INDIA METEOROLOGICAL DEPARTMENT

FORECASTING MANUAL

IV-23

WEATHER RADAR AS AN AID TO FORECASTING

BY

S. RAGHAVAN

DEPUTY DIRECTOR GENERAL OF METEOROLOGY(RETIRED)

ISSUED BY

DEPUTY DIRECTOR GENERAL OF METEOROLOGY

(WEATHER FORECASTING)

PUNE 411 005

INDIA

DECEMBER 1991

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FOREWORD

Thirtytwo Forecasting Manuals dealing with various aspects of Indian Weather, Climate and selected general topics of weather were published by the Deputy Director General (Forecasting), Poona between the years 1967-1974. These manuals have been found to be very useful to the forecasters, even to this day.

There has been a persistent demand to bring out new manuals dealing with those topics that have not been covered earlier. The present manual "Weather Radar as an aid to Forecasting" has been brought out in this context. The author Shri. S. Raghavan, is an expert in the field of Radar Meteorology and has presented the subject in a very lucid way in this manual.

My heartfelt thanks are due to him for the time and effort he has spared in producing this very important publication. I am sure forecasters will find this publication very informative and useful.

New Delhi
August, 1991

Dr. S. M. Kulshrestha
Director General of Meteorology

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The author is particularly indebted to numerous colleagues who had worked with him in the field of Radar Meteorology and also to several forecasters for very useful interaction.

The author is thankful to the D.D.G.M.(R.M.C.), Madras, the Director, C.D.R. Madras and other officers and staff of the I.M.D. for providing the photographs and diagrams in this manual, for their help in updating the bibliography and for the secretarial assistance.

<u>CONTENTS</u>

WEATHER RADAR AS AN AID TO FORECASTING

1. INTRODUCTION TO WEATHER RADAR

1.1 RAdio Detection And Ranging was a technique invented immediately before and during World War II when it was used successfully for detection of enemy aircraft. It was soon found that the radar exhibited echoes from precipitation (and various other phenomena) which came in the way of detection of aircraft. These echoes were considered an unwanted 'clutter.' However meteorologists soon exploited this not only to detect precipitation but study the characteristics of precipitation in detail. Today ground-based, shipborne and airborne radars are extensively used for meteorological purposes.

1.2 One of the two principal meteorological uses of radar is to track radiosonde balloons or 'chaff' dropped by rockets for determination of upper winds. The other is to detect precipitation (and certain other meteorological phenomena). We shall consider here only the latter application as 'Weather Radar.'

1.3 The India Meteorological Department experimented in the early fifties with wartime disposal radars, but later more refined and specialised equipment became available. At present (early 1991) the Department has an operational network of what are known as X band radars (Fig.1) operating on a wavelength of 3 cm. mostly at airports, being used mainly for aviation meteorological services. Some of these stations have what are known as "Multimet Radars" which are normally used for tracking radiosonde balloons but can also be used as 'Weather Radar.' There is also a network of S-band radars (10 cm. wavelength). The S-band radars along the coasts are primarily intended for detecting tropical cyclones (Fig.2). Both these networks consist of what may be called conventional pulsed microwave radars and only the phenomena which can be detected by such radars will be considered in detail in this chapter. More versatile radars with facilities such as realtime computer processing of radar data and Doppler facility for detection of winds in weather systems are now available. Dual polarisation and dual wavelength radars are also useful in various research applications. As these are not yet in operational use in this country they will be touched upon only briefly (Section 9).

1.4 This ~~chapter~~ manual consists first of a presentation of

(1) the basic principles of Radar Meteorology

followed by discussion of

(2) meteorological phenomena detected by radar

(3) the application of radar for detection of localised precipitation systems

(4) application of radar to aviation meteorology

(5) quantitative estimation of precipitation

and (6) radar observation of tropical cyclones.

Operational procedures including transmission of radar reports as well as general remarks on the capabilities and limitations of the radar follow. Finally the recent developments in the field are briefly presented.

1.5 This ~~chapter~~ manual is intended for the meteorologist who is not a specialist in radar meteorology. Hence a detailed theoretical treatment is avoided. It must be emphasized that this ~~chapter~~ manual is limited in scope and deals essentially with the current operational use of radar in the India Meteorological Department. Even so, the reader is likely to ask many questions which are beyond the scope of this chapter. To facilitate an in-depth study of the subject by those interested, a fairly comprehensive bibliography is given at the end of ~~the chapter~~.

