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Review Article

Indigenous Development of Acoustic Sounder (SODAR) in India as an Upgraded Technology for Environmental Protection: A Review

Anjali S Nair[a,c], Kirti Soni[b,c]*, Priyanka Singh[a,c], Nishant Kumar[b], Parag Chourey[a], Rohan Kamra[a], Kuldeep Meena[a,c] & Mahavir Singh[a,c]

[a]CSIR-National Physical Laboratory, New Delhi, 110 012, India

[b]CSIR – Advanced Materials and Process Research Institute (AMPRI), Bhopal- 462 026, India

[c]Academy of Scientific & Innovative Research, Ghaziabad 201 002, India

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Sound Detection and Ranging (SODAR) has moved to the forefront of consumer technology due to the pressing need to engage the Atmospheric Boundary Layer (ABL) in environmental protection. An active ground-based remote sensing system (SODAR) is used to determine the lower-atmosphere wind profile and temperature structure. SODAR can detect turbulence parameters in the ABL from a distance and can be used for wind profiling. SODAR, with its significantly enhanced capability, is expected to be a futuristic remote sensing device with several uses in the near future. Including an emphasis on its applications and current developments, this article examines SODAR's early history, with a review of Indian studies. The article examines past breakthroughs in SODAR as well as its advancement and applications, with an emphasis on India due to the worldwide nature of SODAR research. Additionally, the article discusses how effective SODAR is in protecting the environment and how important it is going forward. After summarising the applications, various opportunities and barriers incurred in SODAR use, a proposed review article to provide insights into previously understudied, unstudied, and studied research work accomplished on SODAR in India is constructed. The article accentuates the role of SODAR as an environmental safeguarding tool.

Key words: SODAR; ABL; Inversion; Convection; Air Pollution

1 Introduction

1.1 Atmospheric Boundary Layer (ABL)

One of the key physical characteristics of land-atmosphere interactions is described by the ABL. The development of the ABL is highly influenced by surface fluxes and reactive heat[1]. Such surface fluxes and turbulence act as a crucial factor, which facilitates the transfer of heat, water vapor, momentum, diffusion of pollutants etc. from one climate to another[2]. The depth and stability characteristics of the ABL vary temporarily and spatially due to the meso, diurnal, synoptic, and seasonal scales and the dynamicattributes of the surface and the intensity of weather patterns[3-7]. ABL is thus turbulent boundary layer influenced by Coriolis force and air density stratification in rotating heavy stratified fluid[8]. ABL is a crucial research attribute and is distinguished into three types: (i) Convective Boundary Layer (CBL), (ii) Stable Boundary Layer (SBL), (iii) Neutral or Dynamical Boundary Layer[9,10]. The vertical extent of ABL can vary greatly, from a few hundred meters to several thousand meters[11]. The ABL height is known to be a crucial parameter affecting the mean flow and turbulence structure[12].

1.2 Remote sensors for probing the ABL

Comparative capabilities of in-situ/conventional and remote sensing techniques for probing lower atmosphere are as shown in Table 1.

Indirect probing of the lower atmospheric layer can be done using remote sensing methods from the ground or from satellites. However, only ground-based remote sensing can offer the necessary vertical resolution and temporal coverage for a complete investigation of the ABL structure. ABL height may be measured using a variety of simple and trustworthy methods, as well as dependable prognostic models of calculation, during the daytime hours[12]. For the night time stable layer, both the measurement and prediction of ABL height have proven to be difficult and less reliable[12]. Conventional in situ techniques like radiosonde data were later found to be limited and inadequate to understand the meso and microscale phenomena in the atmospheric layer[6-7]. It was discerned that radiosonde was unsuitable to deliver

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*Corresponding authors: (Email: 2006.kirti@gmail.com)

Table 1 — Comparative analysis of in situ and remote sensing techniques for probing lower atmosphere

Instrument	*Continuous Data Output*	*Range*		*Resolution*	*Advantages*	*Limitations*	Nature of Tracers / Patterns	*Time Between Successive Measurements*
		Max	Min					
In-Situ Techniques								
Refractometer	A	10000	Ground	10	High accuracy with instant response time	Costly	Refractivity	2-12 hours interval
Radiosonde	A	1800	150	60	Long Range	Poor resolution, discontinuous data	Temperature, Humidity and wind	2-12 hours interval
Instrumental tower	B	300	3	3	High resolution with continuous yield of data	Very low Max. range	Temperature, Humidity and wind	10 sec
Tethered Balloon	A	1000	10	10	High resolution	Low max. Range and discontinuous data	Temperature, Humidity and wind	2-12 hours interval
Remote Sensing Techniques								
SODAR	B	3000	50	10	Abundance of natural tracers, low cost, high scattering cross section	Low range	Radialvelocity and thermal structures	10 sec
Mini-SODAR	B	250	20	10	Abundance of natural tracers, low cost, high scattering cross section, high sensitivity	Low range	Radialvelocity and thermal structures	5 sec
RASS	B	5000	50	30	Continuous temperature measurement	Expensive	Temperature profile	10 sec
RADAR	B	50000	200	100	Long range, high information rate	Poor spatial resolution	Radialvelocity and atmospheric structure	1 sec
LIDAR	B	5000	20	3	High resolution high data rate	Possible radiation induced hazards	Radial velocity Aerosol distribution	0.01 sec
Satellite Beacon	C	Integrated range		-	Potential technique in case of geostationary satellite	Difficulty towards accessibility of satellites	Refractivity	-

Note: - A - not fulfilled; B - fulfilled; C - partially fulfilled

continuous information having finite vertical resolution and meteorological masts was restricted for few hundreds meters[10]. Later, a vivid variety of remote sensing techniques have been deployed like optical (like Light Detection And Ranging (LIDAR)), radio (like Radio Detection And Ranging (RADAR) and Radio Acoustic Sounding System (RASS)), and acoustic (like Sound Detection and Ranging (SODAR)) waves to put out feelers to the lower atmosphere.

Gilman *et al.*[13] built the first SODAR in 1946. The backscattered intensity was recorded by SODAR for vertical probing of the lower atmospheric layer. It was found that the lower atmosphere can be better probed using acoustic techniques (such as SODAR) than with any other remote sensing technique due to a thousand times stronger refractive index fluctuations for sound waves than for electromagnetic waves in the boundary layer, making the scattering efficiency of sound waves one million times greater than that of electromagnetic waves[7,14-15]. With the remote acoustic sounding of ABL, it became easier to assess and evaluate the peculiarities of ABL, which precedes the commonality. Using SODAR as a distant sensing technology came into the forefront. SODAR works by sending sound pulses and monitoring the intensity and frequency of the returned signal, relative to the time it takes to assay the radial velocity and thermal structure of the atmosphere[16-18].

SODAR detects backscattered signals from atmospheric fluctuations of eddies after the acoustic pulses have been sent. SODAR signal dispersion was also explored by an integral equation technique on a rough circular body. An integral equation method was used to determine the scattering of SODAR signals to determine whether the scattering depends on the statistical properties of circular bodies[19].

