First Results of Experimental Tests of the Newly Developed NARL Phased-Array Doppler Sodar

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ABSTRACT

A multifrequency phased-array Doppler sodar system has been installed recently at the National Atmospheric Research Laboratory (NARL) for the continuous observation of the lower atmosphere from near ground to the atmospheric boundary layer (ABL). The NARL sodar, developed in technical collaboration with the Society for Applied Microwave Electronics Engineering and Research (SAMEER), was built using piezoceramic tweeters, which are capable of generating 100-W acoustic power. In favorable atmospheric conditions, the sodar gives wind profiles up to 1 km. The performance evaluation is one of the most important aspects for quality assurance of sodar operations. This paper presents the first results of experimental observations of the NARL sodar system and its scientific validation. The NARL sodar has been validated using the simultaneous observation of another sodar system (Scintec model MFAS64). Various physical parameters of the atmosphere are derived using the results obtained from both of the systems. Comparison of simultaneous measurements by both of the sodars, located about 100 m apart, shows good agreement on wind speed, wind direction, and vertical wind variance. The correlation coefficient of more than 0.80 in wind speed and direction between the sodars shows the usefulness of the system for observing the atmosphere and deriving physical parameters below the ABL.

1. Introduction

The National Atmospheric Research Laboratory (NARL; 13.45°N, 79.18°E) is a premier research organization conducting atmospheric research in India. It is equipped with the state-of-the-art mesosphere–stratosphere–troposphere (MST) radar, lower-atmospheric wind profiler, lidar, boundary layer lidar, sodium lidar disdrometer, optical rain gauge (ORG), and automatic weather station (AWS) (Rao et al. 1995; Jain and Anandan 2002; Bhavani Kumar et al. 2006; Bhavani Kumar 2006). Now, because of the installation of sodar system at NARL, lower-atmospheric wind profiling is possible right from the ground to 22 km. The sodar technique is an established method for profiling the lower atmosphere from near ground to the atmospheric boundary layer (ABL). In the last three decades a large number of studies were carried out using sodar that mainly addressed ABL characteristics and dynamics for example, the convective boundary layer (CBL), formation of the nocturnal boundary layer (NBL), inversion layers, wind climatology below the ABL, sound absorption in the atmosphere, and new technology development (Engelbart et al. 2007; Kouznetsov et al. 2007, 2004; Coulter and Kallistratova 2004, and references therein; Giannini et al. 1996; Kramar and Kouznetsov 2002; Mastrantonio and Fiocco 1982).

A basic requirement in the development of any remote sensing system is the verification of its data using quantitative comparisons against data from another sensor whose measurements are of known quality. Sodar data are frequently compared with the measurements of in situ sensors mounted on towers, radiosondes, and tethered balloons, and also can be compared with ground-based sensors such as lidars and other sodars. Testing using the same type of device is the primary means of assessing the performance of the sodar. Since different instruments use different techniques for measuring winds and other parameters, each system has its own biases and measurement limitations. Therefore, the most suitable method is to use simultaneous observations of two sodars having same measurement technique and position in a nearby location. Out

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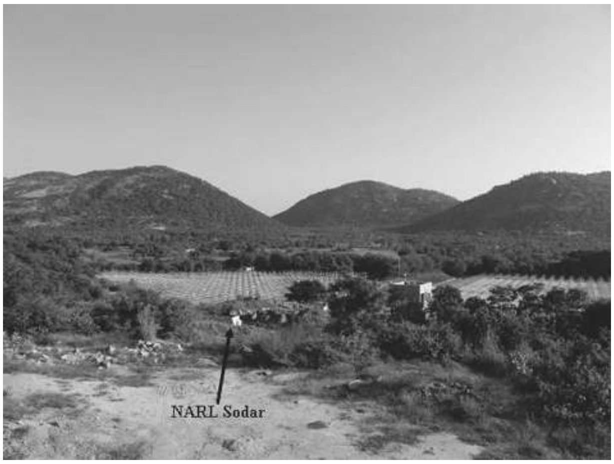


FIG. 1. The NARL phased-array Doppler sodar system. The hills are approximately 2–3 km from the sodar system.