2. PRINCIPLES OF RADAR METEOROLOGY

2.1 Radar sends out a powerful beam of electromagnetic radiation which when it meets an object is partly absorbed and partly scattered in all directions. The scattered energy depends on the frequency of the radiation, the nature of the object and its surface area. The part of the energy which is scattered back in the direction of the radar (back-scattered radiation) arrives at the radar at a time t which is related to the distance r of the object from the radar by the relation

$$r = \frac{ct}{2} \qquad (1)$$

where c is the velocity of electromagnetic waves in space, t being measured from the moment of transmission. Knowing t the distance r can be determined. If the radiation is emitted continuously it will be difficult to identify which particular wave is returned at any time t*. Hence the transmission is done in pulses of short duration τ (say about a microsecond) separated by a long interval of several milliseconds when no transmission is made. The reciprocal of the time interval between the pulses is called the pulse repetition frequency (p.r.f). Fig.3 illustrates the process. The received 'echo' signal is amplified, detected and fed to a cathode ray tube (CRT) display. If the time base of the display sweeps at a constant rate with time, the horizontal axis of the display can be directly graduated in terms of range. The vertical axis represents the voltage at the output of the radar receiver which is a function (not necessarily linear) of the incoming echo signal strength. Echoes of the same object from successive transmitted pulses will be superimposed as the timebase is repeated in synchronism with the transmission. This kind of display is called an A-scope (Fig.4) and is often used in weather radars.

2.2 Since it is necessary to know the direction or bearing of the target besides its range, it is necessary to direct the radar beam over a very narrow angle as in a search light and rotate it in order to scan different directions from which echoes are expected. Hence a weather radar uses a highly directional antenna (most often a paraboloid dish) capable of radiating a beam about one or two degrees wide and the antenna is rotated around a vertical axis. The timebase on the CRT display is rotated in synchronism with the antenna. Thus we get a Plan Position Indicator (PPI) display (Fig.4) which gives a quasi-horizontal map of the area around the radar giving the range and bearing of each echo. (The word 'quasi' is used because the height of the radar beam increases with the range). Similarly by rotating the antenna

* For certain applications 'continuous wave' radars are used wherein the identification is done from the phase lag of the received signal.

around a horizontal axis it is possible to depict the height of the echo on a magnified scale as ordinate and range as abscissa constituting a Range Height Indicator (RHI) (Fig.4). The echo looks elongated in the vertical because the height scale is expanded. There are other types of display which are sometimes used but are not considered here in this chapter.

2.3 The frequencies of transmission usually used in weather radars are in the range 3 to 10 Gigahertz (1 Gigahertz is 10^9 Hertz i.e. 10^9 cycles.sec.$^{-1}$) corresponding to wavelengths of 10 to 3 cm. It is necessary to use these 'microwaves' because the longer the wavelength the larger is the antenna required to obtain a specified beamwidth. Hence larger wavelengths will need an unmanageable antenna. There are also other considerations in choosing the wavelength. According to the Rayleigh law of scattering which applies if the scattering objects are small in comparison with the wavelength (this is true for most precipitation particles at the wavelengths mentioned above) the back-scattered signal is proportional to λ^{-4} where λ is the wavelength. Hence the use of a short wavelength will result in a stronger echo. However as the wavelength decreases the absorption by atmospheric gases, water vapour and liquid water increases. In the range of 3 to 10 cm. mentioned, the attenuation due to atmospheric gases and water vapour is quite small and can be corrected for if considered necessary. The attenuation due to intervening liquid water (in the form of precipitation) between the radar and the desired target is negligible at the 10 cm. wavelength. At the 3 or 5 cm. wavelengths which are commonly used, the attenuation due to rainfall is high. Hence

(i) it is advantageous to use 3 cm. wavelength when qualitative monitoring of raining clouds over short distances are required,

(ii) it is advantageous to use 10 cm. wavelength when quantitative measurement of the rainfall is required or when distant precipitation is to be detected in the presence of intervening heavy precipitation (as in tropical cyclones).

This explains the two networks used by IMD, though in principle radars of either network can be used for cyclone tracking or for detection of local phenomena such as thunderstorms. As a compromise, a wavelength of 5 cm. is used in many temperate countries where the rainfall rates are not as heavy as in the tropics and hence the attenuation is not so heavy.

2.4 A raining cloud has a finite volume in which there is a large number of precipitation particles (*liquid or solid*) of various sizes. When a radar beam illuminates the cloud, the volume V sampled by the beam <u>at any instant</u> is approximately*

$$V = \pi . \left(\frac{r\theta}{2}\right) . \left(\frac{r\phi}{2}\right) . \frac{h}{2} \quad \ldots . \quad (2)$$

where ϕ and θ are the radar beamwidths# in the horizontal and vertical planes and h is the pulse width in linear units i.e.

$$h = \tau \times c \quad \text{(See Fig.5)} \quad \ldots \quad (3)$$

Typically h may be a few hundred metres and the other two quantities in brackets may be 1.5 to 3 kilometres at a range of 200 km. Assuming that the entire beam is intercepted by the particles, the echo signal will consist of the sum of the backscattered signals from the various particles in the volume V. It is assumed that each particle scatters radiation independently of the others. The combined effect of all these particles is represented by a 'backscattering cross section per unit volume' or 'radar reflectivity' designated by the symbol η. This quantity is in turn dependent on the dielectric constant of the surface material of the scattering particle (water or ice) and the size of the particle. If the Rayleigh law is assumed it can be shown that the reflectivity is proportional to the sum of the sixth powers of the drop diameters in unit volume. The latter quantity is termed the '<u>radar reflectivity factor</u>' represented by the symbol Z and usually expressed in units of $mm^6.m^{-3}$.

