A versatile 205 MHz stratosphere–troposphere radar at Cochin – scientific applications

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A state-of-the-art, indigenously developed, and the world's first 205 MHz stratosphere–troposphere (ST) wind profiler radar installed at the Cochin University of Science and Technology, Kerala, with the support of Science Engineering Research Board, Department of Science and Technology, Government of India, is introduced in this article. This radar provides a cost-effective and high precision technology capable of monitoring in all weather conditions round the clock. Its primary goal is to understand the characteristics of the Indian summer monsoon at its gateway at Cochin. Brief technical details and the validation of radar data with the co-located GPS radiosonde observations are mentioned. Applications of the ST radar data for various studies of atmospheric, ionospheric and radio astronomical features are discussed. Cochin ST Radar is open to all researchers from national institutes, universities and other academic institutions for conducting regular as well as special experimental campaigns, based on their scientific proposals.

Keywords: Atmospheric waves, monsoon, ST radar, turbulence, VHF radar.

ATMOSPHERIC radar, a state-of-the-art system to study atmospheric features, is quite useful for better prediction of weather and climate. They are also called wind profiler radars, which are vertically directed pulsed radars, capable of analysing the back-scattered signals to determine the velocity vector of air in the beams[1–3]. They depend on signals scattered from gradients in the radio refractive index associated with turbulent eddies with scales of one-half the radar wavelength[3,4]. The goal of detecting the very weak clear air signals dictates the use of long coherent dwell times, low noise system, low antenna side lobes, and careful attention to siting, and potential interference[5]. Generally atmospheric radars are categorized as mesospheric stratospheric tropospheric (MST) radar, stratospheric–tropospheric (ST) radar, and tropospheric (T) radar, or boundary layer (BL) radar, corresponding to the observable region for the radars[2].

In recent years ST radars have emerged as powerful tools for atmospheric research around the world. It is the most powerful and versatile wind-profiling instrument. ST radar can be operated in all weather conditions on a continuous basis and provides precise high resolution measurements of the vertical as well as horizontal wind in altitude and time[6].

As a part of establishing a network of ST radars at various parts of India, Science Engineering Research Board, Department of Science and Technology, Government of India had identified the Advanced Centre for Atmospheric Radar Research (ACARR), Cochin University of Science and Technology (CUSAT), Cochin (10.04N, 76.33E, 32 m amsl) for installation of the most sophisticated and advanced ST wind profiler radar to understand various circulation features of the troposphere and lower stratosphere and study its influence on the underlying monsoon circulation over the Indian subcontinent. The high resolution and unique ST radar facility enables us to study the horizontal and vertical circulation pattern[7], wave and turbulent activity[8], interaction and coupling of the lower, middle and upper levels in the convectively active troposphere as well as the radiatively sensitive stratosphere.

CUSAT ST radar at 205 MHz is fully designed, developed and fabricated indigenously. The 205 MHz ST radar is designed indigenously with technical advice and direction of Indian scientists/engineers. The development, installation and operation of the system was carried out by M/s Data Patterns India Pvt Ltd, Chennai, a well-recognized sophisticated electronic design and development company in our country. Thus CUSAT ST radar comes under the *Make in India* programme of the Government of India. This national facility is open to all academicians and researchers across the country.

Geographical importance of the site

Kerala, known as the land of monsoons, receives the first burst of southwest monsoon over the Indian subcontinent (gateway of monsoon)[9]. Timely onset, optimum duration and reasonable strength of southwest monsoon are of vital importance to the life and economy not only of India but the entire South Asian region.

The rainfall over Cochin is influenced by both the coastal effect and the orographic effect due to its proximity to both the Sea and the hills (Figure 1). The highest

