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On fine structure of dot echoes as observed by acoustic sounder

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Abstract. Sometimes in the lower atmospheric boundary layer, depending upon the prevailing micro-/meso-scale meteorological condition, 'dot' (also known as 'lump') type echo structures appear generally during night-time with light wind and stable stratifications. They are associated often with disturbed atmospheric boundary layer conditions like the occurrence of thunderstorms and/or of precipitation. Digitization and scanning of individual dot/lump echo structure can indicate a cluster of points with varying echo intensity levels. In the coastal region of Calcutta they are found to be spreading vertically and the size of the cluster depends on the vertical height of occurrence. Using image processing technique fine structures of these echoes have been processed, their statistical nature has been analysed and reported in this paper.

1. Introduction

For the last few years, during continuous soundings of the atmospheric boundary layer (ABL) by SODAR at the Indian Statistical Institute (ISI) Calcutta, we have often observed, within the shear echo layer a peculiarity in the form of 'dot' shaped echo structures above the surface-based layer. Usually, at the coastal station in Calcutta, they appear at night-time with the presence of a light wind and also at saturated or near-staturated moisture conditions prevailing in the rainy weather. Gaynor *et al.* (1976) reported cylindrically shaped (hummock) echoes with vertical structures of several hundred metres and attributed them to the region of enhanced temperature stability and moisture gradient in broken tropical cumuli. In the disturbed weather condition associated with thunderstorms, Hall *et al.* (1976) successfully observed density current echo structures. Zhou *et al.* (1981) studied the characters of the irregular 'lump' echo structures observed mostly in the rainy season with stable stratification and light wind. Singal *et al.* (1985) also reported the presence of 'dot' echo structures in moist weather, temperature gradient with strong winds and determined their presence as the indicator of approaching depressions.

The elevated and multi-layer structures also observed above the surface-based layer under disturbed weather conditons, but they are quite different from the dot echo structures. Multi-layer echoes are often attached to certain atmospheric conditions such as subsidence and advection with the passage of a cold front over uniform/complex terrain. Elevated layer formations near the sea-coast were attributed to the advection of a marine boundary layer and were recorded in the sodar echograms (De *et al.* 1990), whereas these short-lived irregular shaped dot/lump echoes were attributed to some inhomogeneous air lumps in density. These dot echoes mainly reflect density fluctuation caused by the cooperative effect of the temperature and humidity inhomogenities.

In this paper we have utilised an image processing technique for analysing the fine structure of individual dot/lump echoes. Individual dot echo structures, as recorded in the sodar echogram, with their signal intensity variation being considered here to determine the number of cluster points in a particular dot echo structure and also to classify or interpret these cluster points through statistical analysis.

2. Morphological character of dot echo

A sonic detection and ranging (sodar) system was installed at ISI-Calcutta to observe and study the behaviour of the lower ABL in this coastal region of Calcutta by round-the-clock vertical sounding of the atmosphere up to a height of 1 km above the ground. In this mode of operation a stable layer near the ground gives rise to more than one quasi-horizontal echo with a band structure in the small height interval. The layers, usually a few 10 m thick, correspond in height to regions of sharp vertical changing in refractive index gradients. Further measurements of the dielectric constant of atmosphere have shown the relatively sharp variations in refractive index gradient that exist both in horizontal and vetical planes. Since the geometrical shape of the boundaries formed by these gradients are not well-defined, one may postulate an atmosphere of many layers with limited extent [Das *et al.* 1990).

In general the scattering of sound waves within the atmosphere, according to Wesely (1976), is caused by turbulence and may be determined by inhomogenities of the refractive index as given in

$$C_n^2 = C_T^2/4T^2 + 2(0{\cdot}307)(C_{eT}/4PT) + (0{\cdot}307)^2(C_e^2/4P^2) \tag{1}$$

where C_n, C_T, C_e and C_{eT} are fluctuation structure parameters for refractivity, temerature, humidity and cross-correlation (of humidity and temperature), and P, and T are average values of pressure and temperature of the atmosphere. One can calculate, utilizing the concept of 'frozen turbulence', the horizontal scale of dot echo in terms of its maintenance time and mean wind speed at the vertical height of its occurrence.

