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A preliminary study of 'Angel' activity near Bombay

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ABSTRACT. During the period March-May 1958 some radar angels were observed on the PPI display of weather radar based at Bombay. These echoes cannot possibly be attributed to the generally accepted type III angel source, *viz.*, reflection of radar waves from ground *via* atmospheric layer or inhomogeneity. It is suggested that these are angels caused by direct partial reflection from a horizontally stratified layer containing shear-gravity waves.

1. Introduction

The reflection of radio waves from stratifications in the troposphere had been envisaged as early as in the thirties. With the development of centimetre radars, therefore, when echoes were received from regions in the atmosphere where no known scattering sources existed, they were naturally attributed to some tropospheric phenomena, and were commonly termed as 'ghosts', 'angels', 'pixies' etc. The term 'angel' has, however, come to stay, at least in meteorological circles and during recent years a sufficiently large number of angel activities have been reported. The observed features of these angels vary considerably and the cases observed so far have been classified into three different types (Plank 1956).

It has been proposed by Plank that angels observed on PPI display at near horizontal incidence (type III angels) are the results of outgoing radar waves being reflected or refracted from an atmospheric layer or inhomogeneity to the ground and then reflected back to the receiver *via* the reciprocal path. During the period March-May 1958 a number of anomalous echoes were observed on the PPI display of the weather radar based at Santacruz airport (Bombay). These echoes cannot possibly be explained on the above mentioned reasoning. Some of these angel observations are presented here and discussed in relation to the prevailing meteorological conditions.

2. Radar characteristics

The radar set utilized for these observations is Decca storm warning radar (Type 41) operating in the frequency band 9320-9500 megacycles, with a pulse width of $0 \cdot 2\mu s$ or $2 \cdot 0\ \mu s$ (The observations to be described here were all taken with the set operating with $2 \cdot 0\ \mu s$ pulses). The peak power is 20 KW and the beam width to half power points is $\cdot 75^{\circ}$ in the horizontal and 4° in the vertical. The pulse repetition frequency is 250 pulses per second. The set is equipped only with PPI display and the aerial is capable of being tilted from two degrees below the horizontal to twelve degrees above. The geographical location of the radar is such that the coast line is only about 2 miles away running roughly north to south. Fig. 1 gives the permanent ground echoes within fifty miles of the station.

The weather radar was installed at Santacruz towards the end of March 1958 and was operated on full time basis only from April. The angel observations on 22 and 27 March 1958 were obtained in course of initial performance check of the instrument and do not exclude the possibility of angel activity on the rest few days of the month. From April onwards, however, the observations were taken regularly. Due to the initial adjustment difficulties, it could not be possible to photograph the scope during all operation nor all the photographs that were taken came out satisfactorily. Only a few of the photographs

TABLE 1

Date	Time (IST)	Location of occurrence relative to radar station		Operator's remark as entered in station log book
		Direction (degrees)	Range (n. miles)	
1958				
Mar 22	1700—1900	240—350	22—30	
Mar 27	1600—1700	249—300	20—25	
Apr 3	1700—1800	W. Sector	18—20	Weak echoes
	2130—2245	W. Sector	18—20	Very weak echoes
Apr 6	1800—1830	W. Sector	19—23	Weak echoes consisting of dots
	1900—1930	W. Sector	20—25	Echoes moving westwards
Apr 9	1815—1945	180—210	18—20	Clear diffuse zigzag patch slowly moving towards west
Apr 15	1730—1745	260—330	20—30	Faint cluster of echoes
Apr 17	1900—1930	W. Sector	20	Fairly strong echoes
Apr 22	1830—1900	340—356	40—50	Fairly thick dots
Apr 23	1615—1635	270—350	37—45	Diffuse patch of echoes prominent upper portion
	1820—1845	270—350	37—45	Diffuse patch has become more bright and compact on a wavy curve, shape changing frequently
May 23	1945	200—350	34—45	Cluster of bright spots

are, therefore, available for presentation. The nature of the echoes was, however, strikingly uniform and whatever the variations they are fully covered by the photographs presented here.