2.5 It has been shown that the power Pr received from this unit volume at the radar is given by

$$P_r = \frac{\pi^3}{2^{10} \ln 2} . \left[\frac{P_t . h}{\lambda^2} . G^2 . \theta . \phi \right] . \frac{1}{r^2} . \partial . Z \quad \ldots . \quad (4)$$

where P_t is the peak power transmitted by the radar, G is the 'gain' of the radar antenna and ∂ is a quantity related to the dielectric constant (and may be taken as 0.93 for water and 0.18 for ice). The quantity within the square brackets is an attribute of the radar while ∂ and Z relate to the precipitation. Since Z

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* This is simple geometry which the reader can work out. h/2 is used instead of h because particles at a range r + h/2 will return their echo from the front edge of the pulse at the same instant as particles at range r give echo from the rear edge of the pulse.

for most of the radars in IMD ϕ and θ are equal. About 2° for S band radars and 1° for X band radars.

by definition is $\sum_{\text{unit vol}} D^6$, D being the drop diameter, it can be seen that the influence of large drops is very large in comparison to small ones. For instance, a drop 0.1 mm. in diameter will return a signal 10^6 times weaker than that from a drop of 1 mm. diameter. The practical result is that at the wavelengths we are considering the echo return from non-precipitating clouds where the drop sizes may be a few tens or hundreds of micrometres will not be detectable by radar*. Only raindrops (diameter of the order of 1 mm) will be detectable. This is an important result which should be borne in mind while interpreting any radar display. On the other hand when the particle is very large (e.g. large hail) and comparable in dimension to the wavelength, the Rayleigh law does not hold good. In such a case Mie scattering is said to occur. As the ratio of particle dimension to wavelength increases, the reflectivity oscillates above and below a mean value. In such cases Z is replaced by a quantity Z_e known as the 'equivalent radar reflectivity factor' which is the value of Z required to give the observed P_r if the Rayleigh law is assumed.

2.6 In empty space electromagnetic radiation may be taken to travel in straight lines. Hence a radar beam directed, say, horizontally will be at a considerable height above the curved surface of the earth and may miss targets at long distances unless they are tall enough to come into the beam. In practice the air through which the beam travels causes refraction of the beam. The refractive index of air at the earth's surface is of the order of $1 + 300 \times 10^{-6}$. The quantity (refractive index - 1) x 10^6 is called 'refractivity' represented by

$$N = \frac{77.6}{T}\left(p + 4810\frac{e}{T}\right) \qquad \ldots\ldots \qquad (5)$$

where p is atmospheric pressure and e is water vapour pressure both in hectoPascals and T the temperature (°K). Hence variations at low levels in the atmosphere, of temperature and humidity cause considerable variation of refractivity. In most normal conditions the beam is refracted slightly towards the earth's surface. For computing the path of the beam it is convenient to treat the path as a straight line but assume a larger radius for the earth. The effective earth's radius is usually taken to be 4/3 times the actual radius for calculating the height of the radar beam at various ranges (Fig.6). However this factor varies considerably from the value of 4/3 especially along our Indian coasts. When there is a low level temperature inversion accompanied by a steep lapse of humidity with height (a typical situation on winter mornings) the refractivity changes with height will be such as to cause a greater refraction towards

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* It is possible to detect cloud drops by using radars of still higher frequencies. This will be touched upon in Section 9.

the earth's surface. The ray may even touch the surface and may make repeated hops over the ground (or sea). Thus the radar will see rainfall or ground objects over much larger distances than normally expected. The heights computed from normal assumptions (as in Fig.6) will be too high. Such a condition is called anomalous propagation (A.P). Besides winter mornings, this may occur in anticyclone situations where the subsidence and dryness of layers immediately above the moist sea surface create ideal conditions for anomalous propagation. When such a condition exists, echoes from ground objects may be seen even at long ranges and may sometimes be difficult to distinguish from precipitation echoes. On the contrary, in situations where relative humidity does not fall steeply with height and there is no temperature inversion (such as when rainfall is occurring) the refraction may be away from the earth's surface. Hence the effective radar range is reduced. Precipitation which might otherwise be seen may be missed and heights computed will be too low.

2.7 Fig.7 illustrates the propagation of a 2 deg. wide radar beam in normal conditions. The spread of the beam in the vertical plane is shown but there will be similar spread in the horizontal plane also. Hence a precipitating cloud nearby will fully intercept the beam while a farther one may fill only part of the beam. Also in the case of the farther cloud, only the upper portion may be seen by the radar resulting in an apparent low reflectivity. Precipitation still further away may not be seen at all as the cloud will be below the beam. Hence the effective maximum horizontal range of a ground-based radar is limited to about 400 kilometres and will vary with the radiowave propagation conditions and with the type of phenomenon to be detected.