Following Little (1969), the sound scattering cross-section in the inertial sub-range is $\sigma(\theta)$

$$\sigma(\theta) = 0{\cdot}033\, K_0^{1/3} \cos^2\theta [0{\cdot}13\, C_n^2 + \cos^2(\theta/2)(C_v^2/4c^2)] \sin(\theta/2)^{-11/3} \tag{2}$$

where C_v is velocity fluctuation structure parameter, c is the velocity of light, K_0 is the wave number of transmitted sound waves and θ is the scattering angle of received sound waves. For a back-scattered signal $\theta = 180°$ and corresponding back-scattering cross-section, after simplification, is given by

$$\sigma(180°) = 0{\cdot}016\, \mathrm{K}_0^{1/3}[C_T^2/4T^2 + 2(0{\cdot}307)(C_{eT}/4PT) + (0{\cdot}307^2(C_e^2/4P^2)] \tag{3}$$

and we may consider its three types:

(i) for the dry air it is $\approx 0{\cdot}016\, K_0^{1/3}(C_T^2/4T^2)$ since in dry air the bracketed second and third terms of (3) are insignificant in comparison to its first term and hence ignored.

(ii) for the wet air with positive correlation of C_{eT} it will be of higher value than its dry part since when C_{eT} is in phase with C_T it will be beneficial to density fluctuation,

(iii) for the wet air with negative correlation of C_{eT} it will be of lower value than its dry part since C_{eT} is out of phase with C_T it will be non-beneficial to density fluctuation.

This theory assists us to find out, in the sodar records, the wondering appearance of some strong echoes at a certain height enduring for a few minutes and then dissolving abruptly. The outlines of these echoes are very much distinct with frequent occurrence before or after rain mostly in the monsoon/post-monsoon seasons. Occasionally presented by a rhombic or rectangular shape, these strong echoes are basically in irregular configuration with different scales in square. These may be termed as dot/lump echo structures as recorded in the ISI sodar system and shown in figure 1.

Morphologically these dot echo structures are different from the usual inversion or thermal ones. Analysis of data obtained from the India Meterology Department (IMD), Dum Dum about 2 km from the sodar site and the facsimile data of the ISI sodar echogram depicts that presence of inversion/stable stratification is necessary and dot echoes are spread over these stratifications. As shown, in some synoptic processes associated with either cloudy, shower, or thunderstorm phenomenon, the appearance of these dot echoes is very frequent but they are rarely found in normal weather conditions or in a few observations their presence is ignored. A detailed inspection cum analysis of dot echo structure as depicted in these figures shows that:

(i) they occurred around night-time;

(ii) they are formed around 00·25 h IST with the condition of wave perturbation superposing over the top of the stable ground inversion (figure 1 (*a*)) just after the passage of a thunderstorm;

(iii) they mostly occur nearer to the ground surface after, or in between, two successive bouts of rain (figures 1 (*b*) and 1 (*c*)) and the vertical distribution of these dot echoes limited within the first 500 m height;

(iv) just before the above mentioned observations (figure 1), no trace of dot/lump echoes were observed;

(v) about 220 numbers of various sizes were recorded in a 3-hour duration with a varying nature of individual dots;

(vi) the fluctuating nature of echo-intensity within an individual dot which is almost inseparable by visual observation of the facsimile recording.

It was observed in figure 1 (*a*) that the spreading of dot echoes covered almost the full height of the recording echogram. Of course, all the dot points in the echogram may not be a true representation of dot echoes and sometimes the atmospheric noises may produce dots. So it is very difficult to isolate noisy dots from true representative dots by a standard technique. However, this separation is very much needed for further analysis and can be implemented by a noise cleaning algorithm based on a computer image processing technique. In order to get a higher resolution and to obtain a fine structure of these dot echoes, suitable transformation of the picture into appropriate grey valued pixels is needed. We have done this separation work by developing appropriate noises, i.e., cleaning algorithm (discussed later) and estimated different statistics on dot echo structures.