3. Observations

The details of these observations with operator's remarks are given in Table 1. It is evident from these data that the echoes appear only from the sea area to the west and the preferred time of occurrence is late afternoon, since the echoes have appeared mostly between 1600—1900 IST. The angel activity appears to cease generally after 2000 IST although on one occasion the echoes have been observed even at 2245 IST. The echoes appear as cluster of dots, thickening slowly and sometimes growing into wavy lines. The most frequent range is 20—25 nautical miles with an aerial tilt of 0 to 2°. On a few occasions they were also observed at 40—45 n. miles at zero aerial tilt. The echoes have been observed moving from north to south and sometimes moving out to the west. On some occasions they disappeared without any appreciable movement. On most of these occasions of angel observations it was found that individual echoes were not present on every successive sweep of the beam. This intermittent appearance of the echoes gives the impression of their shape changing frequently and the movement being jerky. This peculiarity has been reported by others (Harper *et al.* 1957) also and is regarded as characteristic of angel echoes.

On 22 March 1958 the echoes first appeared at 1800 IST as a group of faint dots in the northwest sector and quickly developed into a thick bright cluster and gradually shifted southwards. Fig. 2 gives two photographs of these echoes taken at 1815 and 1830 IST. At 1815 IST the echoes were extending from northwest to west, though some faint echoes had started appearing in southwest also. The central portion was the most prominent and the waviness could be clearly seen. The solid appearance of this portion is partly due to observations being taken at 100 n. miles range. At 1830 IST the echoes had started weakening, but more prominent part was to be found to westsouthwest. A slightly different nature of these echoes is shown in Fig. 3, the photographs having been taken at 1730 and 1740 IST on 15 April 1958. In this case also the echoes first appeared as clear dots and quickly thickened to form the zigzag cluster. The intensity was maximum at 1730 IST. The echoes weakened and disappeared without any appreciable movement. The weakening of the echoes can be seen even at 1740 IST. Fig. 4 shows another instance of the echoes. The echoes appeared at 1800 IST on 6 April 1958 at a range of 18—20 n. miles and gradually moved westwards. In the photograph taken at 1825 IST these echoes can be seen to the west just moving out of the scope at 25 n. miles range. Another wavy structure on these echoes is shown in Fig. 5, the photograph being taken at about 1630 IST on 27 March 1958.

4. Weather at the time of observation

The weather was fine with either clear skies or with negligible amount of high clouds on all the days of angel observations except on 22 March 1958. At the time of observation on this day the sky was nearly overcast with altocumulus with a few patches of high stratocumulus. Winds over Bombay were on most of the days northerly upto 3000 ft. Wind, temperature and dew-point profiles as observed over Bombay nearest to the period of observations for some of the cases are given in Fig. 6. It may be mentioned here that the information contained in these diagrams by no means characterises the small scale features of the atmosphere that affect radio propagation and they are meant to give only a broad indication of the conditions prevailing. However, it may not be unreasonable to assume that the upper air temperature and humidity conditions 25—30 miles west of Bombay would be the same as represented by the soundings at Bombay.

5. Discussion

The angels described above have been observed mostly at an aerial tilt of 1° and at a range of 20—25 n. miles to the west. To the west of the radar site there is a vast stretch of Arabian Sea and, therefore, these echoes cannot be identified with the type III angels as classified by Plank. The changing shape and position of the echoes rule out any possibility of super-refraction effects. Observations apart, with a nominal peak power of 20 KW, it is difficult to visualise (however efficient a duct be) the return of minimum detectable signals from distances of the order of 1000 miles. The echoes, therefore, are most likely to be associated with some atmospheric phenomenon. Earlier studies (Plank 1956, Chmela and Armstrong 1955, Harper *et al.* 1957) have shown that day time angel activity is associated with convective regions, where convective bubbles (Scorer and Ludlam 1953) provide the reflecting source. An examination of radiosonde observations on those days showed that the echoes occurred in association with high temperatures. On most of the days, there was shallow inversion at 100—400 metres with super adiabatic or adiabatic lapse rate below. Therefore, the possibility of these echoes being produced by convective regions is also ruled out even if one ignored the slow moving or stationary nature of the echoes.