of two, one should be validated for its scientific utilization. Since both of the systems give the same kind of physical parameters, it is advantageous to compare wind components and their derivatives. An important aspect of the sodar validation is the evaluation of the data for internal consistency. This evaluation provides an independent assessment of the operational characteristics of the sodar. Independent wind measurements of two sodars were considered for the evaluation, since a properly designed sodar system produces accurate data when compared with the same type of device. Horizontal winds and fluctuation of the vertical wind component of two sodars were estimated for comparison purposes. This comparison brought out the scientific validation of the observational system. Here we are presenting the first observations of the NARL sodar system and its comparison with a calibrated sodar system (Scintec model MFAS64). The system description and the data processing techniques are discussed in section 2. Sample observations of winds and comparisons are presented in section 3. The conclusions are given in section 4.

2. System description and data processing

The NARL phased-array Doppler sodar system (Fig. 1) consists of an 8 × 8 array of antenna elements made with piezoelectric transducers (CTS model KSN1165). Three elements from each corner have been removed to get the circular array pattern with a maximum sidelobe suppression of 17 dB. The transmission and reception are in reflected mode, so the antenna having 52 elements is placed at 70° inclination and the reflector at 35° with respect to the ground plane. This orientation makes the transmit/receive beam vertical to the horizontal plane when no beam tilting is applied. The sodar can be operated with a frequency range of 1600–2500 Hz. The NARL sodar is capable of transmitting multiple frequencies with a maximum up to 10 in sequence; that is, it can also be operated in multifrequency mode. The piezoelectric tweeters generate 100 W acoustic power. The receiver is designed with a dynamic range of 70 dB. The data acquisition and control system is designed with a National Instruments data acquisition (NI DAQ) card supported by the LabVIEW package. The pulse width and interpulse period are programmable for getting a range resolution of 10–200 m for an altitude coverage of 1500 m. Observations can be conducted in three directions (east, north, and vertical), with a tilt angle up to 22°.

The received signal is digitized and subjected to the process of fast Fourier transform (FFT) for online computation of Doppler spectra for each range bin of the selected window. The data are recorded in a personal computer. The parameterization of the Doppler spectrum follows estimation of mean noise level, removal of interference (if any), incoherent integration (as desirable), and computation of three lower-order moments. For estimating the mean noise level an objective method developed by Hildebrand and Sekhon (1974), which is widely used, has been adopted here. This technique is based on the statistics of a Gaussian random variable and the expected mean and variance for the spectrum of a white noise source. The noise level thus determined is subtracted from the received power for each Doppler bin. An interference band that might run through the entire range window, as experienced often, is subtracted out by estimating it in a range bin where it dominates the real signal. At this stage any incoherent integration of the spectra is carried out to improve signal detectability at the expense of time resolution. The signal identification is done followed by the adaptive moments estimation technique adopted for Indian MST radar (Anandan et al. 2005). Since the frequency of operation between MST radar and sodar differs, suitable modification in the algorithm has been incorporated before analyzing the data. This adaptive technique is based on certain criteria, set up for the Doppler window, signal-to-noise ratio (SNR), and wind shear parameters, which are used to adaptively track the signal in the range-Doppler spectral frame. The adaptive moments estimation algorithm has a significant advantage in terms of better height coverage compared to the conventional single-peak detection method. The three low-order spectral moments are computed through numerical integration using the expression given by Woodman (1985). The three moments represent signal

TABLE 1. System parameters of the NARL and Scintec sodars.

Parameter	NARL	Scintec
No. of elements	52 (8 × 8)	64 (8 × 8)
Frequency	1800–2500 Hz	1650–2750 Hz
Acoustic power (output)	100 W	50 W
No. of beams	3 (zenith, north, east)	9
Beam angle	16°	0°, 22°, 29°
Maximum range	1500 m	1000 m
Pulse width	Programmable	Programmable
Pulse repetition frequency	Programmable	Programmable
No. of FFT points	4096	1024
Transmission type	Reflecting mode	Direct
Beamwidth	5°	5°
Range resolution	User defined	User defined

strength, weighted mean Doppler shift, and half-width parameters of the power spectrum.