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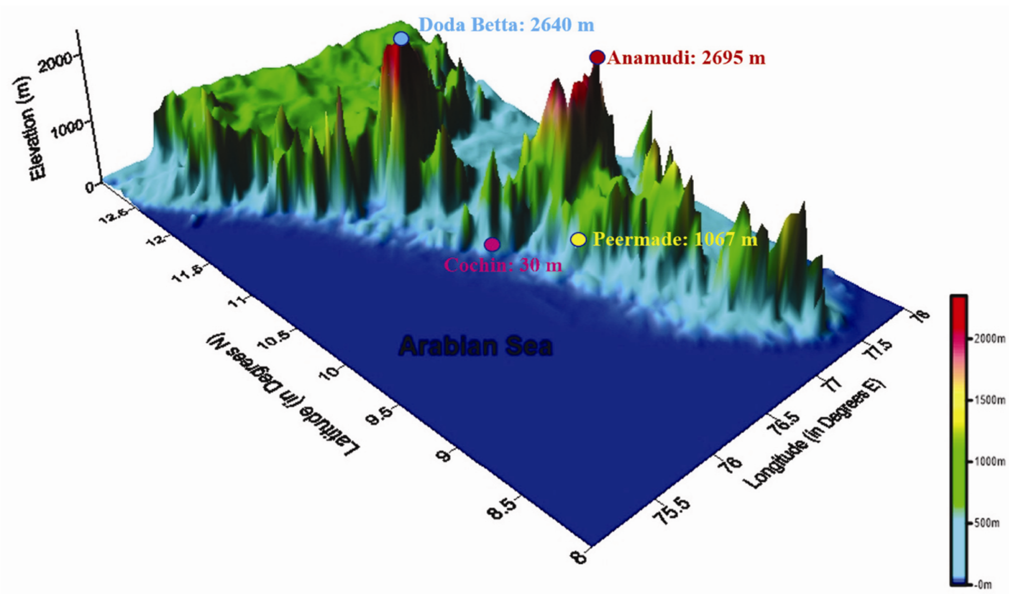

Figure 1. Topographical map of Cochin.

mountain peak of the Western Ghats, Anamudi, lies just 100 km to the east in the same latitude belt of Cochin. During the southwest monsoon season, the Arabian Sea behaves as a reservoir of water vapour which is pumped into the land region under the forcing of strong westerly winds reaching a maximum speed of 15–25 m s^{-1} (ref. 10). On the other hand, the presence of Western Ghats, extending to an altitude of about 2 km, orographically lifts the strong wind, and helps in enhanced cloud formation and precipitation in the windward side of the Western Ghats.

Uniqueness of Cochin ST radar

Conventionally, the wind profiler radars were developed around three frequency bands, viz. 50, 400 and 1000 MHz. A feasibility study conducted by NASA for monitoring the wind for space shuttle launch suggested that frequencies of 50, 225 and 400 MHz are suitable for stratospheric and tropospheric probing[11]. Earlier, no attempt was made to design and develop wind profiler radar in the frequency near 200 MHz, because this frequency range is widely used for radio and television broadcasting. Advantage of this frequency band is that highly reliable wind measurement is possible in the entire troposphere and lower stratospheric levels.

The ST radar at Cochin operating at 205 MHz VHF range (wavelength – 1.4624 m) is the first wind profiler radar in the world in the 200 MHz club, successfully functioning in the near-equatorial site to study the monsoon features. This radar measures zonal, meridional, and vertical winds from 315 m at lower altitudes up to a height of about 20 km, at very high resolution in both time and vertical levels, continuously for 24 h a day. It has several advantages compared to the existing conventional wind profiler radars developed by other countries in the world[3].

(a) The wind profiling radar (WPR) working around the 50 MHz range suffers from no coverage below about 2 km. On the other hand, WPRs working in the UHF band (300–1200 MHz) have a disadvantage of no data coverage at upper troposphere and lower stratosphere. However, the ST radar in 200 MHz frequency range is capable of probing the atmosphere right from 315 m to beyond 20 km. Hence, it is a trade-off between the 50 MHz and 400 MHz band, and provides a unique opportunity for unravelling not only the monsoon dynamics, but also the stratosphere–troposphere exchange processes in the upper troposphere lower stratosphere region[12], thus fulfilling our major scientific objectives.

(b) The bandwidth of CUSAT radar is 5 MHz (ref. 6), while the allotted bandwidth for the 50/400 MHz is at or below 2 MHz. Hence, the vertical resolution of wind data is coarser (varying from 150 m and amsl) for the 50/400 bands compared to the 200 MHz range (45 m in the lower levels).

(c) Another advantage with the 200 MHz band is that it is less affected by galactic or cosmic noise (~1000 K), whereas the 50 MHz range is more vulnerable to this type of noise (~6000 K)[12]. The galactic noise being less for 200 MHz, the signal-to-noise ratio is improved for wind measurements.

(d) The 50 MHz antennae necessitate larger physical size and space (square area of about 100 m × 100 m) for installation, while the modest and compact hardware of 200 MHz requires only lesser area (circular area of 30 m diameter) and hence cheaper costs. This cost-effectiveness makes it an attractive option over other frequency bands.

