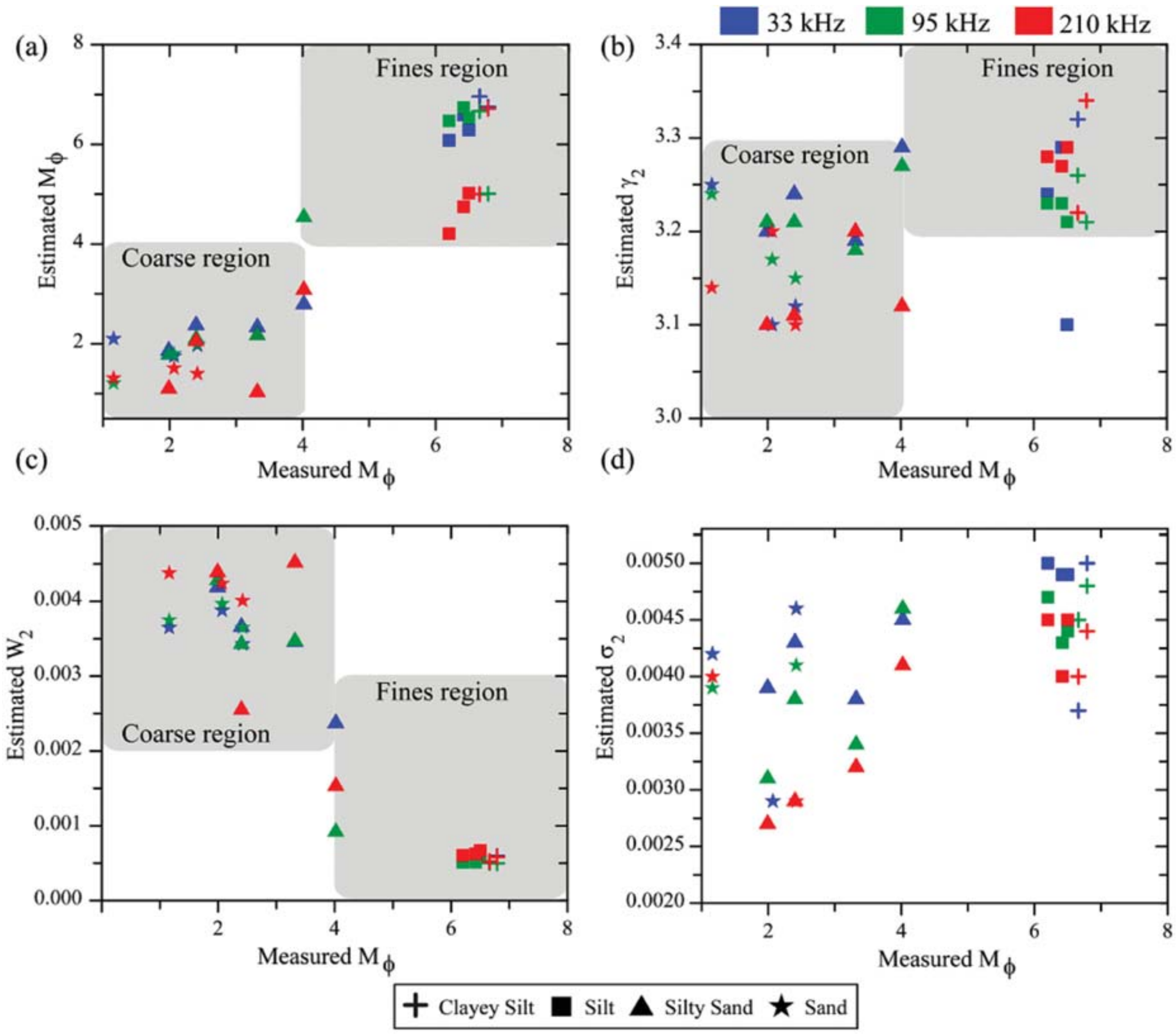

Fig. 5. The scatter plot showing multi-frequency inversion results (adopted from Haris *et al*, 2015).