The mean Doppler shift provides a direct measure of the radial velocity. The adaptive moments estimation algorithm has a built-in quality check. Backscattered echoes of SNR below –15 dB are not considered for wind vector computation. Consistency of the radial wind component is also checked in the adaptive moments estimation method by comparing the current mean Doppler velocity profile with the previous Doppler velocity profiles. A threshold is set for checking the validity of the retrieved velocities using the relation $|(\mathrm{DV_{diff}}/\mathrm{MD})| < 0.2$, where $\mathrm{DV_{diff}}$ is the difference in mean Doppler velocities for the same range gate between the two consecutive frames, and MD is the mean of the mean Doppler velocities in the previous and current frames. The threshold value of 0.2 is found to be the most acceptable after checking a number of profiles in different conditions. Further details of the algorithm may be obtained from Anandan et al.(2005).When the observations are made at three look angles in anoncoplanar direction, the wind vector (zonal, meridional, and vertical) can be determined using the standard expressions given by Kouznetsov et al. (2004).

The Scintec (2008) sodar operates in multifrequency (1.65–2.75 KHz) mode for different tilt angles and in different directions. The phased array consists of 8 × 8 tweeters vertically pointing (direct upward). The system can generate 50 W of acoustic power with a beamwidth of 5°. Pulse width, pulse repetition rates, and

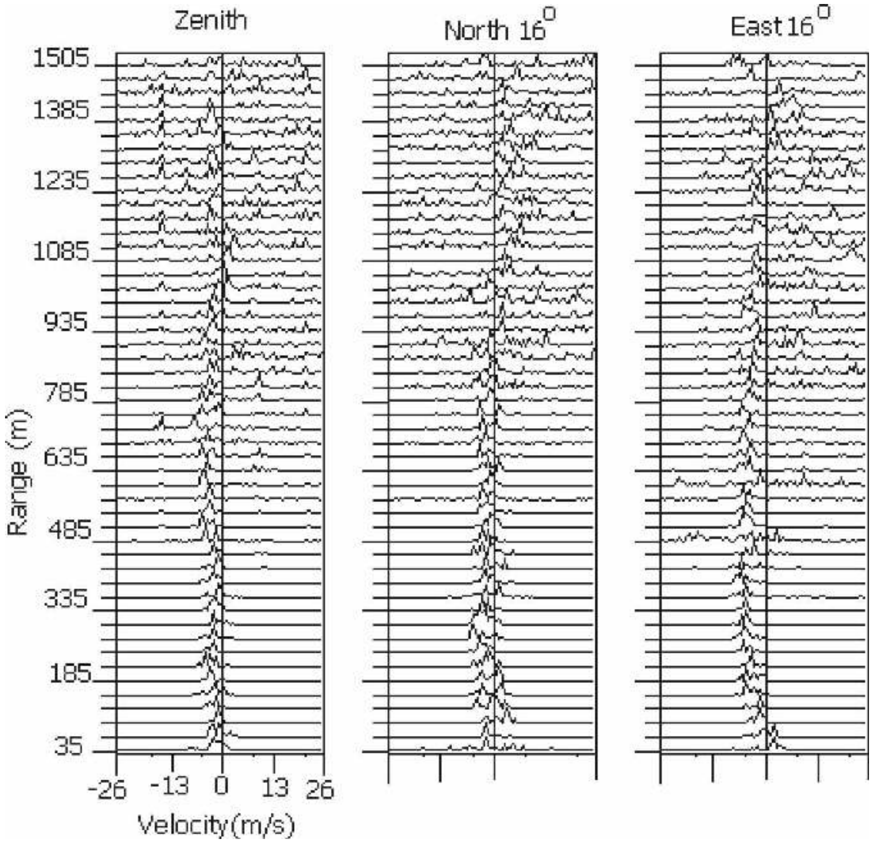
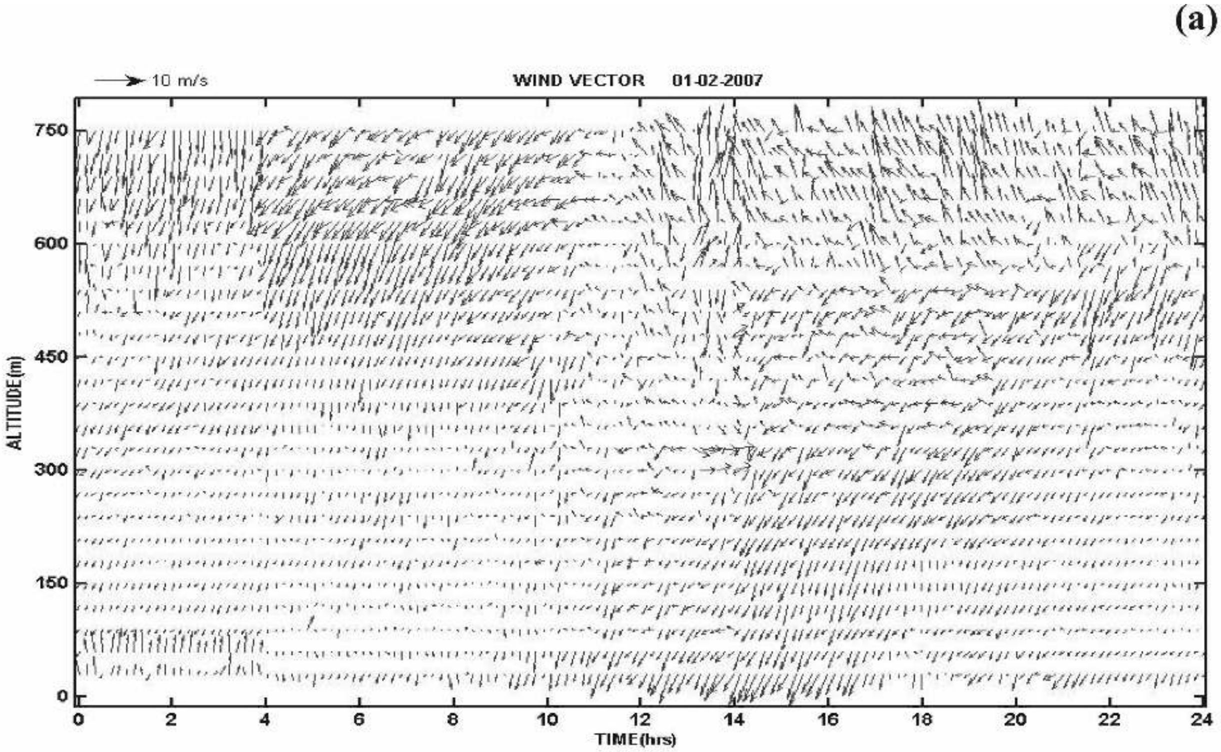