Table 1. Specification of 205 MHz WPR

Parameters	Specification
Frequency	205 MHz
Bandwidth	5 MHz
Type of system	619 element active phased Array with TRM
Antenna element	Three element Yagi–Uda antenna
Height coverage	315 m to 20 km
Range gates	1024 (programmable)
Modes of operation	DBS/SAM
Height resolution	~45 m to 720 m (programmable)
Beam width	~3.2°
Off-Zenith angle	0–30° in steps of 1° (programmable)
Azimuth angle	0–360° in steps of 1° (programmable)
Pulse width	0.3–76.8 μs
Modulation	Binary phase shift keying coded compression
Code	Complementary code/barker code
Baud	0.3–4.8 μs in steps of 0.3 μs (programmable)
Parameters	Specification
Pulse repetition frequency	100 Hz to 16 kHz selectable
TRM peak power	500 W (typical per element)
Duty ratio	up to 15% (max)
PAP	$\sim 1.6 \times 10^8$ Wm^2
Radar system sensitivity	–165 dBm
Dimension of antenna array	27 m diameter circular array
Dynamic range	73 dB (min)
No. of coherent integrations	2–1024 (programmable)
No. of FFT	64–4096 (programmable)
No. of incoherent integration	1–128 (programmable)
Master reference oscillator 10 MHz	Rubidium oscillator
AD converter resolution	16 bits

(e) WPRs operating in UHF range are known to get saturated under rainy conditions[13–16], while such issues do not affect radars working in the 200 MHz range[12].

(f) The 200 MHz band has a special advantage over other bands, as there is a clear separation between the background wind echo and the echo due to falling hydrometeors. This specific advantage makes it possible to explore the fall velocity and hence the droplet size spectrum in cloud physics studies.

Technical specifications of Cochin ST radar

The ST radar at Cochin is a clear air active phased array WPR. The radar has the capability of beam-steering of 0–30° along off-zenith, and 0–360° along azimuth with a step of 1°. This enables a three-dimensional view of the atmosphere. The principal mechanism is detection of backscattered electromagnetic waves as a result of refractive index perturbations due to atmospheric turbulence. A measure of atmospheric turbulence is the refractive index structure coefficient (C_n^2), which is a function of temperature, pressure, partial pressure of humidity and electron density[17].

ST radar is a pulse Doppler radar which is capable of analysing the back-scattered signal to measure the Doppler shift from different heights. The system consists of 619 Yagi–Uda antennas arranged in a circular aperture with a diameter of about 27 m. The power aperture product of the radar is designed such that the weak back scattered signal coming from 20 km altitude should fall well above the sensitivity limit of the system. The system consists of two modes of operation: Doppler Beam Swinging (DBS) and Spaced Antenna Mode (SAM). Table 1 shows the specification of the ST radar.

The basic block diagram of the ST Radar is shown in Figure 2. The radar consists of mainly four sub-systems – the antenna subsystem, transmit/receive module (TRM) distribution network and radar computer.

Figure 3 *a* shows the arrangement of 619 Yagi antenna in a circular manner. Each dot represents a 3 element Yagi antenna. The individual antenna has a gain of 7.5 dBi and the full array has a gain of 35 dBi. To avoid the grating lobes in the visible region, the inter element spacing is kept at 0.7λ. The full array has a half power beam width of ~3° and can tilt the beam 30° off-zenith.

TRM acts as the interface between the feeder network and antenna array. Based on the TR pulse and command from the radar processing computer, the module performs the phase shifting of RF signal for beam steering, amplification of RF signal to the desired power level in both transmit/receive chain and TR switching. The RF signal is routed to TRM through the feeder network from a coherent signal generator in which the power level is in the