2.8 Resolution : Since the pulse from the radar has a finite width h in space, the radar picture cannot resolve two echoes which are separated in range by a distance less than h/2. Since h is usually less than a kilometre for most weather radars, this is usually not a serious problem. However the azimuthal resolution is limited by the beamwidth. This means that while at short ranges the resolution is good, it becomes poorer with increasing range. For example for a 2 deg. beam the beamwidth at a range of 200 km. is over 6 km. So two cumulus cells separated by less than half a beamwidth will be seen as one. However if the cells travel closer they may be seen separately due to the improvement in resolution. This will give the impression that the cell has split into two. Also a point target or small cell will be seen stretched out into a tangential line as wide as the beam. This explains why the echo of a ship may appear a few kilometres long (Fig.8) or a hill appear much higher than it is (Fig.9). Also since the amount of distortion is more in the tangential direction than in the radial direction there will be an appreciable distortion of the shape of small echoes.

2.9 Determination of heights of echoes :

2.9.1 It can be appreciated from Fig.7 that when the radar antenna elevation is gradually increased, the echo from a precipitating cloud will just disappear when the bottom edge of the beam is just above the top of the cloud. If the antenna elevation angle reading of the radar is noted at this time and half of the beamwidth is subtracted from it, one obtains the actual elevation angle of the bottom of the beam. Using this angle and referring to a nomogram such as Fig.6, the echo top height can be determined. However, there can often be large errors in this value because of the variations in propagation conditions referred to in section 2.6.

2.9.2 The above reasoning assumes that the top of the cloud (as understood in meteorology) is giving a radar echo. Usually it will happen that the top of the cloud contains hydrometeors which are too small or too few to give a radar echo. Hence the radar echo top as determined by the above procedure may often be well below the visible cloud top.

2.9.3 During operation the above procedure of raising the antenna while radar is scanning in the PPI mode, is convenient for quick estimation of heights of tops of a large number of echoes. The heights can be read off on the RHI, but it is time-consuming and a great strain on the equipment to stop the antenna at every required azimuth and scan in the vertical plane to get RHI presentation. Hence the RHI is usually used mainly to study the vertical structure of selected important echoes. However even when the RHI is used the observed height is to be corrected for half beam width error, normal wave propagation and earth's curvature. In some radars a correction for earth curvature and normal propagation is incorporated electronically in the display.

2.9.4 In some radars the vertical beamwidth (Θ) may be much more than 1 or 2 deg. With such radars height determinations should not be attempted as the error involved may be so large as to make the observation valueless.

2.9.5 Table 1 gives the heights of base and top of the radar beam and its horizontal width, assuming a 2 deg. beam directed horizontally, in normal propagation conditions. As can be seen the beam spread is very large at long ranges. Hence it is the usual practice in IMD to evaluate and report heights of only echoes within about 200 km. of the radar.

2.9.6 Because of large variations in propagation conditions, the echo height information reported by a radar should be evaluated carefully by the forecaster.

Table 1

Range (km)	Ht. of base of beam (limited to zero elevation) (km)	Ht. of top of beam (km)	Vertical extent of beam (km)	Horizontal width of beam (km)
10	Almost Zero	0.17	0.17	0.33
50	0.15	0.98	0.83	1.66
100	0.6	2.25	1.65	3.32
150	1.35	3.81	2.46	4.98
200	2.4	5.67	3.27	6.63
300	5.4	10.28	4.86	9.94
400	9.5	16.06	6.56	13.25
500	14.8	23.02	8.22	16.56

2.10 Determination of intensity of echoes :

2.10.1 The peak power P_t transmitted by the radar is usually several hundred kilowatts. But the echo return P_r is relatively small and may be in the range of 10^{-14} to 10^{-6} watts. The minimum detectable signal P_{min} (also denoted by MDS) of most meteorological radars in use in the IMD is of the order of 10^{-14}W. Since the ranges of power being dealt with are very large, it is convenient to use the decibel notation. Taking 1 milliwatt (mw) as a reference level, any power level can be expressed as so many decibels above or below one mw. e.g. a power of 30 dBm refers to 10^3 milliwatts (i.e. 1 watt) and similarly 10^{-14}W would be expressed as -110 dBm. Power expressed in decibels is 10 times the common logarithm of the power expressed in milliwatts. The use of this logarithmic unit enables power levels to be added or subtracted. e.g. the radar equation (Eqn. 4, para 2.5) can be rewritten as

$$10 \log P_r = C + 10 \log P_t - 20 \log r + 10 \log Z \quad \ldots (6)$$

or

$$P_r \text{ in dBm} = C + P_t \text{ in dBm} - 20 \log r + dB(Z) \quad \ldots (7)$$

Here C is a constant representing the other factors in equation (4) and dB(Z) represents the value of Z in logarithmic units with reference to a value of unity. This is also a convenient representation of Z as its value can go upto about 10^6 i.e. 60 dBZ in intense precipitation. If we can measure P_r knowing P_t and r, we can easily compute dBZ which is a measure of the intensity of the echo. Since Rayleigh scattering is assumed what we obtain is really dBZ_e and not dBZ but this distinction is ignored in practice. The INTENSITY of an echo is expressed in dBZ.