In the coarse sediment region, the average σ_2 values are restricted around 0.0039±0.00059, 0.0034 ± 0.00063 and 0.0031 ± 0.00048, respectively, at 33, 95, and 210 kHz. In the fine sediment region, the average σ_2 values are found to be within 0.0047 ± 0.00056, 0.0045±0.00021, and 0.0043 ± 0.00026, respectively, for 33, 95, and 210 kHz. The computed σ_2 are important to provide convincing model-data comparison at the three acoustic frequencies (Fig. 5). Jackson and Briggs (1992) have reported dominant volume scattering in fine sediments. The experiment carried out by them demonstrated improved model-data comparison in the fine sediment region with relatively higher values of σ_2 (0.004 – 0.006). The σ_2 values computed in the fine sediments have been found to be relatively higher as compared with the coarse sediment region. An appropriate assessment on the accurateness of the estimated σ_2 values is difficult due to lack of supporting data and further studies are required to draw better conclusion.

3. CONCLUSIONS

The initial part of our review covers a broad classification of UA applications from the civilian and military perspectives. We primarily covered three aspects relevant to Underwater Acoustics (UA). A general historical aspect of the underwater transducer is discussed along with the array transducer development, which is an important 'wet end' component of any UA devices. Broadband transducer array and its design principals are covered, with a particular emphasis on the mutual interaction effect between the array elements. This effect, which degrades the transducer radiation pattern, is a significant aspect of underwater acoustics that warrants investigations. Our analyses include a number of references which can be useful for the readers.

UA propagation is a complex process that depends on many factors. One of the key factors is the sound speed gradients in the water, which play a crucial role in determining the direction of sound propagation. These speed gradients transform the sound wave through refraction, reflection, and dispersion, adding to the intrigue of underwater acoustics. In the ocean, the vertical gradients are generally much more significant than the horizontal ones. Combining this with a tendency towards increasing the sound speed at increasing depth due to the increasing pressure in the deep sea causes a reversal of the sound speed gradient in the thermocline, creating an efficient wave guide at the depth corresponding to the minimum sound speed. The sound speed profile may cause regions of low sound intensity called "Shadow Zones", and areas of high intensity called "Caustics". A Ray-tracing method is generally used to find these areas. Some basic aspects of the ocean's sound speed and the ATOC's historical elements, enlightening the readers about the intricacies of sound propagation in the ocean are briefed.

We covered investigations related to bottom scattering carried out in the Arabian Sea using hull-mounted sonar. The composite roughness scattering model (Jackson *et al.*, 1986) derived seafloor parameters using the 95 kHz MBES data are compared with the ground-truth data as well as with the inversion results obtained using 33 and 210 kHz SBES data at the same locations. The resulting geoacoustic parameters provide important information that can be utilized for acoustic seafloor characterization, demonstrating the practical applications of our research. Statistically significant correlations are noticeable between the models derived sediment mean grain size values and the ground truth sediment information, substantiating the multi-frequency inversion results. The sediment mean grain size $M_{\emptyset}$ and γ values estimated at 33 and 95 kHz appears to be marginally better as compared with 210 kHz. In the absence of measured roughness data, the computed roughness spectrum parameters are compared with the published information available in the literature. The computed γ and *w2* values are corroborated well with the published data, displaying subtle variations among 33, 95, and 210 kHz. Williams *et al.* (2002) have postulated transition of the scattering theory in the critical frequency range of 150-300 kHz. Utilizing the backscatter data of the experiments SAX99 and SAX04, Williams *et al.* (2009) have reported the emergence of a new scattering mechanism at 200 kHz or higher frequencies. Significant difference in scattering strength from the surrounding medium and the embedded coarse material in the controlled laboratory experiments is also obvious at higher frequencies between 150 kHz to 2 MHz (Ivakin and Sessarego, 2007). Besides, it has been reported that at higher frequencies (> 200 kHz), even a small portion of the embedded shell fragments can significantly alter the seafloor scattering characteristics, resulting in the subtle difference among the roughness parameters computed at 33, 95, and 210 kHz. In the context of multi-frequency inversion, the results derived using the 95 kHz MBES data are more correlated with the seafloor parameters corresponding to 33 kHz as compared with 210 kHz SBES data (Haris *et al.* 2011).

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