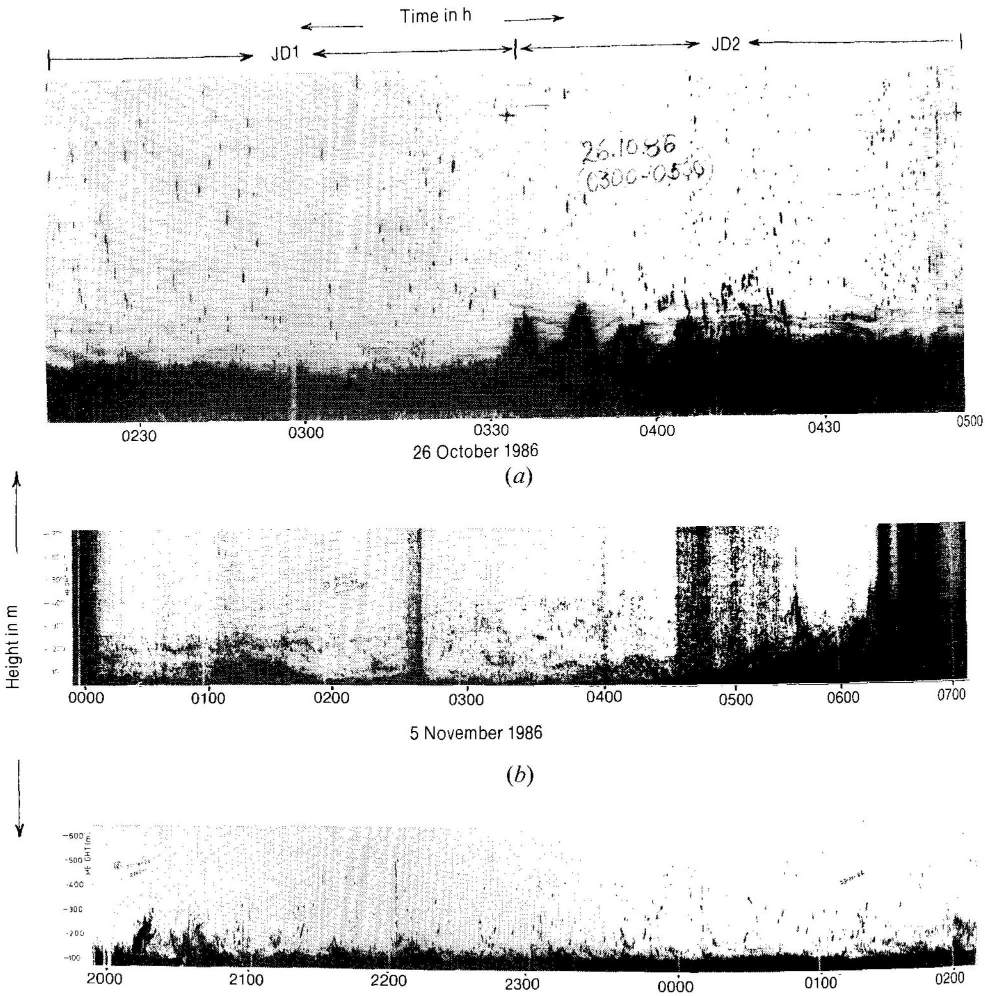

Figure 1. Recorded dot echo structures at ISI, Calcutta.

3. Noise cleaning of dot echo

Apart from the atmospheric information sodar echograms are usually associated with some atmospheric and/or man-made noises. So an echogram data must be free from these noises for better atmospheric interpretation. The sodar record is, therefore, first digitized by a video camera-cum-scanner and then processed to separate image pixels (information) from the non-image pixels (noise).

In the digitization process a capture zone of the 10 cm by 7 cm image area from a facsimile record has been transformed into a matrix of 256 by 256 grid points or pixels. Since this matrix corresponds 1 hour 20 minutes along time (or X-) axis and

700 m along the vertical height (or Y-) axis, resolution of each pixel is 18·75 seconds by 2·73 m. Some portion of figure 1 (a) has been shown in figure 2 as the capture image. In digitization of the intensity values of sodar echogram, we have assigned the lowest grey value almost at 0 for the maximum darkest part of the image and obviously the whitest part of it corresponds to a grey value of 255.

