551·593 : 621-396·9

A study of Radar Angels near West Coast of India

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(*Received 20 July 1960*)

ABSTRACT. A new type of well marked radar angels often having characteristic wave structure has been frequently observed on the P.P.I. scope of a 3-cm radar based at Bombay. Observations over a period of fifteen months have been analysed. The echoes are observed in the late afternoons and early night hours only during the months March—May; the activity reaching its peak in the month of April.They are most prominent on days with markedly high temperatures.The possibility of these echoes being caused by back-scattering from horizontally stratified layer containing very sharp refractive index gradients, is discussed. The wave structure of the echoes is attributed to the existence of shear-gravity waves in the stratified layer.

1. Introduction

In recent years a large number of angel observations have been reported from different places. The echoes have been obtained at wavelengths as low as ·86 cm and as high as 23 cm. Plank (1956) has summarised the available information regarding angels and has examined the angel-meteorology correlation giving also an account of different theories put forward to explain these echoes. A number of other observations have subsequently been reported (Elder 1957, Harper *et al.* 1957, Atlas 1959) with suggestions regarding the possible sources. Quite recently Jones (1958) has quantitatively examined the possibility of some of these echoes being caused by refractive inhomogenieties in the lower atmosphere.

During the year 1958-59, particularly well-marked angel echoes, often having characteristic wave structure, were frequently observed on the P.P.I. scope of a 3-cm radar based at Bombay. Observations during the period March-May 1958 had been reported by the author earlier in a preliminary study (Rai 1959). The form and nature of the echoes are such that the birds-insects hypothesis has to be rejected. The geography of the area excludes the possibility of reflections from ground objects *via* some atmospheric inhomogenieties. Some of these angel observations are presented here and the possibility of these echoes being caused by back-scattering from atmospheric layers containing refractive inhomogenieties discussed.

2. Observations

The radar set utilised for these observations is Decca type 41 storm detecting radar. The set characteristics are given in Table 1. The radar has got provision for P.P.I. display only and the aerial is capable of being tilted from two degrees below the horizontal to twelve degrees above. The angels were mostly observed at 0 to 2° tilt angles, though on some occasions the echoes persisted even upto 4° tilt.

The geographical location of the radar is such that the coast line is only two miles to the west running roughly north to south. The echoes are obtained exclusively from west at ranges 20 to 40 miles, ranges near 20 being more frequent. Table 2 gives the details of angels observed during the period March 1958 to May 1959. Although the radar was operated at regular intervals these echoes were not observed on other days. The appearance of the echoes exclusively during the period February—May is conspicuous. The observations also show a uniquely preferred time, *viz.*, late afternoon although on one occasion the echoes appeared as early as 1140 IST and persisted till 2030 IST. The echoes are generally coherent in nature and often have wavy appearance. At least the