1.3 Types of SODAR

The SODAR is classified depending on its applicability and structure. The collocated transmitter and receiver configuration form the monostatic SODAR. The transmitter and the receiver are recurrently merged into a single transceiver antenna[20]. In these SODARs, the thermal structure of the atmosphere is solely responsible for the intensity of backscattered signals[31]. Monostatic SODAR is thereby meant to study the qualitative nature of atmospheric thermal structures. Monostatic SODAR requires less space for its setup, which makes it advantageous in comparison to bistatic mode. However, monostatic SODAR accounts for a major limitation, as it cannot be used for continuous wind profiling. In contrast, the bistatic SODAR has a distinct transmitter and receiver separately placed to function individually[20]. The bistatic mode enables the transmission of signals scattered by minuscule velocity fluctuations and temperature in homogeneities in the atmosphere[20]. Total wind vector determination requires three transmitter-receiver combinations at a minimum, which began to be used in monostatic SODARs[20].

Phased array Doppler SODARs are modified versions of three-axis monostatic SODAR. An array of vertically pointing transceivers is used instead of three antenna dishes with a diameter of 1-2 m[20]. Total transceivers in phased array Doppler SODAR range between 20 m and over 100 m. The transceivers are slightly out of phase, allowing the acoustic beam to be electronically "steered" away from the vertical. As a result, a phased-array SODAR closely resembles the acoustic beam pattern generated by a three-axis monostatic system[20]. A bistatic Doppler system utilizes a separate receiver-transmitter pair, which usually points vertically, and a monostatic transceiver. A single transmitter and two independent receivers are used in one setup. Another design consists of single central receiver (the same as the monostatic receiver) and two separate transmitters. Depending on the setup, the transmitter or receiver is tilted at an oblique angle from the vertical of 15^0 to 30^0 toward the other[20]. The monostatic SODAR were meant to study the thermal structure; bistatic configuration for wind-shear structure and Doppler SODAR for three-dimensional wind information in-the lower atmosphere[6-7].

2 Development of SODAR

2.1 Progress history of SODAR

The development of SODAR started with the first investigation into acoustic echoes that began in 1874[21]. Due to the flocculent composition of the atmosphere, Tyndall[21] was the first to discover the persistence of sound echoes of a siren heard on a foggy day[22]. Later, in 1941 Russian researchers stated the existence of a statistical theory of sound scattering by turbulence[23]. Thereafter, the theory behind sound wave scattering was better explained and propounded during the last two decades by Monin[24] and Tatarskii[25].

In 1944, findings began to be made to study the heterogeneities in the atmosphere where it was found that the inversions and lapse rates due to strong humidity that caused abnormal radio refraction could also lead to favourable reflection of sound, which induced an attempt to deploy a sonic method for detecting the atmospheric heterogeneities[13]. This was the first study to record the observation of acoustic echoes from the lower atmosphere while working on anomalous transmission of microwaves in 1946 using SODAR for the first time[26-27].

Later, Gilman *et al.*[13] in 1946 used the ground-based explosion to determine the temperature profiles of the upper atmosphere. All these subsequent findings were derived from Kallistratova[28] scattering experiments, which led to Monin[24] estimate of the scattering cross section in terms of temperature and velocity, which coincided with Batchelor[29] results in 1957. After two decades of Gilman *et al.*[13] finding, McAllister[30], McAllister and Pollard[31], and McAllister *et al.*[32] took a significant step toward the contemporary SODAR system by being the first to use a facsimile recording of echo intensity referred to as SODAR gram. This recording enabled us to visualise the temporal variation of acoustic reflectivity of the atmosphere.

In the foreground, uses of acoustics echo for disparate utilization came forth. McAllister[30] in 1968 deployed the use of these acoustic echoes for measuring the incursions of marine air received from the fluctuations in the lower atmosphere. For the first time in 1964, Kelton and Bricout[33] used SODAR for measuring the wind speed and direction. Little[34] in 1969 conferred about various acoustic methods used for remote analysis of the atmosphere and evaluated the feasibility and limitations of the acoustic RADAR. Along these lines, Little[34] and McAllister[30] described SODAR as a research tool for delving into the lower atmosphere. Thereafter, during the1970s in the USA, the developmental studies on ground-based remote sensing of ABL began, which further expanded worldwide[23]. Since then, SODAR efficiency has improved with advancements in its model to deploy it for vivid practices. Further us abilities came forth with the advent of time.

Derr and Little[35] suggested several methodological approaches for wind measurement using SODAR. Beran and Willmarth[36] demonstrated that Doppler SODAR may be used to measure a component of horizontal wind in both monostatic and bistatic systems. Beran and Clifford[37] employed Doppler SODAR to determine wind speed utilising three refraction effects: the remotion of the scattering volume, the shift in the Doppler wind component's axis of resolution, and the shift in magnitude of the recorded wind[38]. In 1975, Fukushima *et al.*[39] used a concrete paraboloid dish as the antenna of the acoustic sounder for studying the lower atmosphere. In 1975, Neff[40] used SODAR derived values of temperature structure parameter C_T^2 and compared its results with the observations made on a 92-meter instrumented tower.

SODAR systems are now widely recognised as semiquantitative remote probes of the lower atmosphere, and they are being used in industrialised countries for monitoring purposes by environmental and industrial sectors, for atmospheric low-level investigations and meteorological services for specific forecasting purposes, and for further developing the technique and interpretation of SODAR data[41]. The technique's recent development to Doppler wind velocity readings utilising dedicated microprocessor analysis for immediately usable wind vector profiles significantly increases the acoustic sounder's potential in its diverse uses[42-43]. Monostatic SODARs and Doppler SODARs have now become a system for providing qualitative information on the stability of different atmospheric layers, depth of inversion studies, deriving mixing layer height as a factor for pollution analysis, thermal structure parameter studies, research related to wind shear and wind velocity in the boundary layer[42-43]. The year 1972 marks the beginning of SODAR's development in India, which is detailed in the sections below, with a focus on future refitting and adaptations in the systems.

2.2 Early SODAR development and its advancement in India

The Council of Scientific and Industrial Research-National Physical Laboratory (CSIR-NPL), New Delhi, initiated SODAR research and development in 1972[42-44]. The work was triggered with the intention of analysing the atmospheric stability for the study of air pollution, wind velocity profile and shear, diffusion coefficient, inversions, turbulence etc. At the outset, a bistatic SODAR (1972) was operational at CSIR-NPL, which gave backscattered signals from a distance up to 200 m on an average during clear nights. Originally, the co-located SODAR system was developed by the end of 1973 at CSIR-NPL[26-27]. However, because of the low range, poor signal to noise ratio, the co-located showed a poor display of the daytime convective phenomena. The co-located SODAR also exhibited various other problems like transducer alignment, beam drift, etc. Directivity and efficiency of the antenna were also different in the transmit and receive mode. With the advent of the use of this preamplifier circuit, a monostatic system was set up subsequently by the end of 1974 utilising the horn-reflector as the transmit-receiver antenna[26-27]. In 1974, improvements in earlier used transducers (antenna, metallic parabolic dish, cross array, and horn reflector) were also directed additionally so as to design and fabricate a reflector-horn acoustic transducer that could collimate the transmitting power into a narrow beam so as to gain sensitivity and directional characteristics[26-27]. Recently, a second monostatic SODAR system was set up at Aya Nagar Observatory of the Indian Metrological Department during the years 1976-77, which operated at acoustic frequencies of 1000 and 1600 Hz with a reflector horn as an antenna. It was basically set up with the idea of calibrating the thermal structures obtained through SODAR with those of radiosonde data. This was a breakthrough initiative as the data used was known to be utilised to study the transport and dispersion properties of pollutants through mixing height and microwave propagation characteristics in the lower atmosphere[45]. In 1976, a major revolution also eventualized where facsimile records for procurement of ABL structures supplanted photographs taken with a camera attached to a cathode oscilloscope. The facsimile records generated through SODAR were used to study the thermal plumes, temperature inversions, convective layers formed during unstable atmospheric conditions, stable layer conditions[46]. Thereafter, SODAR became a widely accepted tool for various observational studies in relation to tropospheric phenomena.