2.10.2 The brightness of the echo seen on the PPI or even the amplitude of the echo on the A-scope is not directly proportional to the P_r. The PPI scope saturates in intensity except at very low intensities. Hence to judge the intensity of an echo qualitatively, it is necessary to reduce the amplification (or gain) of the receiver gradually until the echo is just about to disappear. i.e. the received signal becomes equal to P_{min}. The more the gain reduction required the stronger was the echo. If we calibrate the gain control (I.F or video stages) of the radar we can read off the intensity directly. Or, can we? The presence of the term 20 log r in equation (7) means that the intensity of an echo from distant precipitation is much weaker than that from a nearer one with the same rate of rainfall. This difference is corrected in some radars by an optional 'range normalisation' or Sensitivity Time Control (STC) circuit which applies a 'log r' waveform to the receiver to equalise the intensities. Even so, the correction is not complete because of two factors. One is that the beam may not be completely intercepted by a distant cloud. The other is that the beam at larger ranges is seeing the upper part of the cloud where reflectivity is low. In routine operation, the intensity of echoes is usually observed and reported qualitatively as weak, moderate, strong or very strong. In quantitatively calibrated radars these categories correspond approximately to the Z and rain rate values indicated in Table 2.

The significance of the Z values in operational work will be dealt with in later sections (3 to 6). Considering the sources of error mentioned above intensity determination is usually done only upto a maximum range of about 200 km.

2.10.3 The echo signal from precipitation fluctuates rapidly due to the movement of the individual scatterers in the sampling volume as well as changes in their shapes or sizes. Hence to get a representative value of the echo signal intensity it is necessary to average the echo over a number of successive pulses. Fig.5 illustrates the process*. Averaging is done in some radars by an optional integrating circuit in the video amplifier. The

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*Not all the pulses calculated in Fig.5 are independant samples. The detailed treatment of sampling and averaging is beyond the scope of this ~~chapter~~ manual.

Table 2

(Reproduced from IMD Radar code 1984)

Intensity Code	For Radars having facility for quantitative measurement dBZ	Approximate rainfall rate Rmm/hr *	Other Radars
WK	23 to 32	less than 4	Qualitatively determined as in draft Weather Radar Manual
MDT	33 to 42	4 to 15	
STG	43 to 52	16 to 63	
VRY STG	53 or more	64 and above	

* Based on the relationship $Z = 200\ R^{1.6}$

signal can also be range normalised and echo above any selected threshold dB(Z) level can be amplified (rejecting all weaker echoes) and presented on the display. By having several such thresholds which can be switched in by the operator, radar pictures at various intensity levels can be obtained. This is called an 'iso-echo' system (see e.g. Figs. 15, 40, 41 and 42). It is also possible in some radars to display several levels at the same time in different shades of grey so that an approximate contour map of reflectivity factor is obtained. (Figs. 11 and 17). In modern digital radars, displays of reflectivity levels are made through software in shades of grey (Fig.30) or in colours.

3. METEOROLOGICAL PHENOMENA DETECTED BY RADAR

3.1 Echoes observed on a weather radar display may be broadly classified into three types

(a) Echoes from precipitation

(b) Echoes due to meteorological phenomena not associated with precipitation

(c) Echoes of non-meteorological origin.

3.2 As mentioned in para 2.5, the radar can normally detect only precipitating clouds and not others. These can be broadly divided into two types - convective and stratiform. These two categories are not mutually exclusive in the sense that the two may not only exist together but convective echoes may also exhibit stratiform characteristics at some stage. The principal difference between convective and stratiform precipitation is that convective clouds (large cumulus and cumulonimbus) have a large vertical extent, they occur as discrete cells or groups of cells with discernible boundaries, they are characterised by large up or down draughts and large sizes of precipitation particles. Instantaneous rate of rainfall is usually high (often several tens of millimetres per hour) and there are large spatial gradients of rainfall rate. The duration of precipitation from any one convective cell is also small (typically several minutes). Stratiform precipitation, on the other hand extends usually over a large area without discrete cellular structure and is associated with relatively stable conditions. The rainfall rate is small but the rain is more uniform and persists for a longer time. The vertical depth of the precipitation is also small.

Because of the above characteristics, radar echoes from convective precipitation (showers or thundershowers) are seen in the form of intense and discrete cells with sharp edges. They may be in the form of isolated cells or occur in groups or be oriented along a line. On the RHI they show up as tall columns. The maximum height may go up to 20 km. as some cumulonimbi overshoot the tropopause. The echo may form aloft initially and grow downwards as well as upwards. It may exhibit rapid changes in height (growth or decay). On the isoecho presentation, the echo often appears at high dB(Z) levels (30 to 50 dB(Z) is quite common) and sharp intensity variations from point to point are exhibited. If hail is present the reflectivity may be very high because of the large size of hail. On the RHI, the reflectivity contours are vertically oriented (Figs. 11 and 17). This is so because up and down draughts produce vertical mixing of the precipitation particles. In cumulonimbi the particles may remain in liquid (supercooled water) phase even at heights much above the zero degree isotherm. Figs. 10 and 11 give examples of echoes from convective precipitation.