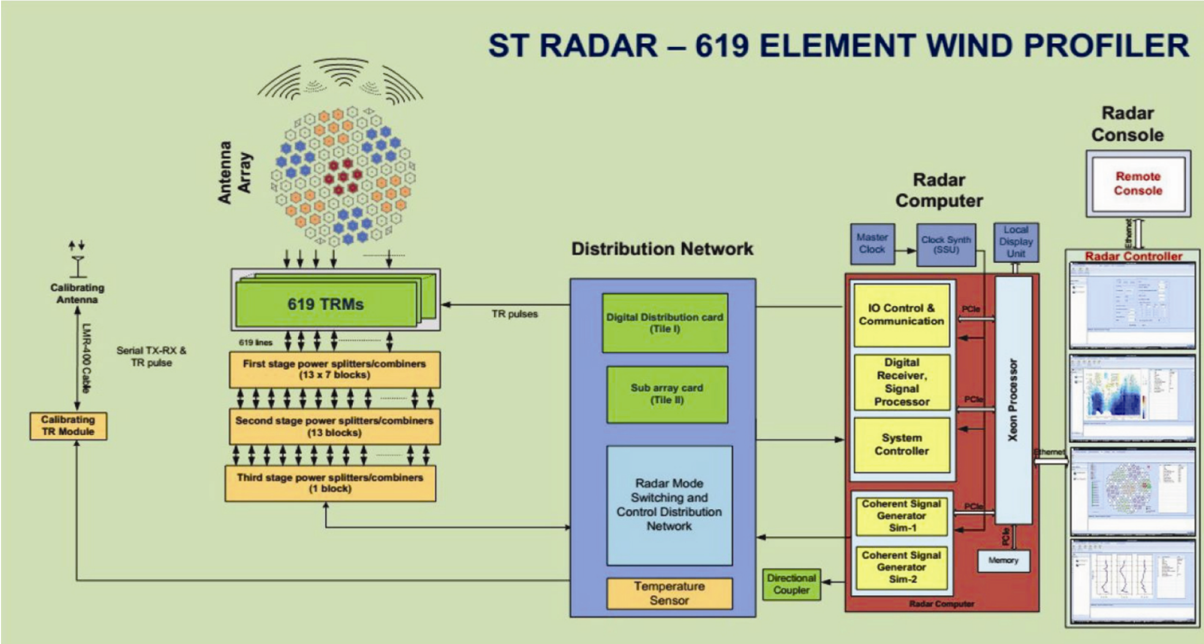

Figure 2. Block diagram of 205 MHz WPR.

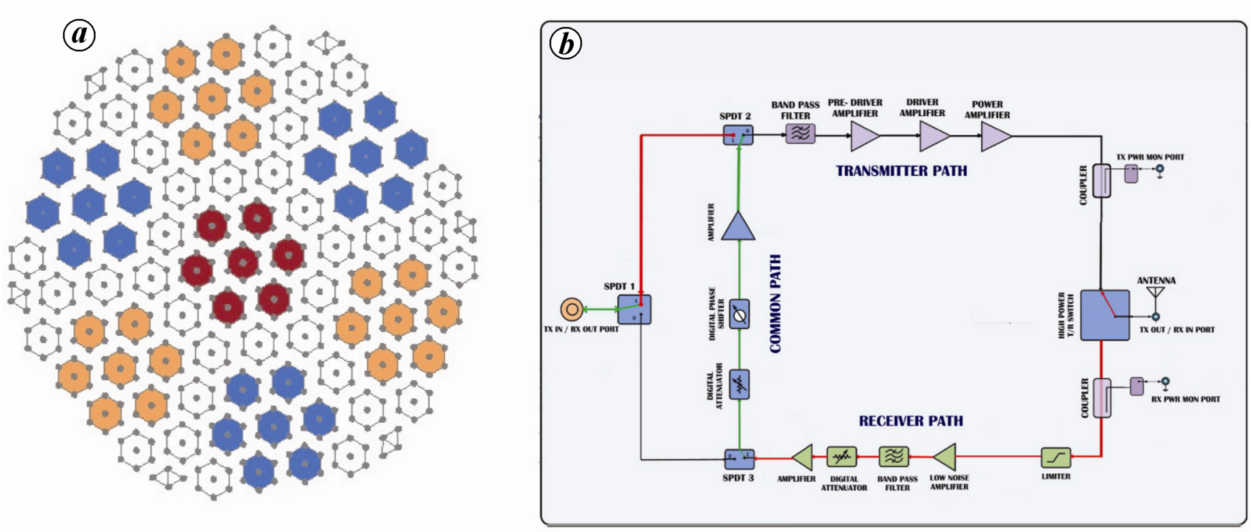

Figure 3. ***a***, Arrangement of 619 Yagi–Uda antenna. ***b***, Block diagram of transmit-receive module.

order of –10 dBm at 205 MHz. The block diagram of TRM, which mainly consists of two paths, transmit and receive paths, is shown in Figure 3 *b*.

The radar processing computer consists of a coherent signal generator, digital receiver and control signal generator. The control signal generator generates the TR pulse, gain control, phase programing of TR modules and monitors the health status of the TRM[6].

Coherent signal generators generate the pulsed carrier signal at 205 MHz which is amplified by TR module and transmitted through the antenna array. The back-scattered signal is digitized by the analogue to digital converter with a sampling rate of 80 MHz. RPC performs all the signal processing steps, and parameters like Doppler width, mean Doppler and wind vectors are analysed.