Akin to this application, SODAR, along with radiosonde, satellite radio beacon technique, RADAR, and microbarograph, was deployed by CSIR-NPL to analyse the tropospheric anomalies incurred during December 1974 over Delhi[47]. In 1977, the SODAR echograms were analysed to appraise the convective and inversion layers formed along with the instabilities and perturbations occurring under stable atmospheric conditions[48]. By 1981, SODAR was ameliorated to a computer-controlled system[49]. Despite the achievements and developments, by the end of 1986, it was sensed that the monostatic systems in use at CSIR-NPL, had a noise problem. The signal obtained by SODAR after backscattering was found to be feeble in comparison to the ambient noise received along the transmission. To surmount this issue, use of a parabolic dish as an antenna covered by a partial sound absorbing and partial sound insulating screen, a 90^0-side lobe rejection of 55-60 dB was achieved[50].

By 1992, it had been discovered that improving side lobe rejection by encircling SODAR with an acoustical absorbent shield was required for operation in an ambient noise environment. To solve the problem, a screen with a horizontal section in an octagon shape was created, with each panel in the trapezoid shape of the sloping octagonal assembly. Another shield, in the form of erecting a wall over the paraboloid dish transducer's edge, was also fabricated[51]. Thus, with the improvement in its constituents, the CSIR-NPL SODAR was able to offer a prodigious juncture to explore the tropospheric disturbances. Tripathy *et al.*[51] at the Indian Statistical Institute (ISI), Calcutta, earlier tried to implement a computational methodology for theseparation of individual plumes represented through facsimile records using monostatic SODAR. The obtained data were initially processed for noise removal before being saved on the computer. This work initiated and induced an opportunity for further improvement in SODAR with the incorporation of computational systems[51].

The restrictions of using electronic hardware circuits in their physical forms, as well as pricey add-on data-gathering cards were still considered one of the major problems encountered in early SODAR system. Therefore, the idea of advancing and modifying the computation part of SODAR was given high priority. Thus, the LabVIEW platform was created for data collection that employed virtual instrumentation software to reduce the need for several electronic circuits. A SODAR data collection system was successfully developed using the soundcard capabilities of new-generation Pentium IV series computers. Using any normal computer, even laptops, the technology allowed cost-effective SODAR creation and trouble-free operation. Producing transportable mobile SODAR programmes for field investigations was one of the benefits of decreasing hardware. Not only can signals be retrieved from heavy noise using the innovative concept of pulse volume data analysis for noise filtration, but it also enhances the signal-to-noise ratio of facsimile plots and extends the operational range. The approach allowed the current SODAR to map degrading inversion across a distance of more than 2000 meters, whereas the prior CSIR-NPL SODAR design could only detect it up to 700 meters. This became obsolete as new technologies emerge[49].

2.2.1 Operational Highlights and Technical Specifications of SODAR at CSIR-NPL

The monostatic SODAR installed at CSIR-NPL transmits highly directional high-power short bursts of sound energy (10-20 Watts) of fixed audio frequency between 1 KHz-4 KHz with a duration of about 100 milli seconds (ms), with a repetition rate of 4 seconds for a 1 km probing range. The backscatter acoustic signal from atmospheric fluctuations of eddy sizes 0.1-1m within the inertial subrange of turbulence is received by the same antenna (monostatic). The signals are refined and processed to produce a pictorial view of the turbulent region occurring in real space and time above the antenna. When the upward-directed pulse encounters temperature in turbulence-generated homogeneities, weak dispersed waves are created within the air itself. The backscattered acoustic waves towards the ground, the echo, are detected using the same transducers that probe beam. The SODAR system reported in the present study has been calibrated in anechoic chambers at CSIR- NPL India, by using a method reported by Danilov[52-53].

The technical specifications of CSIR-NPL operated SODAR is enlisted in Table 2.

Development stages of new SODAR at CSIR-NPL, India

The evolution of SODAR in India (CSIR-NPL) is summarized chronologically through the flow chart as shown in Fig. 1.

3 SODAR Echoes

Depending on the type of stability (stable or unstable) in the lower atmosphere, the SODAR records show two distinct classes of echoes: thermal echoes and shear echoes[54]. Thermal echoes are demarcated as vertical lines on the facsimile record and resemble stalagmites rising from the ground. They are accurate representations of vertical mixing with an unstable vertical temperature profile[54]. Thermal echoes occur during conditions when the surface is comparatively much warmer than the air above the surface[55]. Shear echoes are horizontal echoes are that depict the turbulent interface between two layers of air[54]. The wind shear that dominates over the stable temperature profile is responsible for the turbulence. As a result, these are wind-driven echoes (shear echoes), which can be shallow or deep and indicate a mixing region aloft or a boundary layer region at the surface.

Varied thermal structures formed by SODAR with varying meteorological conditions

Depending on the weather, SODAR develops a range of thermal structures. However, the structures shown on SODAR echograms are not necessarily simple and uniform. The classification of prominent, though distinctively important, ABL structures using SODAR echograms encompasses the Rising Layer (Solar energy erodes the nocturnal stable layer at dawn, resulting in ground-based thermal plumes capped by a rising stable layer), Foggy: SODAR can aid in predictive modeling of fog clearance by measuring real-time variations of the fog layer's vertical depth and properties of foggy ABL[56]; Kelvin-Helmholtz Billows (KHB) (KHB are gravity-shear waves which are responsible for the generation of turbulence and vertical exchange of heat and mass in a stable stratified atmosphere); Multilayer (SODAR

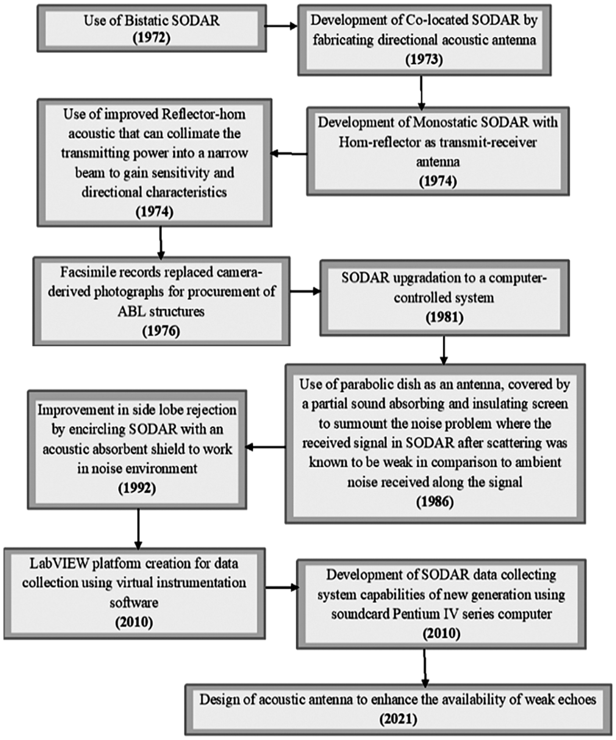

Fig. 1 — Flow chart for the developmental stages of SODAR at CSIR-NPL, India

Table 2 — Technical specifications of CSIR-NPL operated SODAR

Transmitted power (electrical)	90 Watts
Transmitted power (acoustical)	15 Watts
Pulse width	100 ms
Pulse repetition period	4 sec
Operational range	1000 m
Receiver bandwidth	50 Hz
Frequency of operation	2250 Hz
Acoustic velocity	340 m/s (average)
Receiver Gain	80 dB
Transmit-receive antenna	Parabolic reflector dish surrounded byconical acoustic cuff
Receiver area	2.5 sq. m
Pre amplifier sensitivity	The fraction of a micro-Volt

echograms with multilayer are obtained during night time). The multilayer (elevated) structure represents shear (stable) structure under the prevalence of light wind[42-43].