It is suggested, therefore, that the echoes are caused by direct partial reflections from

TABLE 2

Date	Wavelength (λ)	Temperature difference ($T'-T$)
22 Mar 1958	4 n. miles	2°C
15 Apr 1958	3 n. miles	1°C

a horizontally stratified layer with appropriate refractive gradient; the primary causative source of the refractive gradient being the variation in specific humidity. This type of layer is known to give type II angels at vertical incidence and 'glint' reflections at near horizontal incidence. If one postulates the existence of shear-gravity waves in the layer, a portion of the radar beam incident on the part of the wave having a curvature towards the radar site, will be reflected back. At a range just beyond the geometrical horizon, the portion of the wave concave or convex towards receiver being maximum, the echoes will be more pronounced. This may partly explain the occurrence of the echoes more frequently at ranges 20—25 n. miles.

The pattern of the echoes would normally approximate to the wave form itself and, therefore, a qualitative idea of the wavelength of the shear-gravity waves can be obtained from the photographs in Figs. 2 and 3. The wavelength thus computed along with the temperature differences observed for the two cases are given in Table 2. For the order of temperature difference and wind shear present, the wavelengths are much above the minimum for stable occurrence.

The velocity of a shear gravity wave is given by the expression (Haurwitz 1941)—

$$C = \frac{\rho U+\rho' U'}{\rho+\rho'} \pm \sqrt{\frac{g\lambda}{2\pi}\,\frac{\rho-\rho'}{\rho+\rho'} - \frac{\rho\rho'(U-U')^2}{(\rho+\rho')^2}}$$

where C is the wave velocity, ρ the density, U the velocity of the undisturbed flow and λ the wavelength. The primes refer to the upper fluid. From Fig. 6 it can be seen that wind shear in both the cases is small and since we are interested only in the order of magnitude we may put $U \approx U'$.

$$\therefore\ C = U \pm \sqrt{\frac{g\lambda}{2\pi}\,\frac{\rho-\rho'}{\rho+\rho'}}$$

$$\text{Or } C = U \pm \sqrt{\frac{g\lambda}{2\pi}\,\frac{T'-T}{T'+T}}$$

assuming $\rho \approx \rho'$

With $\lambda = 4$ n. miles, $T'-T = 2°$ C and $U = 10$ kt/hr

$$C = 5 \pm 10 \text{ m.p.s.}$$

In this case (22 March 1958) the echoes were observed to move southwards and the upper sign has to be taken. Therefore C=15 m.p.s. or 27 knots, which is quite consistent with the observed movement of the echoes as far as order of magnitude is concerned.

With $\lambda = 3$ n. miles, $T'-T = 1°$ C and $U = 10$ kt/hr

$$C = 5 \pm 4 \text{ m.p.s.}$$

Since the echoes were changing shape and weakening rapidly on 15 April 1958 even if we take the upper sign, a velocity of this order could not possibly be detected over a small period of observation and the echoes, therefore, showed no appreciable movement.

The expression for the wave velocity used above is derived on the assumption that the fluid layers on both sides of the discontinuity are infinitely deep. This is obviously not true in case of low level inversions. For deriving the expression for C, therefore, at least one boundary condition, *viz.*, $u=0$ at $z = -h$ (where h is the height at which inversion starts) has to be applied. In these cases, however, the result would not be affected as far as the order of magnitude is concerned, although the velocities obtained would be smaller.