Special system capabilities

More than a wind profiler, ST radar at CUSAT is a phased array radar which consists of 619 active elements. The radar beam can be tilted in any azimuth angle with a step of 1° and up to 30° off-zenith again with an interval of 1°. This capability can be utilized to scan the atmosphere in a three-dimensional manner for the imaging application. Research opportunity exists for augmenting the number of receiving channels up to 91. As far as the multi-receiver operation is concerned, there are two modes of operations: (1) DBS mode; (2) SAM mode. In DBS, only one channel for the full array will transmit and receive alternatively. In the case of SAM, only the central cluster consisting 49 elements will radiate and a group of three 49 element clusters will receive simultaneously. In SAM operation, three receiving channels are utilized for the multichannel reception.

Validation of radar wind observations with GPS radiosonde measurements

A comparison of daily zonal and meridional wind profiles between radar and radiosonde is shown in Figure 4. In general, the radar wind profiles match very well with radiosonde wind profiles and the radar is seen to capture the day-to-day wind variations quite well.

In order to validate the radar estimated winds, we use winds derived from a co-located GPS based radiosonde (GRAW radiosonde; URL: http://www.graw.de/products/radiosondes/) and compare between them on a routine basis. The GRAW radiosonde provides precise and reliable measurement of wind speed (<0.1 ms^{-1}) and direction at finer vertical resolution (4–5 m). Figure 4 depicts the comparison of wind components obtained on 13 December 2016. It is seen that both the zonal (u) and meridional (v) components from the radar (depicted in blue colour) agree reasonably well with the respective component from radiosonde. It should be noted that wind speed matches more closely in the lower heights than at higher levels. The discrepancy at higher heights could be due to greater horizontal drifts of the balloon from the launching site in accordance with the prevailing wind with time (Figure 4 *b*). From the above figure, it is clear that the radiosonde drifted considerably away from the conical scanning volume of the radar. For example, at an off-zenith angle of 10°, the scanning radius of the radar is only 3.751 km at a height of 14 km, whereas the balloon drifted about 16.5 km away from the site at this height range, which could be one of the reasons for the observed discrepancy. The comparison between the differences in both zonal and meridional components from radar and radiosonde can be seen in Figure 4 *c*.

During the one-year period of validation[3], it was observed that the correlation for zonal component was 0.99 and that for meridional was 0.96. The radar system is designed, such that it is able to retrieve the wind speed with an accuracy of 1 ms^{-1} for the horizontal component and 0.1 ms^{-1} for the vertical component. For a detailed comparison and validation test, the reader is asked to refer to Mohanakumar *et al.*[3].

Scientific problems to be addressed using ST radar

Several atmospheric features and underlying mechanisms can be explored by continuously monitoring the atmosphere from near surface to the tropopause level and above, using the high resolution ST radar system. Precise monitoring of vertical wind provides unique information that helps in understanding the coupling that takes place at various levels in the atmosphere. By utilizing data from ground-based instruments and satellites over the peninsular region, juxtaposed with those from sites in other parts of the country, it is proposed to address certain key scientific questions such as:

How do the changes in the tropospheric and lower stratospheric winds affect the onset, propagation, intensification and weak phases of Indian summer monsoon for unravelling the inherent intra-seasonal and inter-annual variabilities?

A trough of low off the Kerala coast is the common synoptic feature, which ushers in the southwest monsoon into Kerala. The subsequent northward advance of the current as well as its strengthening is also invariably associated with the development of such troughs. It is well known that the low level jet stream (LLJ) that exists over Kerala during the southwest monsoon season is the main artery feeding moisture for the monsoon rains over the entire south Asia. The associated upper air circulation extends to the upper troposphere and even to the lower stratosphere. The altitude of jet-core, strength of wind speed, and the north–south oscillations of LLJ and tropical easterly jet stream show strong association with monsoon activity[18].

How do the synoptic scale conditions create a conducive atmosphere for the instigation and development of meso-scale convective clusters and extreme rainfall events?

Thunderstorms are frequent during the pre- and post-monsoon seasons over the Kerala region. The sharp contrast between land and ocean air mass, and the peculiar orography of the Western Ghats favour the formation of thunderstorms. Radiosonde, WPR and Doppler Weather Radar are crucial instruments for investigating the atmospheric vertical characteristics. In addition to the above, the meso-scale and synoptic conditions will be studied to examine if large-scale dynamical forcing[19] drives thunderstorm formation or if they are forced by local thermodynamics only. The local thermodynamical instability may be triggered by intense convective boundary layer that are at times formed during the pre- and post-monsoon seasons. The influence of each of these forcing will be categorized based on model studies.