4 EPA amendment for regulatory guidance of deployment of SODAR for air quality management

SODAR has been approved as a part of Environmental Impact Assessment (EIA) studies for the past many years[55-56]. The prominent examples include the United States of America (USA) wherein more comprehensive guidance was provided for the use of remote sensing (SODAR) and radiosonde in upper-air meteorological monitoring[57]. SODAR been tagged to be used as a part of air quality modelling in EIA in many parts of the world. SODAR data is required for EIA studies and real-time risk analysis, traffic transit planning, chimney design, and the establishment of industrial operational hours in order to take advantage of the ABL convective state for maximum pollution dilution[55-58].

5 Stability class and SODAR structure classification

Atmospheric stability is a measure of the prevalent strength of turbulence that extends over a large spectrum. It goes from strong turbulence (very unstable ABL) to almost no turbulence (very stable ABL)[59]. Pasquill[60] divided the stability classification for atmospheric turbulence into six classes, namely A, B, C, D, E, and F, where class A was meant to be the most turbulent or highly unstable class and Class F being the most stable or least turbulent. An attempt was made to correlate SODAR induced structures with Pasquill stability class[4-5,15,61-63].Thus,six stability classes (A, B, C, D, E, and F) were assigned to the thermal structures depending on their variations. The stability class was assigned with the aim of using these data for monitoring and regulating air pollution. However, a major drawback noted was that the data on wind direction changes used to explore the link of Pasquill stability classification to SODAR structures was only for a short period (around l000 h), so some of the conclusions may not be truly representative for longer periods. An advanced study using LabVIEW (Laboratory Virtual Instrument Engineering Workbench) based programme was successfully developed to study the stability classes (A-F) for different ABL height structures where ABL height variability in association with the meteorological parameters to govern the stability of the atmosphere was studied[63].

6 Major applications of SODAR

There are numerous parameters that SODAR can measure directly and indirectly which are listed in Table 3 and are explained in the below sections.

6.1 SODAR in microwave and radiowave propagation

In the post liminary, Singal[58] stated the role of SODAR in radio wave propagation studies, where monostatic SODAR was used to derive real-time data of ABL height, its stratification, and the structural strength of the inversion layer, which aided in planning radio wave propagation at a locus in India, since 1982. It was also highlighted during the course of the findings that SODAR data, when combined with humidity data, can greatly aid in the planning and operation of Ultra High Frequency (UHF), Very High Frequency (VHF), and microwave communication connections[58]. Gilman *et al.*[13] was the first to employ an acoustic sounder to investigate the fading in the tropospheric trans horizon microwave radio circuit running between New York and Neshanic, New Jersey. Withal, in 1980, studies in India demonstrated that SODAR could also act as an indicator of microwave propagation[64].

A correlation between SODAR structures and microwave signal characteristic patterns was canvased and checked over using monostatic SODAR along with a sensitive microwave receiver placed at CSIR-NPL used to study the characteristics of microwave signals over the line-of-sight path between Delhi and Sonepat[64]. Similarly, three line-of-sight microwave lines in the southern portion of India were monitored 24 hours a day, 7 days a week for a year. The study was based on acoustic sounding data collected over Tirupati from January to December 1988. It was discovered that in the months leading up to the monsoon, there had been a noticeable dimming of microwave signals. It was concluded that these

Table 3 — Parameters measured(Directly/indirectly) from SODAR

Marine boundary layer characteristics
ABL characteristics during seasonal transition and solar eclipses
Prediction of air pollution and civil aviation via weather surveillance
Prediction of natural calamities
Wind profiling
Idiosyncratic monsoon study
Probing the lower layer of atmosphere (ABL)
Determination of cross wind dispersion coefficient
Determination of effective stack height
Determination of Ventilation Coefficient (VC)

signals were known to be unaffected by daytime convective conditions, but ground-based inversions, raised layers, rising inversions, and wave motions were blamed for the observed fading[65]. Rao[66] tried to explore radio wave propagation characteristics of LOS microwave links positioned over hilly terrains. Simultaneous observations of SODAR echograms, infrasonic pressure fluctuations, and microwave amplitude measurements were made and monitored around the clock for a period of one year. For this the LOS microwave linkages connecting Tiruttani-Tirupati, Elagiri-Tirunnala, and Pallavaram-Triumala were used. These investigations revealed ground-based inversions, raised layers, rising inversions, and wave motions are the sole responsible factors for signal fading[66]. Analogously monostatic SODAR was utilized in a study where an attempt was made to evaluate signal fade-outs in prolonged way observed over the Line of Sight (LoS) microwave link between Tiruttani and Tirupati[67].

A study carried out in the Assam regarding the fading of microwave signals over Milmilia-Durgasarovar, Maopet- Durgasarovar and Laopani-Habaipur links of the Assam valley was found to be attributed to the changing meteorological and atmospheric variabilities derived from two SODAR units[68]. Consonantly, the microwave signal fading characteristics collected over Milmilia, Maopet, and Laopani LoS over the Assam valley were analysed using supporting meteorological parameters and ABL characteristics collected from SODAR[69]. Further, in a similar investigation, six microwave links were utilised in Southern India to evaluate the strength of the microwave signal using monostatic SODAR. It was discovered that the most fading occurs during dissolution and the formation of night time temperature inversions[66]. The influence of path inclination on fading of microwave signal was investigated using data acquired from three LoS microwave lines throughout the Indian subcontinent[70]. Later, strength of microwave signal was studied for three years along two hop LoS microwave links in southern India between Elagiri-Tirumala and Pallavaram-Tirumala, and the study was connected with the ABL structures reinforced by SODAR and Radiosonde data[71].

The field strength data of three LoS links operating at 6-7 GHz distributed across the southern plains, east coast, and northern plains were used to conduct a thorough investigation into the fading phenomenon. The microwave field strength data was collected every 24 hours utilising the microwave links Delhi-Sonepat, Dumdum-Andul, and Tirupati-Tiruttani. The radiosonde flight data was used to deduce the meteorological conditions affecting the operation of the LoS connection. These were augmented by SODAR observations. At the receiving ends of the communication cables, SODARs were in use[72]. Rao *et al.*[73] studied radio-wave propagation characteristics on a LoS microwave link over hilly terrains, utilising SODAR echograms and microwave amplitude measurements on an operational communication link between Tirupati and Tiruttani in Southern India. Rao *et al.*[74] studied the dynamics of ABL structures and their influence on microwave propagation. For the analysis, a monostatic SODAR with a frequency of 2.2 KHz during operation was developed by S.V. University, Tirupati[74]. An inversion was discovered to be the atmospheric condition affecting microwave signal amplitude in the investigation. SODAR was also used to study the effect of terrain and environmental effects on microwave frequencies over areas of the Assam valley[75].