3.3 Echoes from stratiform precipitation (Figs. 12 & 13) are usually extensive and of weak intensity (reflectivity factor usually less than 30 dB(Z)) as particle sizes in stratiform rain are smaller. They are also almost uniform in intensity. A reduction in radar receiver gain will make most of the echo disappear at the same gain control position. The heights usually are within 7 or 8 kilometres. As the vertical currents are small the particles tend to stratify as liquid drops below freezing level and solid particles above. Snow, gives an echo which is usually weaker than that from liquid precipitation because of the lower dielectric constant of ice. The snowflakes also vary in orientation and therefore the scattering cross section varies resulting in large fluctuations of the signal. In the case of liquid drops, the drops are spheres or spheroids and so do not exhibit such large changes in effective cross section.

3.4 The particles of solid precipitation which fall through the freezing level melt gradually and therefore get coated with water but retain their large surface area until they melt completely. Hence there is usually a layer of a few hundred metres thickness at the zero degree isotherm level (about 4.5 to 5 km in most parts of India) in which the particles have a large dielectric constant and large cross section. Hence the echo from this layer is stronger than those above or below. By reducing the gain on the RHI picture, a 'bright band' can be seen as a horizontal layer at about the freezing level. A comparison of Figs. 13 and 14 will illustrate this. This phenomenon is known as the 'BRIGHT BAND' or 'MELTING BAND'. This does not normally happen in individual convective cells as the particles are well mixed. However in the dissipating stages of convective cells, the bright band may be seen.

3.5 It has been shown in recent studies of tropical convective precipitation in coastal and oceanic areas that clusters of convective cells or squall lines often develop a large 'mesoscale anvil' around them. The anvil is several kilometres thick and is stratiform in character with low rates of rainfall and exhibits a bright band. (Figs. 15 and 16 illustrate this). The appearance of the bright band is usually taken as an indication of the stratiform character of precipitation. Fig. 17, a grey scale presentation, illustrates the contrast in reflectivity contours between stratiform (the echo on the left part of the picture) and convective (echo to the right) precipitation. The contours are horizontally oriented in the first case and vertically oriented in the second.

Stratiform echo may be seen sometimes at close ranges at higher antenna elevations without any precipitation reaching the ground. Such elevated echoes may be reported by radar operators as 'echo aloft'.

3.6 Echoes of meteorological origin not associated with precipitation.

3.6.1 Anomalous Propagation :

As explained in section 2.6 a favourable low level vertical profile of temperature or humidity may produce downward refraction of the radar beam. Hence echoes from the ground surface or from hills which are not normally seen, may be observed. These can usually be distinguished from their position and shape (e.g. the coast line or other geographical features are usually known). Fig. 18 shows an example of extensive A.P. echoes. Also compared to precipitation echoes the fluctuations in intensity from pulse to pulse are very small. Hence the texture of these echoes is different from precipitation echoes. All the same, it is sometimes difficult to distinguish them especially at longer ranges. Observations on the RHI may give a greatly exaggerated height because of the refraction. One other means of distinction is to observe the movement over several minutes. An echo from a ground object should not move appreciably though it may show 'growth' or 'decay' because of changes in propagation conditions. A.P. echoes can come from distant ships also but these will be in the form of short thin lines and should move with the ship.

A.P. echoes can usually be expected on winter mornings and in anticyclone situations. However A.P. also often occurs in the wake of a thunderstorm where the interface between the downdraught air and the environment may produce a favourable temperature and humidity profile. In such cases care is necessary to distinguish the A.P. echo from the thunderstorm echo.

Digitised equipment may print out A.P. echoes as precipitation echoes. To prevent this special circuits based on measurement of the variance of the signal are used in some radars.

3.6.2 Echoes due to refractive index discontinuities :

Echoes in the form of very thin lines or dots or rings can be returned because of sharp changes in atmospheric refractive index caused by various meteorological phenomena. The sea breeze front is a notable example of discontinuity between the moist and cool maritime air at the surface and dry, warm land air above. The discontinuity produces a partial reflection of the radar beam and shows up as a thin line on the PPI with no vertical extension on the RHI. (Fig. 19). As the sea breeze advances the line will move and can often be traced several kilometres over land until the mixing of the air destroys the discontinuity. Edges of fair weather cumuli or other discontinuities caused by low level turbulence, gust fronts ahead of thunderstorms or elevated layers of discontinuity can all give rise to such echoes. Thin line echoes have also been observed well ahead of squall lines. All these echoes can usually be distinguished from precipitation echoes by their fine texture and lack of vertical extension. Such echoes were clubbed together in the early days of radar meteorology with non-meteorological echoes such as from bird or insect swarms and termed 'angels' to denote that their origin was not well understood. Angel echoes have in some cases been identified with clear air turbulence. See also section 9.3.4 and 9.7 regarding echoes from clear air phenomena.