FIG. 2. Doppler spectra observed on 1 Feb 2007 in three beam directions: (a) zenith, (b) north 16°, and (c) east 16°.



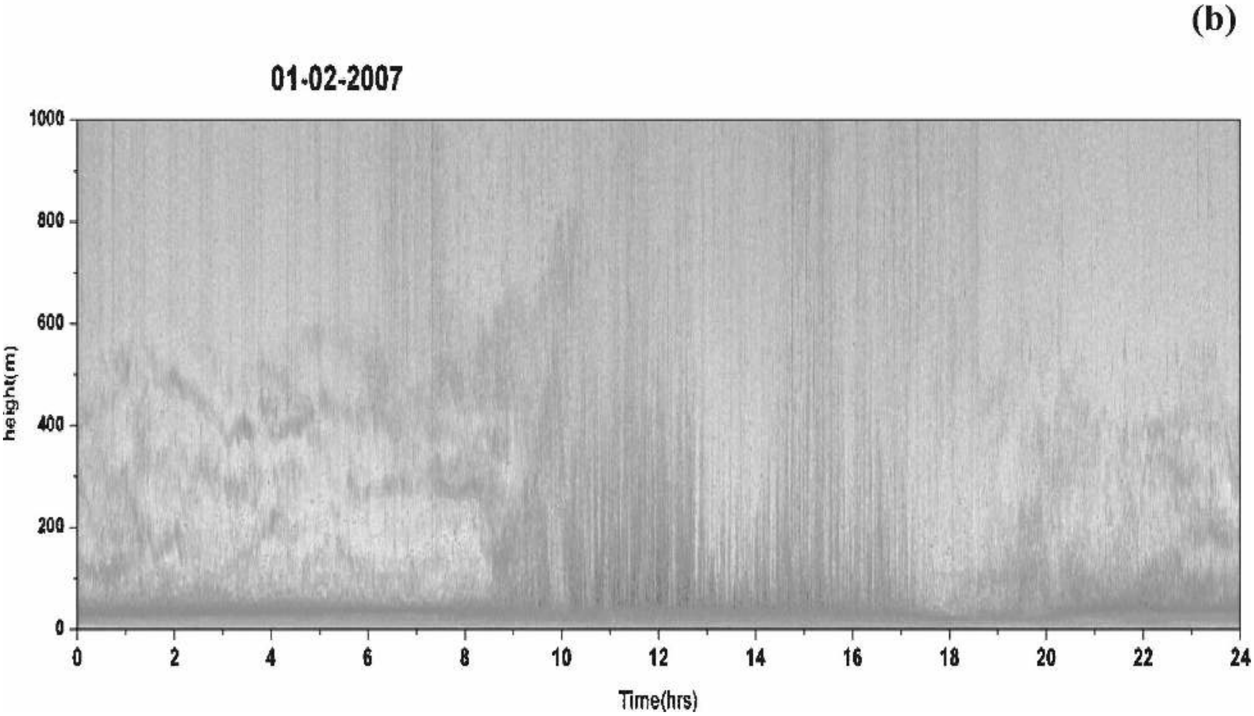


FIG. 3. Observation by the NARL sodar for 24 h on 1 Feb 2007 depicting typical boundary layer evolution and characteristics. (a) Wind vector. (b) Echogram.

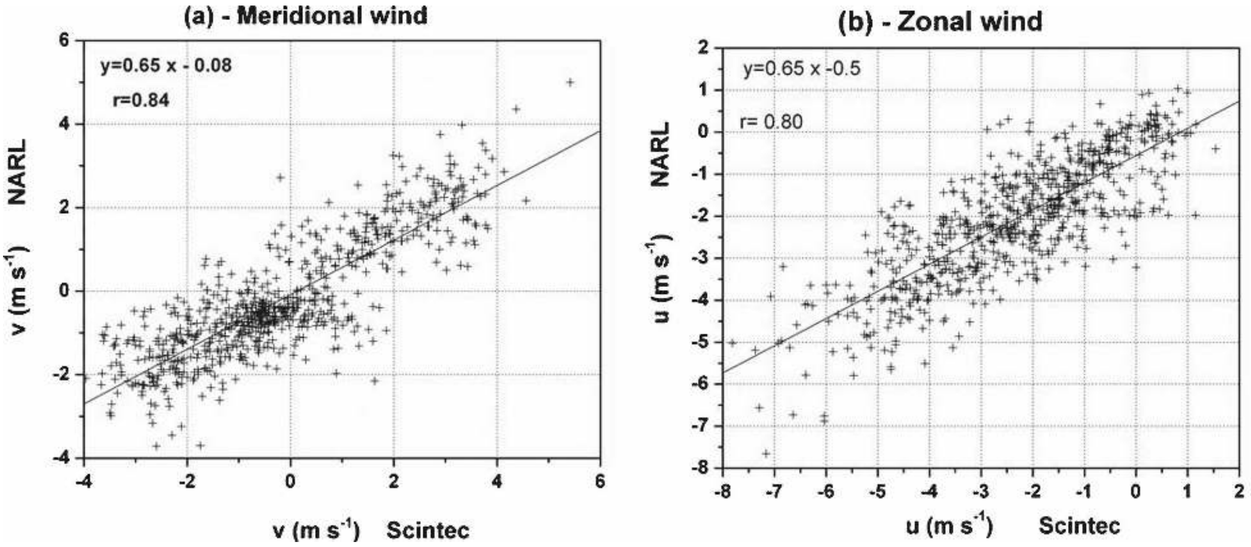


FIG. 4. Comparison of winds from height 60–500 m between two sodars. (a) Meridional. (b) Zonal.

integration time are user-selectable for getting different ranges and temporal resolutions. The time series data obtained are subjected to FFT to get the Doppler power spectrum. Lower-order moments and wind velocities are derived from the Doppler power spectrum. Complete signal analysis and the processing package are developed and supported by Scintec. The main specifications of the NARL and Scintec sodars are given in Table 1. Background acoustic noise is found to be below 36dBa in the transmission frequency range of the Sodar systems.