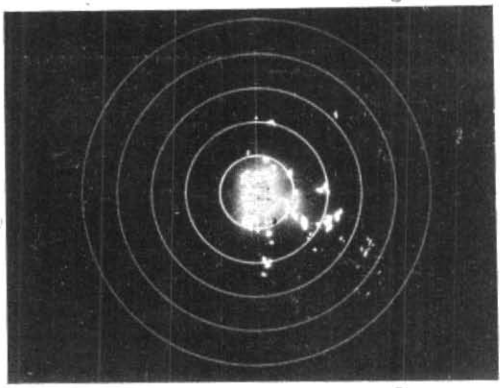
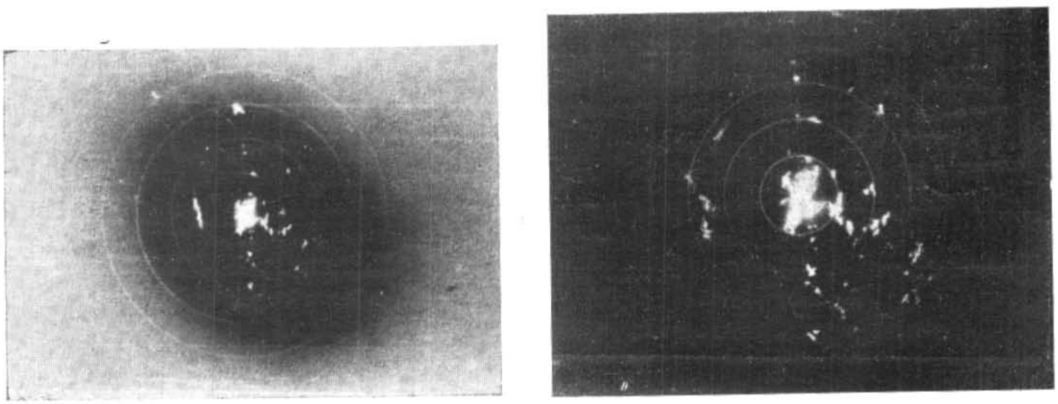


Fig. 1. Permanent echoes within 50 n. miles range

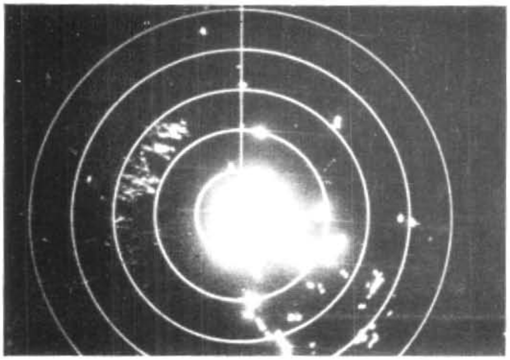
Range marker interval 10 n. miles, aerial tilt zero degree



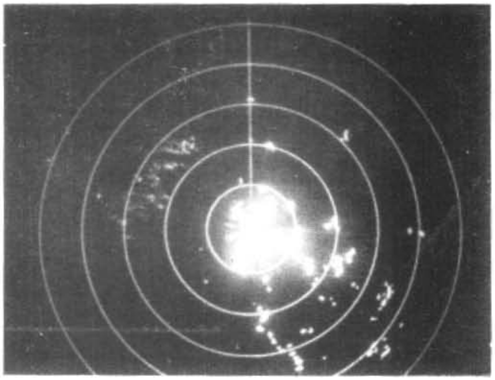
1815 IST
Range marker interval 20 n. miles

1830 IST
Range marker interval 10 n. miles

Fig. 2. Photographs of PPI scope showing angels on 22 March 1958



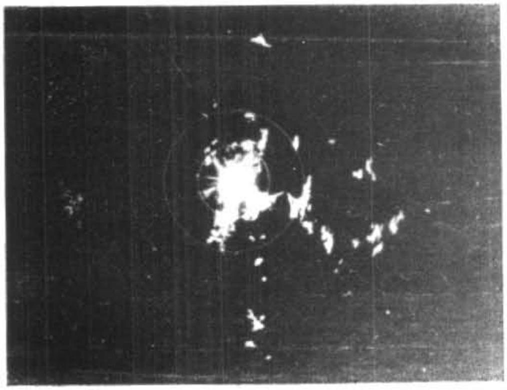
1730 IST



1740 IST

Fig. 3. Photographs of PPI scope showing angels on 15 April 1958

Range marker interval 10 n. miles



1825 IST

Fig. 4. Photograph of PPI scope showing angels on 6 April 1958

Range marker interval 5 n. miles

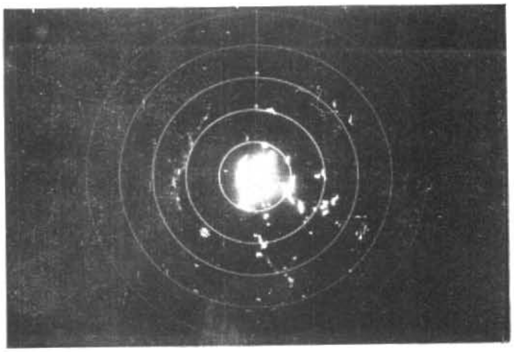


Fig. 5. Photograph of PPI scope showing angels on 27 March 1958

Range marker interval 10 n. miles

(Group of echoes to the southwest is from known objects)