TABLE 1

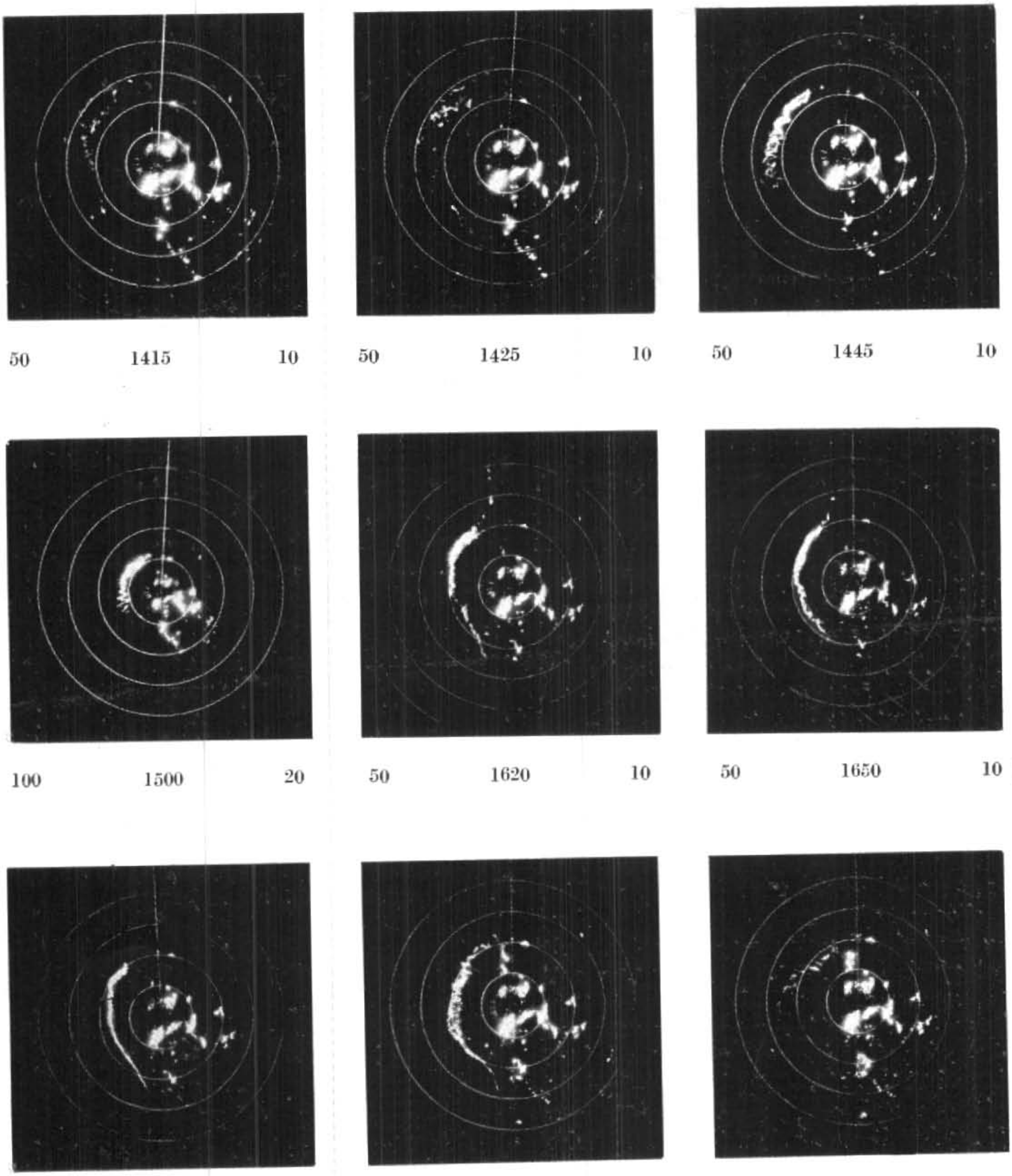
Wavelength	3·2 cm
Transmitted power	20 kw
Pulse length	2·0/0·2 μ sec
Pulse repetition frequency	250 p.p.s.
Beam width in the horizontal	0·75 degrees
Beam width in the vertical	4·0 degrees

TABLE 2

Date	Time (IST)	Location of angels relative to radar station: Direction (°)	Location of angels relative to radar station: Range (n. miles)
22-3-58	1700—1900	240—350	22—30
27-3-58	1600—1700	240—300	20—25
3-4-58	1700—1800	Western sector	18—20
	2130—2245	Do	18—20
6-4-58	1800—1830	Western sector	18—23
	1900—1930	Do	20—25
9-4-58	1815—1945	180—210	18—20
15-4-58	1730—1745	260—330	20—30
17-4-58	1900—1930	Western sector	20
22-4-58	1830—1900	340—356	40—50
23-4-58	1615—1635	270—350	37—45
	1820—1845	270—350	37—45
23-5-58	1945	200—350	34—45
23-2-59	1425—1445	240—325	12—18
24-3-59	1815—1910	205—320	15—20
	2000—2045	260—315	25—30
25-3-59	1715—1725	260—300	20
28-3-59	1700—1725	235—340	20—25
7-4-59	1600—1615	280—320	15—18
	1810—1820	240—330	15—20
8-4-59	1630—1730	255—320	15
13-4-59	1800—1900	270—350	35—45
22-4-59	1730—1900	215—340	30—40
23-4-59	1730—1930	200—340	28—35
30-4-59	1145—2030	190—350	17—30

more intense part of the echoes appears in the form of arcs roughly concentric with the range rings. The extent of the echoes is at times 80 miles in length and 5 miles in width.