3. Sample observations

For the scientific validation, two sodar systems were operated simultaneously from 31 January to 2 February 2007. The observation reported here for the NARL sodar is with 1800-Hz transmission frequency, 180-ms pulse width corresponding to 30-m range resolution, repetition interval of 9 s (1500 m), and beam tilt angle of 16°. Scintec sodar operates in multifrequency mode with multiple tilt angles in different directions. We selected the same range and temporal resolutions as those of the NARL sodar for the Scintec system. The other operational parameters are preprogrammed inside the system. Both of the systems were operated in a nearby location separated by 100 m and oriented toward true north. Wind vectors are averaged for every 10 min for both of the sodars. This is a tropical rural station free from urban air pollution. Observations are conducted on clear and sunny days with moderate winds up to 10 m s^{-1}. Figure 2 shows Doppler power spectra of the NARL sodar from three beams (zenith, north, and east). During convective conditions, the vertical velocities reached the values of 2.5 m s^{-1}. The wind vector plot for 1 February 2007 is shown in Fig. 3a. Height coverage of wind profiling is varying from 750 to 1200 m during the observation period. After the quality check, data are plotted only up to 750 m. This figure indicates that the day was predominated by the northeasterly winds. There is a clockwise change in the wind direction from northeast to southeast at noontime. There were calm winds in the night, and windy conditions prevailed in the daytime during the period of experiment. The sodar echogram recorded for the same day (Fig. 3b) clearly shows a typical diurnal behavior of the ABL with a stable NBL, roughly between 2000 and 0800 LT, and an unstable CBL, roughly between 1000 and 1800 LT. The surface layer with a height of 50–75 m is discernable in the figure. The NBL develops after the sunset and attains a maximum height of 550 m around 0200 LT and then stays constant until sunrise. After sunrise, due to solar heating the NBL is changed into the convective boundary layer and the start of the convection process is observed. Development of thermal plumes and their rise up to 400–500 m in a period of 15–20 min can be clearly inferred from the echogram. The energy needed for thermals to persist is given by the turbulence mechanism and buoyancy forcing. Because of the dissipation to the turbulence in the upper heights, thermals will also disappear into the free atmosphere by the mixing of free air into the mixed layer. When turbulence is minimal, thermals disappeared, especially at upper heights. Since most of the time the Scintec sodar could give wind profiles up to 500 m, all the comparisons presented here are restricted to below 500 m.