6.2 SODAR for characteristic study of Marine Boundary Layer and Sea-Land Breeze

Eventually, SODAR began to be modified to study the varied patterns in atmospheric structures over the marine boundary layer[76]. The aforesaid study was done over the Tarapur coastal site to determine the thermal structure characteristics of seashore areas using SODAR and meteorological towers during land and sea breeze[76]. This study was put forward anew over Tarapur to ascertain the base and thickness of sea breeze[77]. In 1981, a preliminary study at Visakhapatnam on sea breeze fronts was initiated using acoustic radar (SODAR). The acoustic radar derived data was used to determine the frequency of occurrence and decay of sea breeze circulations, their variability in structure, depth, and intensity, capping layer formation during the sea breeze and the influence of the sea breeze on convective plumes[78]. A congruous study was propounded in Visakhapatnam to study the turbulent and thermal inhomogeneity of the sea breeze front using SODAR during the Southwest monsoon season[79].

In 1985, the study of sea breeze was repeated in Visakhapatnam, using two monostatic SODAR installed near the university site and the airport meteorological observatory, respectively, where the main features of sea breeze were studied as it penetrated the inland, in order to find the sea breeze at two locations that differ markedly in terms of their onset, duration, depth, and thermal turbulence distribution[80]. A special study on the variability of sea breeze structure during the month of May was also conducted at Visakhapatnam using Monostatic SODAR[81]. A collaborative study discovered that the presence of sea breezes along coastlines reduces convective instability and nocturnal stability of the marine boundary layer[82]. SODAR was used to study the sea breeze circulation over Tarapur and Vishakapatnam where the marine boundary layer structures were scanned and analysed[83]. Kunhi krishnan *et al.*[84] performed a case study of sea breeze circulation over Thumba using SODAR, GPS sonde, Radiosonde, and surface data that was then numerically simulated using High Resolution Model (HRM). Each instrumental data was specifically destined to derive different observations during the circulation period.

Studies related to changes in stability over marine areas are useful as they can act as an input to atmospheric diffusion prediction models in coastal industrial cities. In addition, Doppler Mini-SODAR to administer the wind profile and development of coastal boundary layer due to land and sea breeze for monitoring coastal dispersion of pollutants was also studied at Kalpakkam nuclear site[85]. The Doppler SODAR system at the National Atmospheric Research Laboratory (NARL), Gadanki, India, evaluated the characteristics of sea breeze circulations over a tropical Indian station based on one-year observations. The impact of sea breeze circulations on the dynamics of low-level flow patterns in the ABL over complicated terrain in the tropics was studied[86-88].

6.3 SODAR at ABL characteristics study during transitional change of seasons

A study was carried out at Anupuram near Kalpakkam nuclear site, using a mini SODAR to study the ABL during a transition from winter to summer. The effect of shifting synoptic scale conditions on Thermal Internal Boundary Layer (TIBL) turbulent properties was examined[89].

6.4 Variation in ABL during Solar eclipse

SODAR installed at Tarapur was used to study the variations in the ABL during the solar eclipse of Feb 16, 1980 where it was found that during the eclipse, atmospheric instability decreased to below normal levels, yet the atmosphere never became stable[90]. SODAR was used de novo to determine the variation in ABL during solar eclipse on 24 October, 1995 at Bombay so as to examine the changes in meteorological parameters, solar radiation pollutant load on the day[91]. A collection of sensors, an automatic weather station, Doppler SODAR, and GPS sonde, was used to investigate variations in the ABL during the solar eclipse over Gadanki[92].

6.5 Prediction of air pollution and civil aviation via weather surveillance

SODAR advancement facilitated it as a tool in predicting situations of severe air pollution and civil aviation where different weather conditions were scrutinised by analysing the anomalies in the echogram structure. One such significant study was the analysis of fog conditions as well as the anomalies observed during this course of time over Delhi during the month of December[93].

6.6 Predicting natural calamities

SODAR is used to study and predict the occurrence of natural calamities. SODAR was deployed to study an unprecedented tornado over Delhi as well as the undulations observed over the surface in March 1978. The observations revealed the occurrence of turbulence by tornadoes in the atmosphere on a random and periodic basis[94]. Gera *et al.*[49] observed a unique atmospheric wave using monostatic SODAR installed at Vapi on 25 January 2001 prior to the earthquake that jolted Bhuj on 26 January 2011. The atmospheric dynamics featured by SODAR echogram were used in Gauhati University for the prediction of earthquakes wherein an earthquake induced gravity wave was seen in SODAR echogram[95]. Monostatic SODAR was used to study the effects of thunderstorms on the propagation of VHF signals over coastal areas of Bay of Bengal. This study enabled the prediction of onset of thunderstorms[96].

6.7 Associating Meteorological parameters with SODAR derived ABL height

In a study, the intensity information derived from SODAR of Delhi was used to study the temperature structure parameter over the area by applying moisture correction and refractive index structure parameter index[42]. It was found that during moist weather with light wind and steady stratified layer conditions, SODAR echograms revealed a unique dot-shaped echo. The back-scattered acoustic energy was known to be the contribution of correlated changes in temperature and humidity (turbulent mixing) in the inertial subrange, according to these dot-shaped echoes, which are clusters of water vapour translated by the wind in the boundary layer[97,54]. Later in 1986, the effects of wind speed on the formation of these structures, where surface wind speed of less than or equal to 2.5 m/s (under stable conditions) was the dominant factor for formation of most of the shear echoes was studied. At Kolar Gold Fields, the influence of meteorological parameters on ABL height was also investigated, as was the estimation of dispersion coefficient[98].

6.8 SODAR as tool for air quality management

Studies began to be diverted towards establishing a correlation between pollutant concentration and ABL stability, aiding as a key factor for air quality management. In 1986, Singal[99] figured outa correlation between the surface level concentration of CO and the stability of the ABL, where SODAR was used as a powerful tool to map the dispersive condition of the 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. The prominence of ABL height in air quality improvement expedited numerous experiments to investigate 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[100]. Again, SODAR was used to extract the ABL height during a study to determine the pollutant dispersion at low wind speeds using steady state mathematical models[101]. 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[102]. Soni *et al.*[103] 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[104]. Goyal *et al.*[106] used SODAR derived mixing height as one of the methods for determination of Ventilation Coefficient (VC) to determine the assimilative capacity of Gangtok city[69]. SODAR was used in a case study to investigate pollutant dispersion modeling in particular[105].

SODAR was used at open-cast coal mining sites as a part of the Dudhichua project and the Bharatpur opencast project so as to determine the dust emission factors over four different seasons[106]. SODAR was used to determine the stability class for both projects during four different seasons (post-monsoon, winter, summer, and monsoon). A Doppler and monostatic SODAR were used to analyse various parameters (wind speed, wind direction, mixing height and VC) over various coal mines of Jharia namely Indian Reserve of coking coal[107], Bharat coking coal Ltd.[108-109], open cast coal project for coking coal, Jharia[110], Jharia coal field[111], and Dhanbad[60]. At the Rajpura mine, a Doppler SODAR was placed to gather detailed micro-meteorological data, including mixing height for air quality modelling[112]. SODAR was used to calculate micro-meteorological data, including the mixing height, in a similar study in Rajpura to build empirical equations for determining emission rate from various open cast mining operations[113].

In a study on aerosol optical depth measurements over different wavelengths over different locations in the central India region ranging from Delhi to Hyderabad as a part of Indian Space Research Organisation -Geosphere Biosphere Programme (ISRO-GBP), the mixing height over these regions was also extracted using SODAR[114]. Doppler SODAR was used to determine the ABL height during a campaign conducted for Aerosols, gases and radiation Budget over India under ISRO-GBP[115]. Facsimile echograms for Pasquill stability classification with a novel approach to correlate depth of stable boundary layer with turbulent parameter and Richardson's number was carried out by Gera and Singal[116].