There are various techniques available for the separation of image/non-image pixels but a good deal of the individual algorithm is problem dependent. For cleaning noises in dot structure we have adopted the histogram method to separate these two types of pixels and a histogram is drawn by considering the intensity values of all the pixels. The general nature of the histogram for atmospheric patterns corresponds to a bipolar type of distribution and in sodar imagery the right-half of histogram is represented by noises. Once a histogram is drawn a threshold line, for separation of image/non-image signal, has to be selected. The selection of this threshold line is a crucial task, because if we set the threshold value towards the left-side of the optimal threshold line, then some border line information will be mixed with noise and will be lost. Similarly, in the case of the right-side setting of it with respect to the optimum thresholding line, more noise will be considered as information and respective cleaning will not be exact. With the developed algorithm we have found the optimum thresholding line at 135 and using figure 2 it has been reconstructed and is shown in figure 3 (Tripathy *et al.* 1992).

On the implementation of noise-cleaning algorithm we only obtained dot echo structures within capturing zone of the record. In figure 1 (a) there are two capturing zones with a number of dot structures (that were counted) 83 and 94 respectively during 02.20–03.40 h and 03.40–05.00 h on 26 October 1986. These dot structures are of a different size with internal variation to backscatter signal intensity representing the individual dot with a cluster of image pixels. We have also developed an algorithm for finding different image pixels within a dot structure. For example, we found an horizontal blob (marked as A) in which the number of pixels were 51, with grey values ranging from 99 to 135. Similarly for a vertical blob (marked as B), there were 20 with grey values 99–106.

4. Statistical analysis on dot echo/structure

Situated on coastal region of the Bay of Bengal, the humidity content of Calcutta is more than 80 per cent for most of the season and the water content available in the free atmosphere within the first 1 km height is also very high when compared to the land region, (Chakraborty *et al.* 1993). Moreover, this coastal region of Calcutta is prone to thunderstorms and northwesterlies, mostly in the pre- and post-monsoon seasons. Detailed analysis of the sodar records over a period of one year reveals the presence of dot echo structures for about 1·5 per cent only. They mostly appear above the top of the stable ground-based inversion and intensively cover to within a height range of 250–400 m, as shown in figure 4 in which the distribution of the vertical dot structures can be seen. On the complete echogram for 26 October 1986 between 02.20–05.00 h, the occurrence of a total number of these echo structures was about 226 but possibly this might have included some noise. We have found that most of the dots are spreading along the vertical direction (height axis) and a few of them over the horizontal direction (time axis). As shown in figure 4 out of 83 dot structures, 63 of them spread in a vertical direction and 8 in the horizontal direction, with the remaining 12 structures spreading diagonally. From our experience of visual observation, each dot echo structure appears to be a single entity. But owing to high

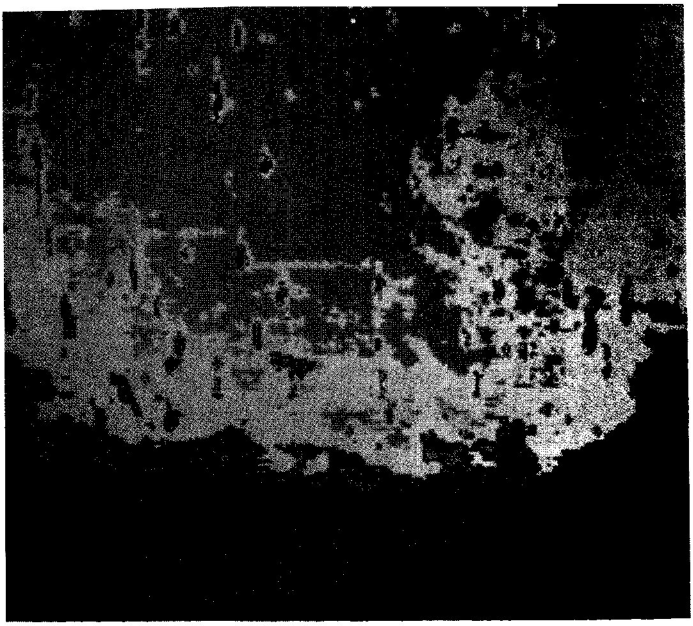

Figure 2. Capture image (part of figure 1 (*a*)) containing dot echo structures.