3.6.3 Sea clutter : This is an echo from the sea surface which is dependent on the wind and sea surface conditions. It is most common in anticyclonic situations accompanied by low level wind flow from the sea surface towards the radar. This can be distinguished usually by its lack of height. (Fig.20).

3.6.4 Lightning : In rare cases lightning may be seen directly as an echo. But since it will be a momentary echo, it is easy to miss it. However, the use of independent lightning detection systems, in conjunction with radar, has been suggested for discriminating between shower and thunderstorm echoes.

3.7 Non meteorological echoes :

3.7.1 Ground clutter is the echo due to the ground and other permanent objects such as hills, buildings and trees. It is usually seen as a strong permanent echo all around the radar for a distance of several kilometres. In addition distant hills may also be seen. The use of the radar in this clutter region is greatly handicapped as the antenna elevation has to be raised considerably to avoid the clutter, losing some of the precipitation echo in the process. In quantitative use of the radar the intense clutter echo is difficult to separate from the relatively weak precipitation echo. In automated equipment with digital processors, the ground clutter may be shown as rainfall. Some radars use special circuitry to suppress ground clutter but the suppression is only partial. Permanent echoes due to hills or buildings also cause radar shadows behind them. For all these reasons, the use of weather radar in mountainous terrain is rather limited. The ground clutter may also vary to some extent in intensity and areal extent depending upon propagation conditions. Standard photographs of ground clutter are usually kept at radar stations to assist in identifying other echoes in the clutter area (Fig.21).

3.7.2 Ships :

Ships produce sharp echoes stretched into a tangential line due to beamwidth distortion. They can be easily distinguished by their appearance and movement (Fig.8).

3.7.3 Birds and Insects :

Birds and insect swarms sometimes produce clutters of dot echoes or thin line patterns.

3.7.4 Multiple-time-around echoes :

When an echo return from a very distant object comes after a subsequent pulse or pulses have been transmitted by the radar, the echo will be displayed at a range equal to its true range minus an integral multiple of the distance interval corresponding to the repetition time interval between transmitted pulses. For example if the repetition rate is 250 pulses per second the distance interval is 600 km. A target at 800 km. will be displayed at a range of 200 km. and may be mixed with echoes at a true range of 200 km. The shape of the echo will also be distorted as its radial dimension is preserved correctly while the tangential dimension contracts. In radars having a choice of two pulse repetition rates, a change of rate will alter the range of the echo showing that it is a spurious echo. These echoes are most common in A.P. situations (Fig.18).

3.7.5 Echoes due to radiation outside the beamwidth :

When a radar beamwidth is specified it refers to the angle between the two directions (called half power points) on either side of the direction of maximum radiation where the power radiated is half the power in the direction of the maximum. Some power is radiated outside this angle though being small, it is neglected. There is also a number of secondary maxima of radiation on either side of the main beam both in the azimuth and elevation planes and these are several degrees away from the main beam. The power radiated in these 'sidelobes' may be about 25 dB lower than in the main lobe. Even so these will produce detectable echoes from nearby targets such as ground objects, hills and even strong convective clouds. These 'sidelobe' echoes will appear on the radar scope at their correct range but in the direction of the main lobe. Particularly on the RHI these may appear as additional images above the principal echo or an upward extension of the principal echo. They may thus give an illusion of a cumulonimbus echo being higher than it really is. These can however be distinguished as spurious echoes by an experienced operator.

3.7.6 Image echoes due to reflection from other obstructions :

A tall building close to the radar may act as a plane mirror showing an image in the direction of the building, of a target which is in some other direction. Thus a precipitating cloud or a ship may be shown as an image moving at the same speed as the object but in the opposite direction (Fig.8).

4. Application of Radar for Detection of Localised Precipitation Systems.

4.1 The most important small scale meteorological phenomenon that the radar can detect is the thunderstorm. By definition a convective cloud can be called a thunderstorm only when thunder is heard or lightning seen. As both these may be present but missed very often, it is not possible to identify any convective echo on the radarscope definitely as a thunderstorm. But it is usually safe to assume that a convective echo which has grown rapidly well above freezing level is or will become a thunderstorm.

4.2 The appearance of thunderstorm cells on the PPI and RHI is shown in Figs. 10 and 11. In a well developed thunderstorm vertically oriented contours of radar reflectivity as shown in Fig.11 will occur. Often a shear is observed. If the shear is in the plane of the RHI, i.e. radially towards or away from the radar, it can be seen on the RHI. If the shear is in a perpendicular (i.e. tangential to line of sight) plane, it may not be obvious on the RHI. But on the PPI there will be a slight shift of echo position when the antenna elevation is raised.

4.3 Due to the strong updraught in a thunderstorm, the precipitation particles are often pushed up and maintained at a high altitude. This results in an elevated reflectivity maximum with sometimes a 'weak echo region' or an 'echo free vault' or a 'dry hole' below. Such a pattern is usually considered characteristic of a very severe storm as it indicates very strong updraughts. When hail is present the reflectivity is very high because of the large size of the particle. A reflectivity of 50 dB(Z) is taken as an indication of hail but this is only a general guideline. Such high reflectivities do sometimes occur even in regions where hail does not fall. Also as the size of hail in many cases is comparable to the radar wavelength the Rayleigh law of scattering does not hold and the measured reflectivities may not be accurate.