A sequence of angel observations taken between 1400 and 2000 IST on 30 April 1959 (a day of typically strong echoes) is reproduced in Fig. 1. The echoes initially appeared at 1145 IST at a range of 30 miles in 230-350° sector. The echoes were, however, weak and continued to be so till 1400 IST. At 1400 IST a fresh set of echoes developed in the same sector at 25 miles. Both the sets of echoes can be seen in the photographs taken at 1415 and 1425 IST; the outer echoes are much weaker. Both the sets appear to have wave form. The two sets slowly started merging and moving slightly in, at the same time becoming brighter. By 1445 IST the two sets had completely merged in the NW-NNW sector while definite overlapping could be seen in the southern portions. By 1500 IST the merging of the two sets appeared to be complete, the wave form being very prominent in the lower portions. During the next one hour the echoes had the upper end at a range of 40 miles towards N and NNW, the lower end at 25 miles towards SSW. The main part, however, remained unchanged except for moving slightly nearer. The wave structure exhibited earlier got smoothed out and at 1620 IST an entirely different wave pattern could be seen, with the main portion of the echoes forming a half wavelength. By 1650 IST the northern portion of the echoes started disappearing while the southern portion became more marked. During the next half hour the echo line shifted in upto 17 miles range, the northern portion beyond 20 miles almost completely disappeared while the southern portion extended further