6.9 Wind Profiling studies and Engagement of Doppler SODAR

The use of SODAR on wind profiling and its related studies in India started in early 1983. Singal *et al.*[5] carried out 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[117]. Adjacently, the use of Doppler SODAR also startedexpanding. Doppler SODAR is meant for wind speed and wind direction studies[118]. Gupta *et al.*[119] found that Doppler SODAR along with a thermal probe was used to estimate sensible heat flux and was applicable to CBL during the morning hours. The findings of the research aided in predicting the dynamics of the inversion layer rise in the inversion capped CBL. Rao *et al.*[120] used Doppler SODAR to study the diurnal variation of horizontal wind speed and direction for the onset of sea breeze.

For a study carried out at the Indian Tropical Station at Gadanki, Doppler SODAR was utilised to investigate the properties of inertia gravity waves in the atmospheric boundary layer during the passage of Tropical Cyclone-03B[121]. At Gadanki, thereafter, 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 the 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)[122]. Latha and Murthy[124] demonstrated alterations in the wind field and thermal structure in the lower atmosphere during thunderstorm events that occurred over Pune using Doppler SODAR[123]. Doppler SODAR was then used to investigate dominant mechanisms that result in the occurrence of jets in India's Western Ghats[124]. Using wind speed data gathered using the SODAR technology, wind characteristics in Kayathar, Tamil Nadu, India were analyzed[125-126]. A comparison of nine alternative Weibull parameter estimation methods was carried out[125]. The wind shear effect was further explored by conducting the analysis at three different heights: 80 meters, 100 meters, and 120 meters. Finally, the accuracy of data gathered using the SODAR methodology and the cup anemometer method was compared[125]. A similar experiment was carried out in 2018 where LIDAR and SODAR techniques were compared in terms of their performance for the analytical testing of nine numerical methods in determining the Weibull function for wind energy applications through statistical testing and observation data analysis[127]. Abdelsalam *et al.*[128] studied wind turbine wake measurements using SODAR for wind speed profiles so as to evaluate the turbulence models. Pithani *et al.*[129] used mini SODAR for obtaining wind profiles in the surface layer at a vertical resolution of 5 m, so as to evaluate the performance of four Planetary Boundary layer (PBL) parametrization and five cloud microphysics schemes in Weather Research Forecasting for a detailed analysis of the fog event occurred at Barkachha, a rural area over the Indo Gangetic Plain (IGP) on 4-6 December 2014. Babu *et al.*[130] intended to design a phased array antenna for Doppler SODARs for effective wind profiling. The antenna has been designed in such a way that it has 8 x 8 array tweeters and the mathematical algorithms used for designing have been computerised using MATLAB.

The 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), to generate 100 W acoustic power and provide wind profiles up to 1 km under favourable atmospheric conditions[180]. Rao *et al.*[131] studied the implementation of multifrequency transmission of a Doppler SODAR and its decoding to extract the atmospheric parameters used for atmospheric profiling.

Doppler SODAR was also used to study the structure of the Nocturnal Boundary Layer (NBL) as well, its seasonal variation, characteristics of different types of NBL[132]. In an experiment carried out at Gadanki during two consecutive monsoon seasons, 2007 and 2008, Doppler SODAR measurements over a tropical Indian station at the NARL, Gadanki were investigated to study the influence of mechanically generated turbulence on temperature structure parameter (C_T^2) in the CBL[133]. Shravan and Anandan[134] 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)[134]. During stable and unstable situations, the influence of complex terrain effects on wind flow patterns was estimated by NCEP/NCAR reanalysis II in comparison to remote sensor (NARL Doppler SODAR)[134]. The 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_T^2), and velocity structure function (C_v^2) of the atmospheric boundary layer are studied using these data. It was found that on most days, (C_T^2) follows a $Z^{-4/3}$ law, whereas (C_v^2) does not follow a systematic pattern[135]. In the interim of the execution of MONTBLEX for probing, the ABL Doppler SODAR was deployed at IIT Kharagpur and Monostatic SODARs at four tower stations (Varanasi, Delhi, Jodhpur and Calcutta)[136]. The Doppler SODAR was meant to access the horizontal wind, vertical wind, and temperature distribution to a height of 1.5 km within a radius of 60 km and the monostatic SODAR was used to derive the height of the boundary layer, stratified layers, thermals, plumes, wind shear layers, and inversion layers[136]. Wind and turbulence characteristics were estimated using similarity relationships for the atmospheric surface layer, which were compared to data from a three-axis monostatic SODAR[137]. During the course of study, SODAR mixing height and vertical velocity variance during daytime convective circumstances were used to calculate heat flux[137].

The inconstancy in the ABL over the coastal station of Thumba, with special attention towards the changes brought about during low level jets was studied using Doppler SODAR inclusive of tethersonde and low based micro-meteorological instrument[138]. To study the turbulent nature of vertical wind (w) and temperature structure parameter (C_T^2) during the convective conditions, a Doppler SODAR was installed at Thumba, Thiruvananthapuram[139]. The seasonal change of vertical and horizontal wind speed over the marine boundary layer is studied using a Doppler SODAR deployed at Indira Gandhi Centre for Atomic Research (IGCAR) Kalpakkam. During the study, vertical profiles were used to investigate the variation in mean horizontal wind speed with height over different seasons[140].

6.10 Idiosyncratic monsoon study

A study conducted in Pune using Doppler SODAR aimed at determining the characteristics of thunderstorms that occur during the pre-monsoon and monsoon seasons[141]. Choudhury *et al.*[142] engaged SODAR to define and observe different structures of ABL that included multi-layered structures, ground-based inversion, wavy structures during pre-monsoon thunderstorm over the eastern region of India. A monostatic SODAR was developed to provide useful information regarding the depth and type of turbulent ABL's thermal structure at Jodhpur to study the ABL dynamics near the western end of the monsoon trough[142]. A careful investigation of the SODAR echograms in relation to meteorological data has also been found to be useful as indicators of monsoon characteristics[143]. The lower atmospheric structure over the western side of the monsoon trough region was studied using SODAR and radiosonde data over Jodhpur. The SODAR echograms were studied to define the stability of the atmospheric layer[144]. SODAR was used to derive the ABL height data to study about the rain episodes over desert region of pre-monsoon, monsoon trough. The purpose of the study was to look at ABL interactions in the monsoon trough region, with a focus on the influence of the desert in regional circulation[145]. The nature of boundary layer during the onset of monsoon was studied at and around Kharagpur fetching data from Kharagpur and Kalaikunda. The study found the existence of low-level jets during morning hours at around 300 m level in SODAR[146]. When significant synoptic scale disturbances from the north Bay of Bengal travelled along the eastern edge of the monsoon trough, Doppler SODAR wind data for the boundary layer over Kharagpur acquired during MONTBLEX- 1990 at a height interval of 30 m from surface up to 1500 m was analysed. The effect of synoptic scale disturbances on the vertical wind profile in the lower boundary layer was investigated[147]. The MONTBLEX data obtained from a Doppler SODAR over the land station Kharagpur was used to investigate characteristic wavelengths for the u and v (horizontal wind components) components of wind (near sea-coast). SODAR, as a part of MONTBLEX-90 experiment, was installed at Kharagpur to study the NBL during the monsoon period[148]. The conserved-variable technique of analysis was used to investigate the characteristics of the convectively driven monsoon-trough boundary layer. The dynamical characteristics of the CBL have been studied using thermodynamic parameters. Mixed-layer heights acquired from SODAR at an inland station in the monsoon trough region were also used to document the saturation of the mixed layer following the start of the monsoon The experiment was carried out in Delhi, Jodhpur, Calcutta and Bhubaneswar[149]. SODAR was installed at Kharagpur, India as a part of monsoon Trough Boundary layer Experiment so as to determine the monthly wind field variation in the convective boundary during South-West monsoon season period, 1990[150].