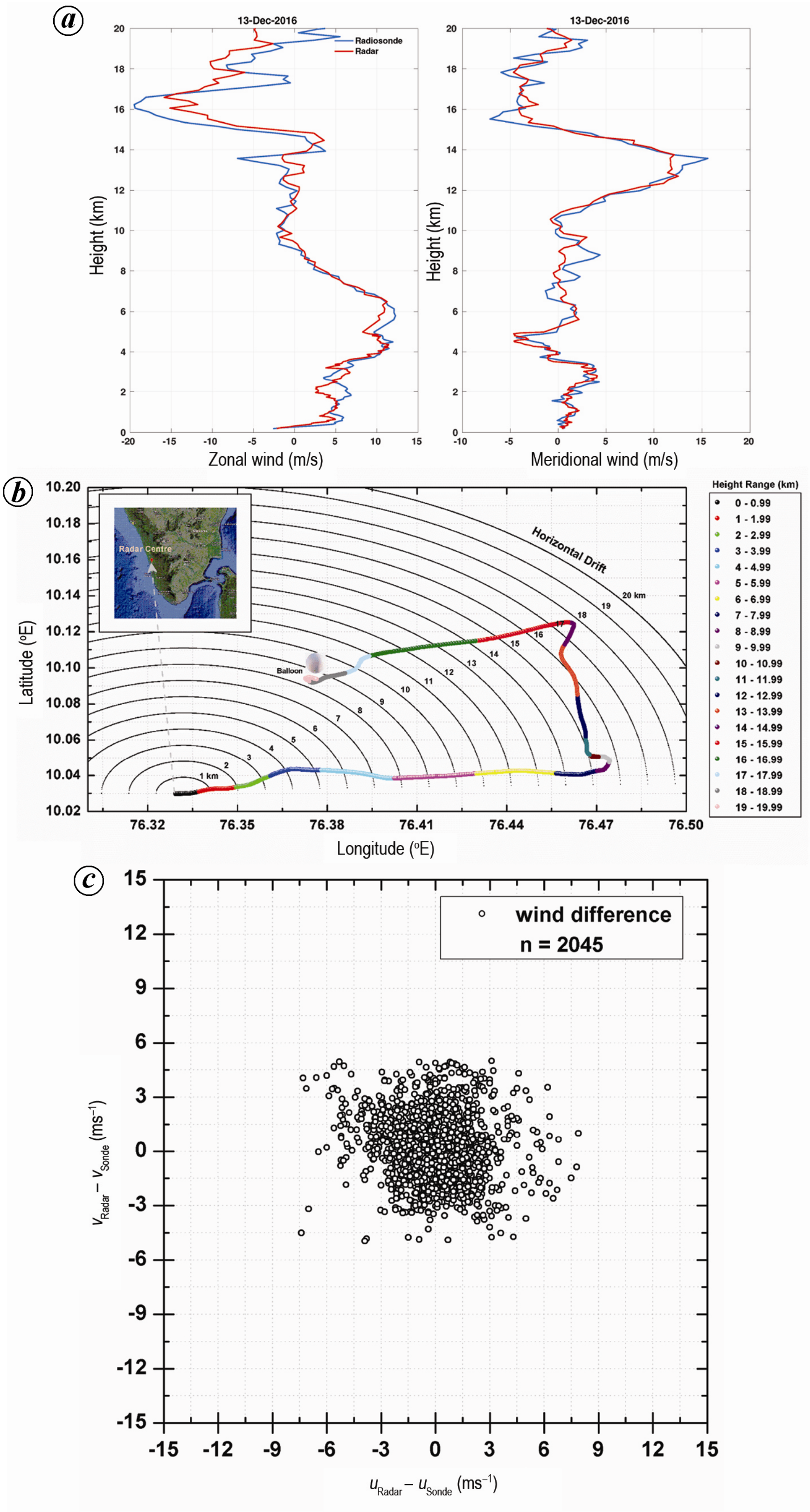

Figure 4. ***a***, Comparison of radar derived wind (*u* and *v* components on the left and right, respectively) with those from radiosonde on 13 December 2016. ***b***, Balloon track as a function of height above the ground level with respect to the radar site on 13 December 2016. The colour bar of the track indicates the height range of balloon, the concentric circles represent the horizontal drift (in km) from the radar centre, and the location of radar centre is provided in-site. ***c***, Scatter plot of differences between radar- and radiosonde-derived zonal and meridional wind components deduced in 2016.