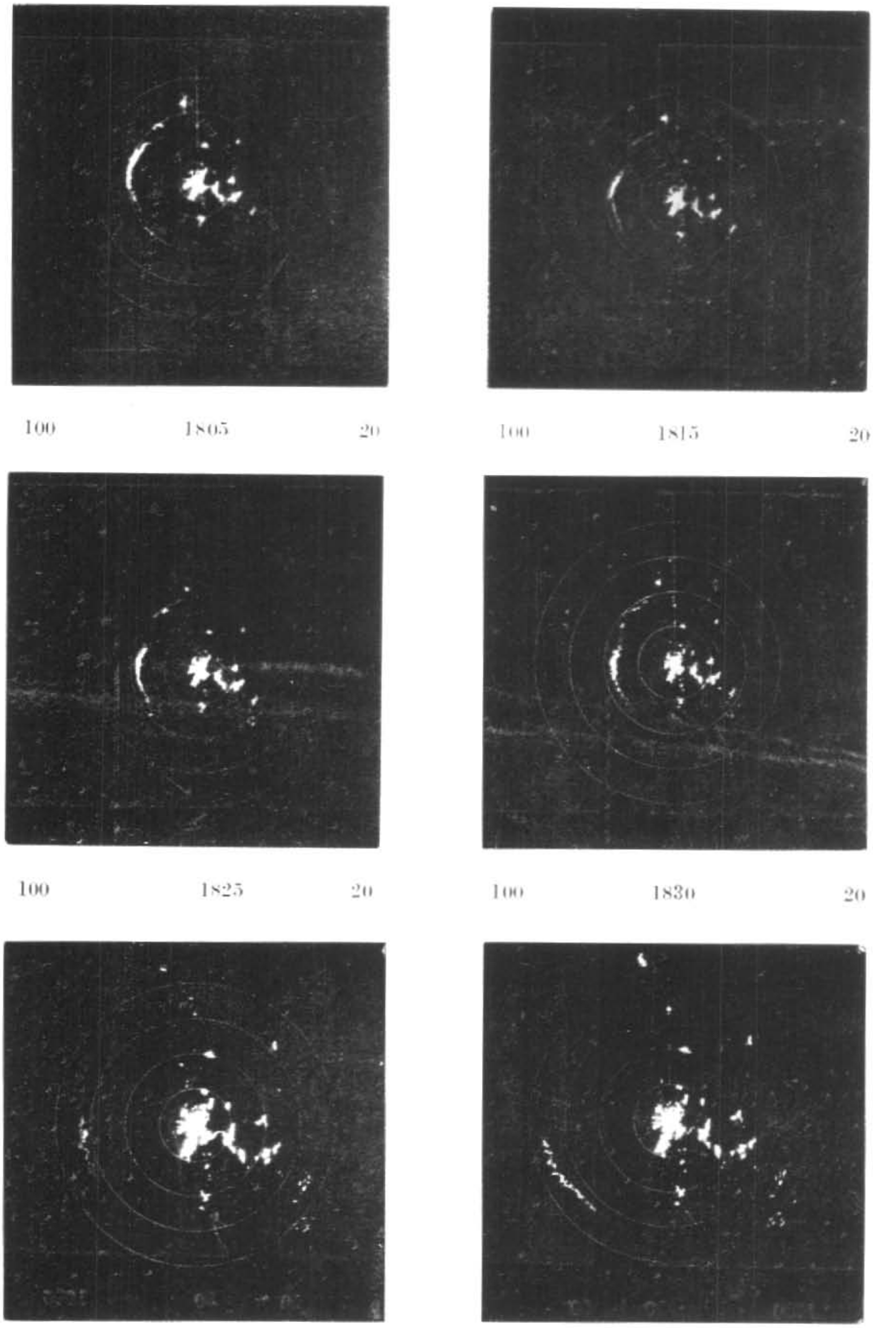
50 1415 10 50 1425 10 50 1445 10

100 1500 20 50 1620 10 50 1650 10

50 1720 10 50 1830 10 50 1935 10

Fig. 1. Sequence of angel observations on 30 April 1959

Figures below the photographs indicate (from left to right)—range (n. miles), time in IST and range marker intervals (n. miles)



100 1805 20 100 1815 20

100 1825 20 100 1830 20

50 1840 10 50 1900 10

Fig. 2. Sequence of angel observations on 22 April 1959

Figures below the photographs indicate (from left to right)—range (n. miles), time in IST and range marker intervals (n. miles) southwards. By 1800 IST the echo started moving out again and at 1830 IST the echoes were almost coinciding with the 20 mile range marker. The wave form exhibited in the initial stages also reappeared in the southern portions. Thereafter the echoes started weakening rapidly. By 1935 IST the southern portion had completely disappeared and the northern portion was now oriented NE-SW. Later the echoes became much weaker and completely disappeared by 2030 IST.

Another sequence of these echoes observed on 22 April 1959 is shown in Fig. 2. Here the echoes first appeared at a distance of 40 mile range in the SW-NW sector. It gradually increased in intensity and at 1805 IST it covered almost the entire 220—350° sector, the middle portion being more marked. It started moving in slowly, the northern portions becoming less marked. At 1830 IST the more intense part of the angels was at about 37 miles. By 1840 IST it had moved upto 35 miles, the echoes now confined only to 220-260° sector. Thereafter the echoes started moving out and weakening. By 1930 IST they were again at about 40 miles but much weaker, and within the next few minutes got dissipated.

In order to find some characteristic meteorological parameters common to the days of angel occurrence, the data from radiosonde observations at Bombay for days of angel occurrence as well as for the neighbouring days of non-occurrence were analysed. The angels invariably occurred in association with high temperatures, the average temperature in the lowest levels being above 30°C. The higher the temperature, the more intense were the echoes. Another common feature was the occurrence of an inversion or at least an isothermal layer in the lowest levels generally a few hundred feet above ground, accompanied with a sharp specific humidity gradient. The temperature and specific humidity profiles for 22 and 30 April 1959, as obtained from the routine radiosonde observations at Bombay are given in Fig. 3. The routine radiosonde observations certainly do not represent the microstructure of the atmosphere with which one is concerned while seeking an explanation for the angels, but they do serve to broadly indicate the prevailing meteorological conditions. The temperature and dew point gradients obtained from these ascents can, therefore, be used only in a qualitative way.