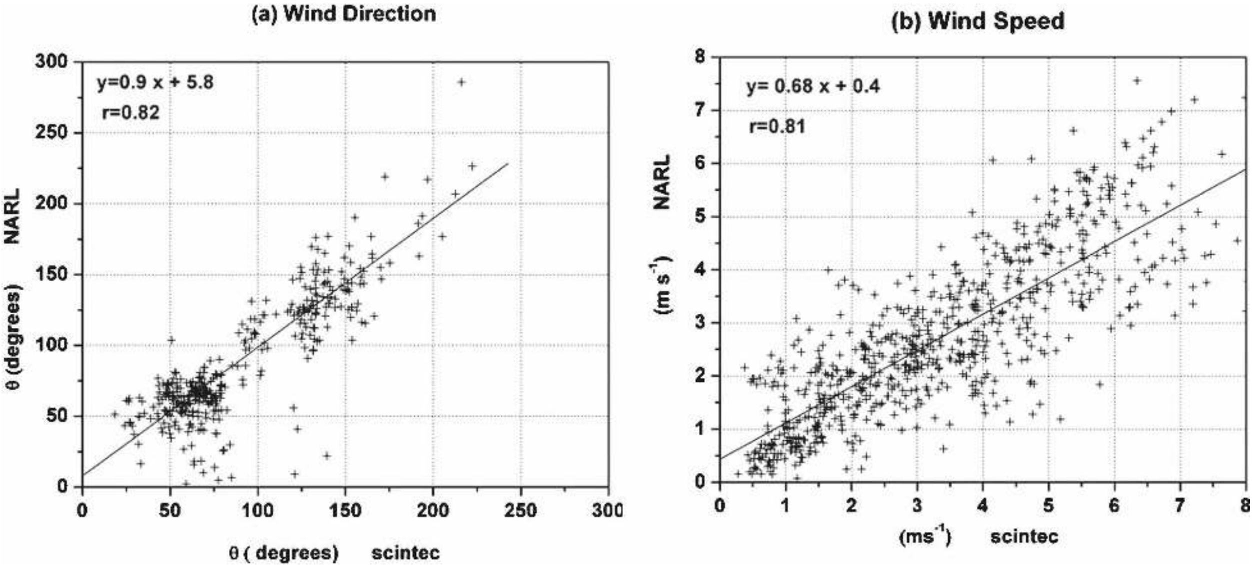


FIG. 5. Comparison of (a) wind direction and (b) wind speed up to 500 m between two sodars.

The comparison plots of zonal and meridional wind components between two sodars are shown in Fig. 4. Both sodars show a good agreement, with a correlation of 0.80 for the zonal component and 0.84 for the meridional component. Complete correlation is not expected because of system biases and separation in the location of observation. It is observed that during the period of observation the wind is predominantly northeasterly. The scatterplots for wind direction and wind speed measured between two sodars during the period

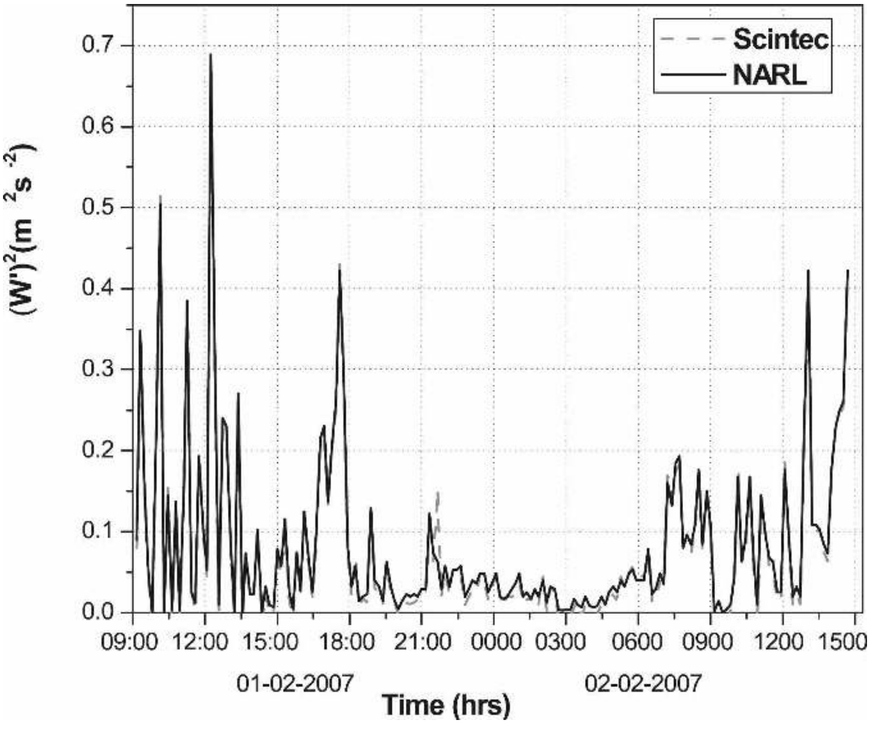


FIG. 6. Temporal variation of vertical velocity fluctuation observed by the NARL and Scintec sodars.

of the experiment are shown in Fig. 5. The wind direction plot gives a good linear fit with a slope of regression of about 0.9 and a correlation coefficient of 0.82. In the case of speed, the comparison has shown a correlation of 0.81 and slope of regression of 0.68. It is important to check the validity of vertical wind fluctuations from the point of view that many atmospheric parameters can be derived from the variance of vertical wind. Figure 6 shows the comparison of $(w')^2$ estimated by both of the sodars at 90-m altitude. A one-to-one match is observed in vertical fluctuations in both of the sodar measurements with a correlation coefficient of 0.99.