6.11 Probing the lower layer of atmosphere (ABL)

Use of SODAR in examining the ABL was the most prominent advantage offered to atmospheric studies. Enormous studies have been carried out where SODAR derived ABL height and its characteristics were taken into consideration during the research. Dutta *et al.*[151] developed a shipborne acoustic sounder for remote sensing of ABL over the ocean. Over the ground-based inversion, SODAR echogram structures were taken and analysed at the ISI, Calcutta, frequently to study the stratified or raised strata. These structures were found to be observed frequently after thunderstorms and rain[152]. Moorthy *et al.*[153] used SODAR as one of the analysing devices to study the ABL over the Indian Landmass. SODAR and microbarograph were used to study the characteristics of thermal plumes in the ABL at S.V. University Tirupati. A better understanding of dynamics of thermal plumes was gathered using these two sensors[154]. During April-August 1991, the Indian Institute of Tropical Meteorology (IITM) in Pune conducted a coordinated experiment employing SODAR and LIDAR to explore the night atmospheric structure. The nocturnal mixing height and stably stratified or multi-raised layers aloft were determined during the experiment[155]. Singal *et al.*[6] examined the acoustic back-scattering intensity of vertical and inclined SODAR antennas in the convective environment that was measured as a function of zenith and azimuth. The observed aberrant behaviour in acoustic back-scattering is thought to be caused by small-scale anisotropic inhomogeneities in the turbulent thermal structure of the atmospheric boundary layer. Simultaneous measurements of backscattered characteristics by SODAR and air temperature via sensitive temperature sensors are used to attempt rain prediction. Guwahati has been the location of the setups. The study looked at backscattered echoes from SODAR for short-term rain predictions (a few minutes to 2/3 hours) and described aspects like (1) ABL height rise, (2) ABL height break, and (3) development of wavy patterns in the echogram as rain forecasters[156]. De *et al.*[157] developed an integrated modular unified strategy for automated interpretation of ABL structures where users can select a wide variety of image processing and the pattern recognition techniques necessary to retrieve weather data from a remote geometric image from the SODAR pattern boundary known by SODAPRETER were developed. The model with further upgradation was expected to interpret almost all possible ABL structure patterns recorded in the SODAR system. Mukherjee *et al.*[158] used a fuzzy c-means classification algorithm for classifying and segmenting the SODAR image for interpretation of ABL structure.

The nature of waves and amplitude of wave motions in terms of diurnal and seasonal variation of ABL were studied over Tirupati for two years using SODAR and microbarograph.The study found the occurrence of gravity waves in the atmosphere during the winter and pre-monsoon seasons due to thunderstorms and temperature inversions. SODAR facsimile record, along with microbarograph data, tend to give a reasonable picture of atmospheric dynamics. The study relevant to this was carried out in Tirupati, where monostatic SODAR was used to study the dynamic behaviour of ABL over Tirupati. Short period wave caused due to onset of drainage low encountered during convective plume activity or ground-based inversions at the evening transition hours were studied through combined efforts deliberated by SODAR and Microbarograph[159-160]. The dynamic state of the atmosphere can be used to get information on the Pasquill stability class of the atmosphere. Additionally, the onset of nocturnal drainage flowing under convection/thermal inversions of variable depth was analysed[161].

6.12 Determination of cross wind dispersion coefficient

Gera and Singal[16] made an approach for calculating the cross-wind dispersion coefficient using SODAR has been disclosed by. The ABL echograms was also studied to differentiate the echo structures to investigate the dispersion of pollutant efficiency.

6.13 Determination of effective stack height

A comparison was made between the actual Stack Height measured using Briggs and the SODAR data calculated in Chittorgarh (India)[55]. The findings stated that the effective stack height of the Briggs equations was found to be approximately 20% lower than that of SODAR records. However, it is also stated that since it is generally known that Briggs equation values can be imprecise by up to 50%, that the projected SODAR record values are in line with the Briggs equation[55]. The role of ABL in the establishment of a super thermal power plant in Northern India with the influence of ABL characteristics in fixing stack height and determining air pollution meteorology was studied using SODAR data[162].

6.14 Sundry appositeness of SODAR

Earlier, geometrical shape features extracted from SODAR were used to classify atmospheric patterns which were scale dependent. Using fractal characteristics, an attempt was made to classify SODAR data, which acted as an immediate solution to the encountered issue[163]. Chatterjee and Das[164] adopted a two-step filtering pre-processing approach to detect continuous boundaries for ABL. The process removed noise that can be found in the SODAR images. The method also enabled joining the fragments of the ABL contour excavated through image thresholding by pattern-specific region growing[164].

SODAR was used to test the reliability of an experiment carried out to derive a new methodology which considers the vertical temperature structure of MONTBLEX'90 for measuring the surface parameters and surface heat flux at the Indian Institute of Technology (IIT), Kharagpur[125]. SODAR was used to define the wave motion and its characteristics in terms of diurnal variation, percentage of occurrence, period, height of waves, its amplitude in the ABL. Wave movements connected with various structures had their power spectral densities been calculated[164]. A microprocessor-based SODAR system was developed to improve operational flexibility and utility by presenting temperature structural properties with greater sensitivity. The system also had more data storage capacity and was more flexible in terms of sampling and display parameter[165]. To remove the majority of the sounds, an algorithm based on image processing techniques was created, as well as a method of global thresholding for pattern extraction from echograms. According to the study, online capture of back-scattered signals and the use of modern image processing techniques can assist in keeping noise levels low[166]. At Kharagpur, SODAR derived vertical velocity variance and inversion height were used to compute the surface heat flux during the convection period of themorning hours[167]. Progressively, similar to Delhi, Tarapur, Guwahati, Agra, Kalpakkam and Visakhapatnam, the Punjabi University of Patiala also installed SODAR to study about the thermal plumes, inversions and small-scale irregularities occurring over the desired site[168]. Babu *et al.*[169] developed an attenuation theory using certain algorithms carried out in MATLAB to provide a better scheme for correcting raw acoustic field data for atmospheric influences and to better comprehend SODAR sound wave attenuation characteristics. The study was basically initiated to predict the scattering of SODAR signals by turbulence. Chanda *et al.*[170] fractalized the temperature field over the CBL using SODAR echograms. The researchers discovered that Fractal Dimensions (FD) of the ABL's normalized rate of thermal energy dissipation can be used to identify plume and interplume features in the emerging mixing layer from an image standpoint.

7 Adapting to the usage of Kalman Filters and logic based adaptive scheme as a part of SODAR advancement

SODAR encountered issues like inherent noise and time utilising image-processing. An alternative method using Kalman filters was developed in 2002 to extract the ABL[171]. As a result, time-consuming picture processing steps are skipped, allowing for speedier real-time interpretation of atmospheric conditions from ABL. Mukherjee and Pal[172] used an 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 were removed by designing a fuzzy logic based adaptive scheme. Kumar *et al.*[173] 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.