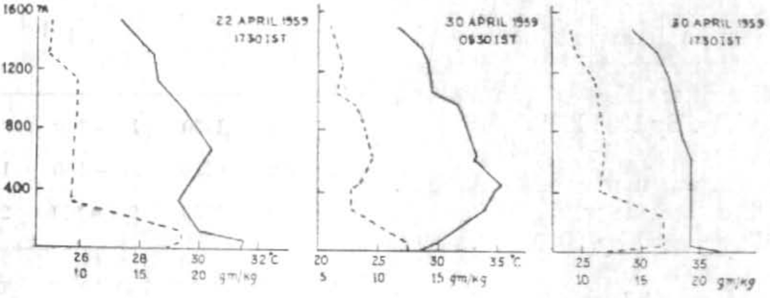
TABLE 3

Date	Time (IST)	Height interval (m)	$\frac{d(n-1)}{dz}$
22-4-59	1730	120—320	$3 \cdot 1 \times 10^{-7}$ m^{-1}
30-4-59	0530	60—280	$1 \cdot 9 \times 10^{-7}$ m^{-1}
30-4-59	1730	250—420	$2 \cdot 4 \times 10^{-7}$ m^{-1}

Using the temperature and humidity gradients obtained from these radiosonde data, the modified refractive index $N = (n-1) \times 10^6$ has been calculated and Fig. 4 gives the N profiles corresponding to the temperature and humidity profiles of Fig. 3. The maximum refractive gradients for the two cases along with the height intervals through which they exist are given in Table 3.

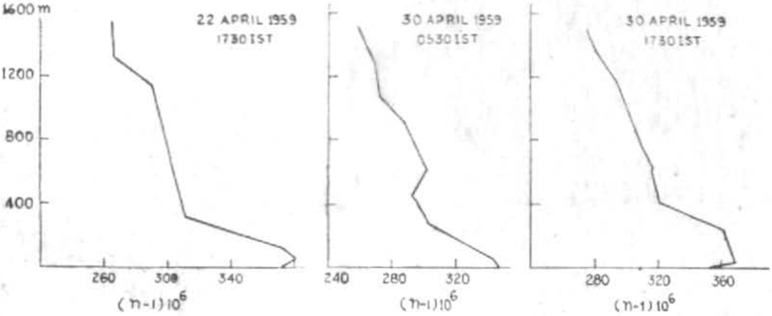
3. Discussion

It is now generally accepted that a large number of angels have a meteorological origin. Although the potentiality of birds and insects as angels' source cannot be denied in cases like the present ones, this possibility may be ruled out. The extent of the echoes and their quasi-stationary or slow moving nature cannot possibly be explained by birds and insects even if we ignored the wave structure. In order to explain an echo twenty miles long and a mile wide the concentration of birds needed will be abnormally high. These echoes cannot also be attributed to reflections from ground objects *via* atmospheric inhomogenieties like most of type III angels in Plank's classification. For an explanation of these echoes, therefore, one may consider the possibility of back-scattering from some atmospheric layers.



(a) (b) (c)

Fig. 3



(a) (b) (c)

Fig. 4

The simplest and possibly a practicable model to assume is a horizontally stratified layer containing sharp temperature and specific humidity gradients. One observed fact which lends support to this view is the concentric appearance of the echoes. As no condensation particles are involved in case of angels, one has to consider the molecular structure of the medium. Since the index of refraction has, as its ultimate source, the polarisation of the gas molecules, the variation in the refractive index may be considered to arise out of the spatial distribution of certain molecules with large polarizability. In the lower atmosphere, as far as the variation of refractive index is concerned, by far the most important contribution is that of water vapour molecules. Under the influence of an incident field each of these molecules will radiate like a dipole and the back-scattering cross-section of the layer will depend upon the density distribution of these molecules.

The problem of back-scattering from atmospheric inhomogenieties has been treated by Siegert (1951). The radar cross-section of an assembly of scatterers is given by—

$$\sigma = |p|^2 \int_0^\infty \bar{n}(r)dr + |p|^2 \left| \int_0^\infty \bar{n}(r) e^{-4\pi ir/\lambda} dr \right|^2 \tag{1}$$

where $|p|^2$ is the cross-section per scatterer and $\bar{n}(r)\, dr$ is the time average of the scatterer per unit distance.

The first term in eqn. (1) represents the usual incoherent scattering and is equal to $N|p^2|$ where N is the total number of scatterers in the volume considered; the second term denotes the coherent scattering, the magnitude of which will depend on the variation in the density function $\bar{n}(r)$.