How is the stratospheric–tropospheric exchange processes, and dynamics modulated by orographically and convectively generated gravity waves?

Atmospheric wave-induced forces drive a kind of fluid-dynamical suction pump, which withdraws air upward and poleward from the tropical lower stratosphere and pushes it poleward and downward into the extratropical troposphere. The resulting global-scale circulation drives the stratosphere away from radiative equilibrium conditions[20]. The troposphere has a strong dynamical effect on the stratosphere, primarily through the upward propagation of waves, both low-frequency large-scale Rossby waves and high-frequency inertia-gravity waves[21–23]. Breaking or dissipating waves exert a systematic mean force that changes the mean flow, which in turn, affects the propagation, breaking and dissipation of waves. The two-way interaction can lead to internal dynamical variability.

How could the diverse atmospheric features be simulated with a sophisticated model from the observed initial and boundary conditions, and how could we improve the prediction of weather on short-range time scale?

A cloud resolving model can be used to examine the sensitivity of environmental parameters on convection and clouds. The model at convection-permitting scales (~1 km grid spacing) can be employed for sensitivity studies of specific meteorological parameters. This high spatio-temporal model output could be used for improvement of experimental short-range prediction.

Collaboration studies with other institutions/universities/colleges

The 205 MHz ST radar installed at Cochin has extensive applications in atmospheric studies. This unique radar provides enormous information on the atmospheric and ionospheric features in the tropical region. This information is open to the scientific community for effective utilization, to understand various unknown mechanisms in the troposphere, lower stratosphere and ionosphere of the tropical region. ACARR welcomes scientific proposals from interested scientific groups from national institutes and academic institutions utilizing the facility available at this centre. Special experimental campaigns can also be proposed.

Ionospheric studies

The 205 MHz ST radar at Cochin has potential applications in probing the ionosphere right from the D-layer to the F-layer. The study of field aligned irregularities (FAI), particularly in the E-layer, is an added advantage of the existing ST radar. A detailed study of spread-F and plasma bubbles could also be undertaken. Furthermore, meteors can be studied by running the radar in meteor mode to measure horizontal velocity and to detect temperature from the power spectral density of the lower thermosphere. This is based on the understanding that a burning meteor causes ionization and that the region of ionization moves with neutral wind.

Radio astronomical studies

The sizable effective collecting area (~400 sq. m) of the CUSAT radar underlines its significant potential for use in radio astronomical studies, even with its 5 MHz bandwidth and system noise temperature of about 600 K, when used in its ‘passive’ receiving mode. Such a ‘receive only’ mode should be free from any interference from its transmission signals, including any switching signals relevant to its radar mode. When achieved, this mode would readily enable routine observations of one or more of strong radio astronomical sources, which can provide useful and independent calibration of the ST radar system. Preliminary tests made using the ST-radar antenna with a portable receiver from the Raman Research Institute, Bengaluru have shown encouraging results, even in the presence of some interfering switching signals.

We expect, in due course, to achieve a clean passive mode operation, and to extend the beam steering range to larger zenith angles, which together would open a range of attractive opportunities for sensitive radio astronomical pursuits, when used with a suitable back-end receiver system. More specifically, these include, but not limited to: (1) study of solar bursts at 205 MHz, using dynamic spectral intensity measurements with high time and spectral resolutions; (2) stand-alone monitoring of about half a dozen strong known pulsars at this wavelength for changes of both intrinsic and extrinsic origin, apparent in their received radiation; and (3) active participation in the Indian SWAN (sky watch array network, a recent strategic initiative in radio astronomy), as one of its special stations for some of its campaign mode observations.

1. Gage, K. S. and Balsley, B. B., Doppler radar probing of the clear atmosphere. *Bull. Am. Meteorol. Soc.*, 1978, **59**(9), 1074–1093.
2. Fukao, S. and Hamazu, K., *Radar for Meteorological and Atmospheric Observations*, Springer, Japan, 2014, pp. 1–537.
3. Mohanakumar, K. *et al.*, Technical details of a novel wind profiler radar at 205 MHz. *J. Atmos. Oceanic Technol.*, 2017, **34**, 2659–2671; https://doi.org/10.1175/JTECH-D-17-0051.1.
4. Hocking, W. K. and Rottger, J., The structure of turbulence in the middle and lower atmosphere seen by and deduced from MF, HF and VHF radar, with special emphasis on small-scale features and anisotropy. *Ann. Geophys.*, 2001, **19**, 933–944.
5. International Telecommunication Union – Radio Communication Sector (ITU-R) Report, Wind Profiler Radars, General subject matter. *ITU-R Report M.2013*, 1997, pp. 1–16.