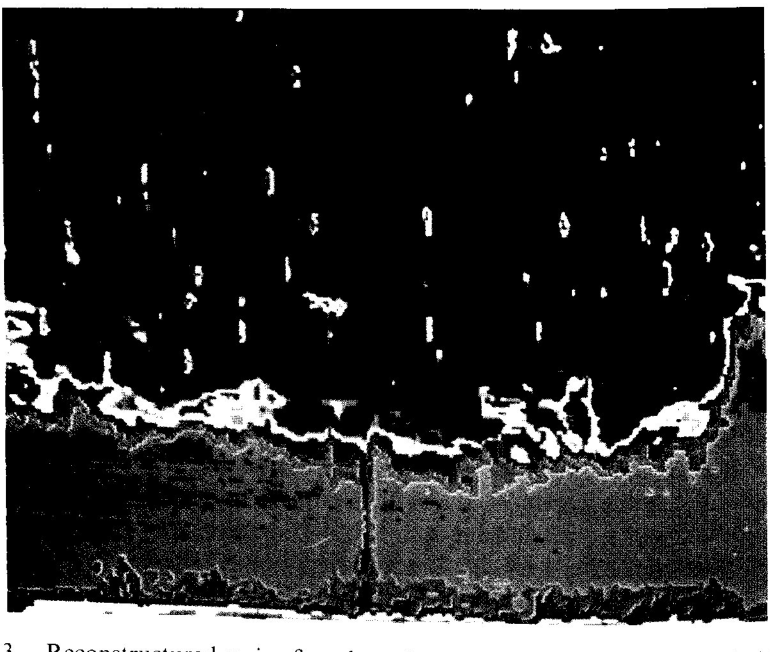

Figure 3. Reconstructured noise free dot echo structure. Image with threshold value 135.

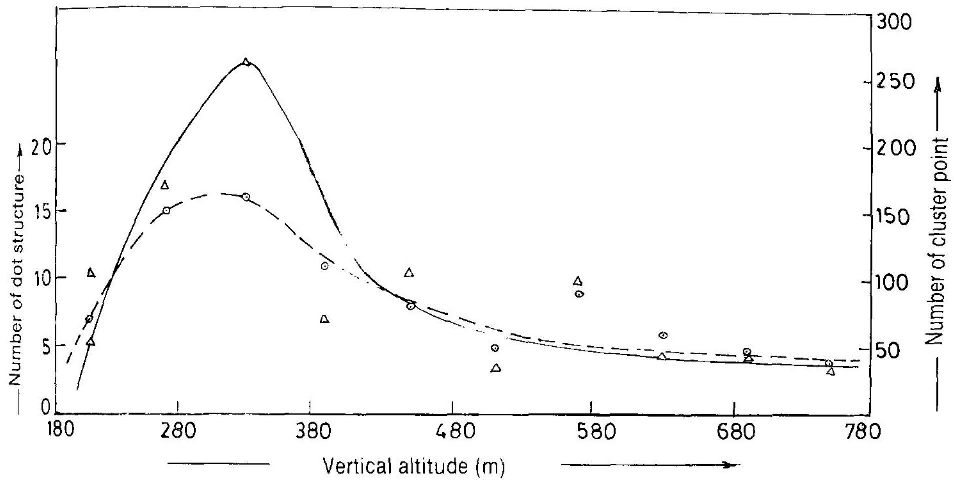

Figure 4. Vertical distribution of dot structures and varying cluster points within the specified capture zone. ---○---, Dot structure; ——△——, Cluster point.

resolution, each dot structure is treated as a cluster of points (or pixels) with varying intensity when it is digitized by a video scanner/digitizer. The vertical distribution of a cluster density as associated by each of the pixel is shown in figure 4. Appearance of the maximum number of cluster points within the height range of 250–350 m has been found and has been noticed, although the water vapour content in the lower atmosphere of this coastal region is exponential in nature to vertical heights, especially after rains, that it increases sharply with falling height (cf. figure 2, Chakraborty *et al.* 1993).