In terms of the density of molecules $\rho(r)$ the radar cross-section for the coherent scattering can be expressed as (Goldstein *et al.* 1951)

$$\sigma_c = |p|^2 \left| \int \rho(r) e^{-4\pi ir/\lambda} dV \right|^2 \tag{2}$$

where the integration is carried over the volume illuminated by the radar beam. For a gas molecule acting like a radiating dipole under the influence of the incident field, p is given by

$$p = \left(\frac{2\pi}{\lambda}\right)^2 \frac{\alpha}{\sqrt{4\pi\varepsilon}} \tag{3}$$

where α is the molecular polarizability. For a gas with density ρ and refractive index n

$$\alpha = \frac{\varepsilon}{\rho}(n^2 - 1) \tag{4}$$

For atmospheric air n is always close to unity

$$\therefore \alpha \simeq \frac{2\varepsilon}{\rho}(n^2 - 1)$$

$$\text{and } p \simeq \left(\frac{2\pi}{\lambda}\right)^2 \frac{n-1}{\sqrt{\pi\rho}}$$

Substituting for p in equation (2)

$$\sigma_c = \frac{1}{\pi}\left(\frac{2\pi}{\lambda}\right)^4 \left| \int (n-1) e^{-4\pi ir/\lambda} dV \right|^2$$

$$\text{or } \sigma_c = \frac{A^2}{\pi}\left(\frac{2\pi}{\lambda}\right)^4 \left| \int (n-1) e^{-4\pi ir/\lambda} dr \right|^2 \tag{5}$$

where A is the area normal to the beam and may be assumed to be constant over the pulse length.

Since we are considering the refractive index variation of a specific volume, outside this volume $(n-1)$ can effectively be taken as zero, we can therefore integrate by parts and write

$$\int_0^\infty (n-1)\, e^{-4\pi i r/\lambda}\, dr = \frac{\lambda}{4\pi i}\int_0^\infty \frac{d\,(n-1)}{dr}\, e^{-4\pi i r/\lambda}\, dr \qquad (6)$$

Eqn (5), therefore, becomes

$$\sigma_c = \frac{A^2}{4\pi}\left(\frac{2\pi}{\lambda}\right)^2 \left| \int \frac{d(n-1)}{dr}\, e^{-4\pi i r/\lambda}\, dr \right|^2 \qquad (7)$$

Now let us consider a horizontal layer with a uniform refractive gradient through a height interval $\triangle z$. For P.P.I. scanning with the beam inclined at an angle θ with the horizontal, the refractive gradient along the beam would be $\sin\theta$ times the gradient in the vertical. Also $r = z \operatorname{cosec}\theta$ and θ being constant $dr = dz \operatorname{cosec}\theta$. In terms of z therefore, equation (7) becomes

$$\sigma_c = \frac{A^2}{4\pi}\left(\frac{2\pi}{\lambda}\right)^2 \left(\frac{d\,\overline{n-1}}{dz}\right)^2 \left| \int e^{-4\pi i z/\lambda \sin\theta}\, dz \right|^2$$

For the gradient existing within the height interval z and $z + \triangle z$

$$\sigma_c = \frac{A^2}{4\pi}\left(\frac{2\pi}{\lambda}\right)^2 \left(\frac{d\,\overline{n-1}}{dr}\right)^2 \left| \int_{-(\triangle z)/2}^{+(\triangle z)/2} e^{-4\pi i z/\lambda \sin\theta}\, dz \right|^2$$

$$\text{or } \sigma_c = \frac{A^2}{4\pi}\left(\frac{d\,\overline{n-1}}{dr}\right)^2 \sin^2\theta\ \sin^2 (2\pi\triangle z)/(\lambda \sin\theta) \qquad (8)$$

For eqn. (8) to be applicable, all portions of the volume of refractive inhomogeniety must start and stop at the same distance from the radar, *i.e.*, for all orientation of the beam the inhomogeniety must be contained within the ranges r and $r+dr$. For a P.P.I. scanning this requirement is reasonably met with, since a horizontal layer at a fixed height will be intercepted by the beam always at a fixed range.