6. Samson, T. K. *et al.*, Technical aspects of 205 MHz VHF mini wind profiler radar for tropospheric probing. *IEEE Geosc. Remote Sensing Lett.*, 2016, **13**(7), 1027–1031.
7. Xavier, A., Kottayil, A., Mohanakumar, K. and Xavier, P. K., The role of monsoon low-level jet in modulating heavy rainfall events. *Int. J. Climatol*., 2017; doi:10.1002/joc.5390.
8. Kottayil, A., Satheesan, K., Mohankumar, K., Sivan C. and Samson, T., An investigation into the characteristics of inertia gravity waves in the upper troposphere/lower stratosphere using a 205 MHz wind profiling radar. *Remote Sens. Lett.*, 2018, **9**, 284–293; 10.1080/2150704X.2017.1418991.
9. Ananthakrishnan, R. and Soman, M. K., The onset of the southwest monsoon over Kerala: 1901–1980, *J. Climatol.*, 1988, **8**, 283–296.
10. Joseph, P. V. and Raman, P. L., Existence of low level westerly jet-stream over peninsular India during July. *India J. Meteorol. Geophys*., 1966, **17**, 407–410.
11. Chadwich, R. B., Frisch, A. S. and Strauch, R. G., A feasibility study on the use of wind profilers to support space shuttle launches. *NASA Contractor Report 3861*, 1984, pp. 1–118.
12. Kottayil, A. *et al.*, Validation of 205 MHz wind profiler radar located at Cochin, India, using radiosonde wind measurements. *Radio Sci.*, 2016, **51**, 1–12; doi:10.1002/2015RS005836.
13. Fukao, S. *et al.*, Direct measurement of air and precipitation particle motion by very high frequency Doppler radar. *Nature*, 1985, **316**, 712–714; https://doi.org/10.1038/316712a0.
14. Ralph, F. M., Using radar-measured radial vertical velocities to distinguish precipitation scattering from clear-air scattering, *J. Atmosp. Ocean. Techol.*, 1995, **12**, 257–267.
15. Vaughan, G. and Worthington, R. M., Effects of humidity and precipitation on VHF radar vertical beam echoes. *Radio Sci.*, 2000, **35**, 1389–1398.
16. McDonald, A. J., Carey-Smith, T. K., Hooper, D. A., Fraser, G. J. and Lublow, B. P., The effect of precipitation on wind-profiler clear air returns. *Ann. Geophys.*, 2004, **22**, 3959–3970.
17. Gage, K. S., Radar observations of the free atmosphere: structure and dynamics, in Chapter 28a. In *Radar in Meteorology* (ed. Atlas, D.), American Meteorological Society, Boston, MA.
18. Mohan, T. S. and Rao, T. N., Differences in the mean wind and its diurnal variation between wet and dry spells of the monsoon over southeast India. *J. Geophys. Res.*, 2016, **121**(12), 6993–7006; doi:10.1002/2015JD024704.
19. Mapes, B. E., Gregarious tropical convection. *J. Atmos. Sci*., 1993, **50**, 2026–2037.
20. Holton, J. R., Haynes, P. H., McIntyre, M. E., Douglass, A. R., Rood, R. B. and Pfister, L., Stratosphere-troposphere exchange, *Rev. Geophys.*, 1995, **33**(4), 403–439; doi:10.1029/95RG02097.
21. Fritts, D. C. and Alexander, M. J., Gravity wave dynamics and effects in the middle atmosphere. *Rev. Geophys*., 2003, **41**(1), 1003, doi:10.1029/2001RG000106.
22. Geller, M. A., Liu, H., Richter, J. H., Wu, D. and Zhang, F., Gravity waves in weather, climate and atmospheric chemistry: Issues and challenges for the community. Technical Report, the Institute for Integrative and Multidisciplinary Earth Studies (TIIMES) at the National Center for Atmospheric Research (NCAR), 2006.
23. Manoj, M. G. and Devara, P. C. S., Quasi-periodic oscillations of aerosol backscatter profiles and surface meteorological parameters during winter nights over a tropical station, *Ann. Geophys*., 2011, **29**, 455–465.

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