8 Recent studies in past three years (2019-2021) that deployed SODAR in India

Scopic preferment of SODAR expedite it wield in contemporary India. The collocated SODAR with Cloud Aerosol Interaction and Precipitation Enhancement Experiment (CAIPEEX) Phase III Integrated Ground based Experiment was conducted in Ganges valley for wind speed and wind direction data extraction so as to study the variability in surface winds over diurnal and inter-seasonal basis[174]. To explore the long-term trends, perturbations, and time series model simulation of VC, a comprehensive SODAR data set of around 8 years was analyzed. To evaluate the VC over the Delhi region, the popular Auto Regressive Integrated Moving Average (ARIMA) model of Box–Jenkins was used[175]. Using the mesoscale model WRF and the Lagrangian particle dispersion model Flexible-Particle (FLEXPART), the impact of land–sea breeze circulation and the Internal Boundary Layer (IBL) on the atmospheric dispersion of airborne effluent releases at the tropical coastal site Kalpakkam was simulated later. Validation was done using data from a 50-meter meteorological tower, a GPS sonde, and a Doppler SODAR[72]. The most recent and notable research has been carried out in 2021 where the latent dynamics of the ABL height pattern was established using a neural network of Long Short-Term Memory (LSTM) model with deep learning-based algorithms for temporal/seasonal and annual prediction of ABL height. For this SODAR derived data was used to compare the model's findings[176-177]. SODAR's performance was improved further by designing antennas that allow for increased data availability despite weak echoes. The design was implemented taking two factors into consideration which includes (i) structure of antenna for signal directivity and (ii) metal sheet of the antenna frame, along with the quality of absorbent material for cancellation of ambient noise. In the recent years active deployment of SODAR for air quality enhancement has been noticed. Recently, SODAR was deployed to study the VC at semi-arid regions of Indo-Gangetic Plains (IGP) using Forward Selection[178].

9 Challenges and Barriers to SODAR technique

A preeminent frailty of SODAR is its narrow vertical range, which is below the normal midday mixing heights and of weaker quality in the measured wind variance σ_v(standard deviation of crosswind component). Determination of dependable values of surface fluxes of momentum and heat using SODAR data is still known to be a challenge. Because reflectivity calibration for received power information requires measurements of humidity and temperature profiles, acoustic calibration of the transducer efficiency, and precise knowledge of acoustic attenuation, SODAR measurements of the temperature structure parameter C_T^2 are also contaminated with some inherent errors[55]. Since SODAR sensitivity is lower during the day than at night due to ambient noise, which limits its probing range, a measurement of the height of the thermal plumes by SODAR during the day would always be underestimated unless they are capped by a low-level elevated shear echo layer[56]. Selecting an appropriate site for the installation of Doppler SODAR to ensure easy and reliable acquisition of wind profiles is still a known challenge.

10 SODAR installed sites by CSIR-NPL

CSIR-NPL has successfully installed SODARs at seven locations across India: Central Pollution Control Board (CPCB) and CSIR-NPL at New Delhi, Indian Institute of Technology (IIT), Roorkee, Aligarh Muslim University (AMU), Aligarh (Uttar Pradesh), Indian Meteorological Department (IMD) Hisar (Haryana), Rajasthan State Pollution Control Board (RSPCB) Alwar (Rajasthan) Punjab Pollution Control Board 42 (PPCB) Sangrur (Punjab), and Maharashtra Pollution Control Board (MPCB), Mumbai (Maharashtra). CPCB, NPL, IIT Roorkee, AMU, IMD Hisar and PPCB Sangrur are parts of northern India that lie along the IGP region. Atmospheric processes, Continuous rate of seasonal stubble burning and prevailing meteorological conditions are the factors which are known to affect the atmospheric composition pollution load over IGP[116]. RSPCB is located over the desert region of north western India, the Rajasthan. The aerosols concentration due to high dust circulation over the place has been a major factor contributing aerosol pollution over its nearby areas, including NCT, Delhi [57]. The Internet of Things-based Sodar Network (IoT-SN), linking six SODAR locations in Northern India using SODAR was used for Air shed Management Planning[179].

11 SODAR as an environment aegis

SODAR acts as a medium for environmental protection through air quality governance. The SODAR measurements bestowed for turbulence and wind were adopted for the determination of the spatial and temporal distribution of many pollutants. Reitebuch *et al.*[58] determined the occurrence of nocturnal secondary ozone maxima over anurban park in Essen, Germany using SODAR ABL structures. Furthermore, unrivalled SODAR merits are recognised for their capacity to offer data on diurnal fluctuations in ABL mixing depth, knowledge of which is critical for dispersion models (e.g., the Box model) that use mixing height to calculate pollutant concentrations. The SODAR derived height of thermal plumes during the daytime and of shear echoes during the night is used for determining the mixing height for effluents[56]. SODAR echograms can be retrieved to determine the stack height[55].

SODAR measurements were pointed out to be a known source dated 20 years ago for deriving the air pollution meteorological parameters[56]. SODAR applicability for EIA studies induces SODAR for dispersion modeling. Furthermore, SODAR echograms, which are live depictions of changing stability class and mixing height in real time and space, provide rich information about the initiation, fading, and extent of fumigation (breaking inversion) period in the morning hours after dawn. This information on fumigation is useful in a variety of sophisticated dispersion models used for real-time risk analysis, EIA assessments, traffic transit planning, and industrial operational hours fixing[56].

12 Future Scope

Investigations at various locations will be required to establish the appositeness of SODAR structures, their height, and C_T^2 values in characterizing stability, mixing and inversion height, application in air pollution and microwave communication. It is also necessary to develop a method for determining the true values of structural parameters. More research into the aspect sensitivity of SODAR scattering is also required. It is also necessary to achieve automated analysis of atmospheric structures and procurement of many generated parameters. This will aid not only in the interpretation and evolution of the objective pattern recognition scheme, but also in the estimation of atmospheric stability, mixing height, and other variables from SODAR data, eventually facilitating the identification of ABL acoustic sounder data and the credible extraction of key boundary layer parameters from acoustic signals in most meteorological applications.

13 Conclusions

SODAR is a simple and cost-effective technology that provides a real-time visual representation of ABL thermal dynamics, mixing height, stability class, and fumigation, among other things. It is superior to other indirect or expensive technologies that rely on extrapolations or interpolations of data. While data on mixing height, inversions, stability class, wind velocity spectra, and velocity structure parameters from SODAR are useful in monitoring hazardous air pollution situations, data on the presence of gravity waves, breaking waves, stability class, and elevated inversions in the atmosphere determines the extent of radio signal fading in line-of-sight propagation. Detailed information covering the historical developments of SODAR in the past and present by CSIR-NPL is special highlight in the article. The review article also mentions the studies done in Indian and international platforms with system's improvements enhancing its capability. To conclude, SODAR has much to offer to society. It is a compelling transformation in its system, modulating it to adapt to changing requirements. The transition could empower the environment and society to simultaneously improve. However, such transformations are not effortless-they must confront an array of obstacles cutting across technical dimensions,such as modulation of antennas to reduce noise issues, accuracy in production of thermal structures to derive mixing height and other cost-effective challenges. Despite the fact that SODAR has been widely accepted tool for numerous applications. There is ample scope for system improvement from the point of view of a well-calibrated digital system that is supported by countries' signal processing groups can add significant indigenous development.

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