The present angel echoes were mostly observed with aerial tilts of 1-2 degrees. Considering the vertical beam width, the maximum inclination of the beam would be 3-4 degrees. In addition the angle of incidence on the layer would also increase due to the earth's curvature, the magnitude of increase depending upon the range. Qualitatively, however, it can be seen that the angle of incidence will have an upper limit of 10 degrees and consequently $\sin^2\theta$ would be of the order of 10^{-1}. With the order of magnitude of $\frac{d\,\overline{n-1}}{dz}$ obtained in Table 3, *i.e.*, 3×10^{-7}/m, and assuming the inhomogeniety to extend over 200 m on a side (at ranges 20-25 miles this will correspond to only ·75 degrees of the vertical beam width being filled with the inhomogeniety) σ_c given by eqn. (8) will be of the order of 10^{-6} m^2.

In addition to the scattering due to the refractive gradient, certain amount of coherent scattering will result from the pulsed nature of the incident field, even if the density distribution is uniform, since in effect the pulsed transmission corresponds to a pulse like spatial distribution of scatterers. This part of coherent scattering is, however, always present along with the usual incoherent scattering and need not be discussed here in detail.

The order of magnitude for σ in case of present angel observations as estimated from the set characteristics and from comparison with ground and cloud echoes at identical ranges, appears as high as 10 m^2 which is very much larger than the computed cross-section above, and for such cross-section to be obtained the refractive gradient must be larger by a factor 10^3. Such gradients appear, at present, to be unbelievably large.

Considering the prevailing meteorological conditions during the periods of angel activity, the assumed model of a stratified layer may well be a normal feature over these areas. During the period February to May low level inversions are a seasonal feature over northwest Arabian Sea. Into the lowest levels, water vapour is being added by evaporation and by the water spray due to breaking of waves. The diffusion of water vapour molecules into the higher levels is limited by the inversion so that the upper limit of the diffusion may be assumed to be some distance above the base of the inversion. Immediately above, the air would be dry and warm owing to subsidence so that the water vapour concentration decreases sharply. As the maximum amount of water vapour is limited by the saturation vapour pressure at the particular temperature, the higher the temperature in the layer, the larger will be the water vapour content and consequently sharper will be the specific humidity gradient in the layer above. This, coupled with the positive temperature gradient, would result in a very sharp decrease of refractive index through the layer.

The large gap between the observed and theoretically required values of the refractive gradient brings in a fundamental difficulty in way of the quantitative application of this theory. However, as it has not been possible so far to arrive at a more quantitative explanation of these echoes, it may well be argued that such gradients do exist in the atmosphere, though it would not be possible to measure them until sufficiently rapid response instruments are developed. This view point is substantiated by recent aircraft observations of temperature and humidity near stratocumulus sheets below subsidence inversion (James 1959) where lapse rates of temperature and water vapour content, much steeper than commonly thought of, were observed. If observations are made at much smaller intervals and with further developed instruments, the possibility of coming across large gradients approaching the required order cannot be ruled out.

The wave structure of the echoes can be explained, if one postulates the existence of shear-gravity waves in the stratified layer concerned. From the prevailing temperature gradients, it can be seen that conditions for the occurrence of gravity waves are quite favourable. The pattern of the echoes will more or less follow the undulations in the layer, the amplitudes of the waves being displayed on a much enlarged scale (It can be shown that if h is the wave amplitude and θ the inclination of the beam, the amplitude displayed on P.P.I. would be h cosec θ). The wave form of the angels may therefore, be expected to change with the gravity wave pattern. The movement of the echoes towards the station in the late afternoon is, in all probability, due to the downward movement of the stratified layer towards the evening. With advance of time the layer possibly moves up again with the result that the echoes move outwards. It would appear, therefore, that the horizontal layer responsible for the angel echoes, forms sometime in the late afternoon and gradually comes down in the evening hours. Later it starts moving up again getting diffused and subsequently unimportant (from angels point of view) in the early hours of the night.

4. Conclusion

It is believed that these angel echoes are associated with horizontally stratified layers at very low levels over the Arabian Sea. Though there is, at present, a large gap between the theory and observations regarding refractive index gradient, it is believed that phenomenally large refractive gradients extending over short height intervals exist in the lower levels of the atmosphere along the west coast near Bombay. Further detailed study of angels may provide a better insight into the structure of the lower atmosphere and may bring out facts hitherto unknown.

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