4. Conclusions

First observations of the newly installed sodar system at NARL are presented. NARL sodar observations were compared and validated with another sodar system (Scintec model MFAS64) located around 100 m away. Wind comparison has shown very good agreement between the two systems. A very good correlation of greater than 0.80 is obtained for horizontal velocities, speed, and direction. Sodar could capture the properties of the CBL and NBL as expected. Temporal variations of vertical velocity fluctuations are also estimated. Both of the sodars have shown good agreement in the observed values. The observations and comparisons of the results obtained with various atmospheric parameters have demonstrated the capability of the NARL sodar for atmospheric observations and to carryout detailed study of characteristics and dynamics of the boundary layer from this tropical rural station.

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REFERENCES

Anandan, V. K., P. Balamuralidhar, P. B. Rao, A. R. Jain, and C. J. Pan, 2005: An adaptive moments estimation technique applied to MST radar echoes. *J. Atmos. Oceanic Technol.,* **22,** 396–408.

Bhavani Kumar, Y., 2006: Portable lidar system for atmospheric boundary layer measurements. *Opt. Eng.,* **45,** 076201, doi:10.1117/1.2221555.

——, C. Nageswara Raju, and M. Krishnaiah, 2006: Indo-Japanese lidar observations of the tropical middle atmosphere during 1998 and 1999. *Adv. Atmos. Sci.,* **23,** 711–725.

Coulter, R. L., and M. A. Kallistratova, 2004: Two decades of progress in SODAR techniques: A review of 11 ISARS proceedings. *Meteor. Atmos. Phys.,* **85,** 3–19.

Engelbart, D. A. M., M. A. Kallistratova, and R. D. Kouznetsov, 2007: Determination of turbulent fluxes of heat and momentum in the ABL by ground based remote-sensing techniques (a review). *Meteor. Z.,* **16,** 325–335.

Giannini, L., S. Argentini, G. Mastrantonio, and L. Rossini, 1996: Estimation of flux parameters from sodar wind profiles. *Atmos. Environ.,* **31,** 1307–1313.

Hildebrand, P. H., and R. S. Sekhon, 1974: Objective determination of the noise level in Doppler spectra. *J. Appl. Meteor.,* **13,** 808–811.

Jain, A. R., and V. K. Anandan, 2002: Applications of facilities at NMRF, Gadanki, in the area of meteorology and coupling processes in the atmosphere: A brief review and future prospects. *Indian J. Radio Space Phys.,* **31,** 357–368.

Kouznetsov, R. D., V. F. Kramar, F. Beyrich, and D. Engelbart, 2004: Sodar-based estimation of TKE and momentum flux profiles in the atmospheric boundary layer: Test of a parameterization model. *Meteor. Atmos. Phys.,* **85,** 93–99.

——, ——, and M. A. Kallistratova, 2007: The vertical structure of turbulent momentum flux in the lower part of the atmospheric boundary layer. *Meteor. Z.,* **16,** 367–373.

Kramar, V. F., and R. D. Kouznetsov, 2002: A new concept for estimation of turbulent parameter profiles in the ABL using sodar data. *J. Atmos. Oceanic Technol.,* **19,** 1216–1224.

Mastrantonio, G., and G. Fiocco, 1982: Accuracy of wind velocity determinations with Doppler sodars. *J. Appl. Meteor.,* **21,** 823–830.

Rao, P. B., A. R. Jain, P. Kishore, P. Balamuralidhar, S. H. Damle, and G. Viswanathan, 1995: Indian MST Radar–Part I: System description and sample vector wind measurements in ST mode. *Radio Sci.,* **30,** 1125.

Scintec, cited 2008: Technique and use. Acoustic Wind Profilers: Product Information. [Available online at www.scintec.com/Site.1/PDFs/Product_Information_FAS_2007.pdf.]

Woodman, R. F., 1985: Spectral moments estimation in MST radars. *Radio Sci.,* **20,** 1185–1195.