Dot echoes are often neglected in normal weather conditions, as their presence is very rare in that situation, but because of the enhancement of water content within the lower atmosphere during disturbed weather conditions associated with either cloudiness, thunderstorms, or showers, these dot echoes can persist for a long time (compared to the normal ones) and are detected more often. According to the concept of 'frozen turbulence', we can determine the horizontal or vertical scale of dot echoes in terms of their maintenance time and mean wind speed with which they appear at a particular vertical height. Around 01.20 h IST, on 26 October 1986, rains occurred and just after the surface wind speed was low, about 2–3 m s^{-1}. In figure 5 the distributions of the horizontal and vertical scale, as analysed by computer algorithm against their occurrence frequencies out of 83 dot echo structures, are shown. Most of those on the horizontal scale are within 18 m and the maximum is 45 m. Similarly most of these on the vertical scale are within 30 m, although its maximum dimensions is 55 m. Zhou *et al.* (1981) also studied the lump echoes over Beijing and found that the maximum horizontal scale of lump echoes was 190 m but most of these horizontal scales were within 30 m. Comparison on these two set of studies shows that the vertical scale of dot echoes over Calcutta is larger than its horizontal scale but in Beijing these are reversed because Beijing has a predominantly horizontal scale.

Very short-lived dot echoes are sometimes observed over the ground based structure, concentrated at 30–40 seconds, but they suddenly disappear. They occur

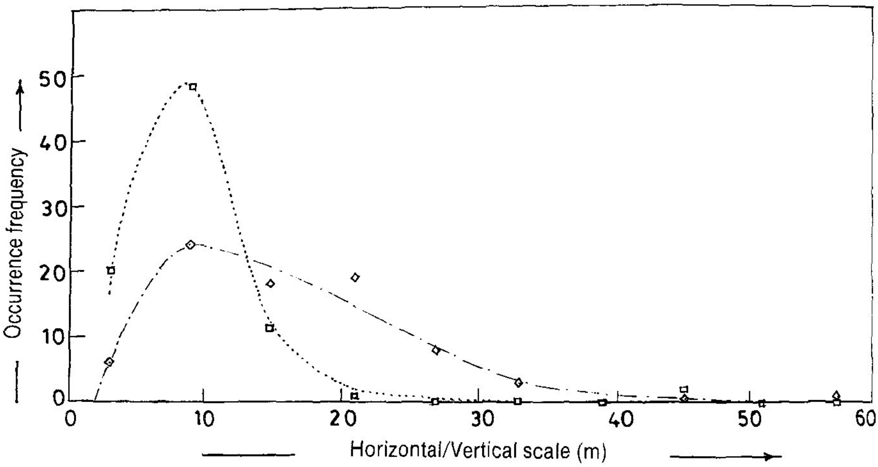

Figure 5. Occurrence frequency of dot echoes along the horizontal and vertical scale within the specified cluster zone. —·—□—·—, Horizontal scale; ······◇······, Vertical scale.

within a 250–350 m height range mostly in a vertical shape and their vertical scale sizes (typical) are around 100 m or more.

5. Conclusion

In most observed circumstances, predominance in temperature inhomogenities would be more acoustically effective. However, theoretical/observational evidence shows that in moist boundary layers humidity structure may also be effective (Wesely 1976, Gaynor *et al.* 1976). It is apparent that enhancement of one or both of these factors may be crucial for the appearance of dot echoes over the coastal region of Calcutta. In cases of light winds and stable stratification and owing to weak turbulent exchanges, the density of these inhomogeneous airmasses would have a certain living time, even though this might finally be smoothed out by turbulence. These inhomogeneous lumps of density often appear in a warm tropical region before and after cold fronts and are usually associated with thunderstorms and precipitation processes in the atmosphere. We are now interested to proceed to study the prediction of some meteorological phenomena, such as the quantity of rain and precipitation, drop size distribution etc., with the various statistical distribution of such dot echo structures. We shall make elaborate observations, as pointed out by one of the referees, to consider whether there are other structures in the absence of dot structures under similar meteorological conditions favourable for the formation of dot echo structures. We will be reporting this in our next paper.

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