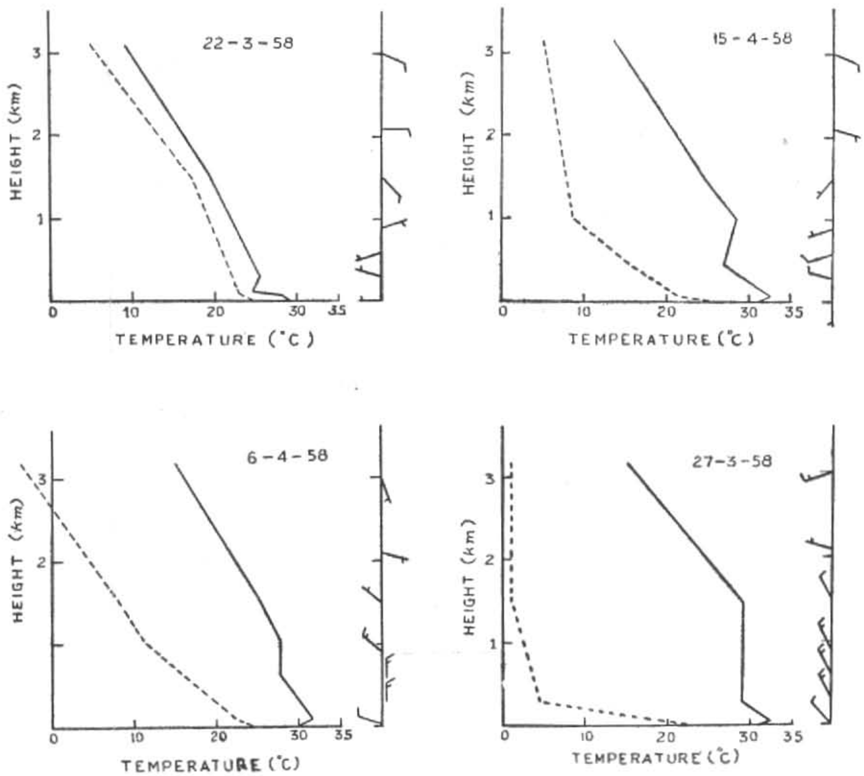


Fig. 6. Wind, temperature and dewpoint profiles

The condition favourable for the occurrence of these echoes, therefore, appears to be the existence of a low level inversion with proper specific humidity gradient. Although on two occasions of these angel observations no such inversion could be noticed it is quite likely that such inversion developed after the time of observation or on a scale not detected by the conventional radiosonde equipment.

Another observed feature which needs explanation is the preference for the area and time of occurrence. As regards time, the preference can be explained on the grounds that the temperature being higher, conditions in the late afternoon are more favourable for building up of proper refractive gradient. The absence of the echoes from the east may be accounted for by the topographic features. To the eastern side of the station, there are extensive hill ranges starting at 2 to 5 miles, the heights of the nearer hills reaching upto 1000 ft. To the southeast in particular, there is a hill range 1002 ft high covering a considerable sector.

It is quite probable, therefore, that the radar beam being intercepted by the hills, the atmospheric layers which may provide sources for angels in these areas are not illuminated at all.

The angel observations reported here were obtained during routine operation of weather radar, rather as a by-product and not as a result of any planned research programme. The absence of RHI display was a handicap in making a detailed study of these echoes. The suggestion as to the origin of these echoes is more or less tentative but in the light of more observations in future, it is hoped to put forward a satisfactory explanation of the manner in which reflections occur from the sources postulated.

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