4.4 An individual cumulonimbus cell can be seen to grow and decay within about half an hour but fresh daughter cells may often be seen to grow around it. Thus a cluster of cells can form by a method of 'propagation'. The group as a whole sustains itself for several hours. Very often the cells are organised in the form of a line (squall line). (Fig.22). Such a group or line may make a translational motion depending on the mean wind in the layers in which it is embedded. The 700 hPa and 500 hPa winds can be taken as good measures. The motion of individual cells is usually more complicated. This is because of the superposition of the propagation and translation effects. In conditions of strong winds the translation effect may dominate. In weak winds the propagation effect becomes more important. Actually secondary cells may form even on the upwind side of the parent cell, indicating an apparent motion against the wind. Hence for short period forecasting, it is desirable to observe the cells and plot their positions at short intervals of time. In the case of distinct small cells the centroids can be plotted. Alternatively a few identifiable protuberances on cells can be plotted. In this there is a risk that some of the protuberances may disappear or change shape or become unidentifiable after a relatively short time. Figs.23 and 25 separated by a half hour interval show a line of convective cells moving east to west. Figs.24 and 26 are iso-echo pictures of the same cells showing the movement more clearly. These cells persisted for about 7 hours. Using isoecho presentations at various thresholds it is possible to plot the maximum intensities (in terms of dBZ at various points on a gridded overlay). By this means, the relative intensity of various precipitation echoes can be quickly evaluated and an approximate idea of the precipitation distribution can also be gained. This is known as Manually Digitised Radar (MDR) technique. Short period extrapolation of echo positions along with their intensities will assist short period local forecasts for aviation or for public broadcast over radio.

Assuming that mid tropospheric winds determine the motion of distinct precipitation echoes, attempts have been made to determine the winds from the observed movement of Small Precipitation Areas (SPA). These are known as Spawinds. However this technique is not highly reliable because of 'propagation' effects mentioned above.

Modern 'pattern recognition' techniques are being tried with computerised data in some countries for estimating movement of echoes and short period prediction. (See Section 9).

Squall lines (see Fig.22) have sometimes definite orientations determined by synoptic conditions (e.g. squall lines preceding tropical cyclones) or they may be dependent on local topographical factors. The apparent orientation may also change because of the propagation effects on individual cells.

Due to their relatively long life squall lines and cloud clusters can often cause prolonged heavy rainfall. Observation of them on radar should enable short period forecasts to be given for aviation and to the public over radio or TV. As mentioned in section 3.5 such clusters or lines often form stratiform anvils around them which also persist for a long time (Fig.15). The rate of rainfall in the convective towers can be upto 100 mm/hr. but the stratiform anvil may have light rainfall-- a few mm/hr. Since the area covered by the anvil is much larger than that of the convective towers the total rain volumes contributed by each type of rain are about equal.

4.5 Echoes from severe thunderstorms can often be distinguished not only by high radar reflectivity, great height, and rate of vertical growth but by sharp protuberances, fingers, hooks or scallops. Positive identification of such a feature with presence of hail made in one case in North India when an aircraft was damaged by hail is shown in Fig.27. It is necessary for the forecaster to look for such features even if he cannot definitely identify them with hail or severe weather. Reflectivity greater than 50 dBZ is also often associated with hail. A 'spearhead echo' i.e. a pointed appendage extending in the direction of motion is associated with a downburst i.e. a downdraught of extreme intensity that induces dangerous windshear of both vertical and horizontal winds. The appendage moves faster than the parent-echo and eventually the latter disappears and the appendage becomes the main echo. (See also Sections 5 and 9).

4.6 Thunderstorm heights are usually highest at most locations in the premonsoon months when conditions are favourable for overshooting of the tropopause. During the southwest monsoon, thunderstorms occur but their vertical growth is usually less. Apparent heights on the RHI may also be exaggerated in the premonsoon season in some locations because of anomalous propagation (AP) effects and underestimated during monsoon because of subnormal propagation (i.e. upward refraction of the radar beam). The observed radar heights may not, of course, be the same as the height of the visible cloud because the top of the cloud may not have enough reflectivity. Statistics of heights of echo tops have been compiled by several authors for some locations in the country (see bibliography). Apart from the inherent limitations mentioned above, it should also be recognised that radars in IMD are usually not operated at all hours and even when operated, heights of only selected echoes, usually the tallest, are recorded. Hence the statistics presented in these studies should be taken only as a general indication.

4.7 'Nor'westers' of eastern India occurring in the premonsoon season are among the most intense thunderstorms in this country. Tornadoes also occur occasionally but have rarely been observed by radar in India. As the life of a tornado is very short and its extent is very small it is often difficult to spot it on conventional radars even in the USA where tornadoes are very frequent. The tornado vortex will exhibit usually a 'hook' echo besides high reflectivity and height. Continuous observation is necessary. On Doppler radar (see section 9) the characteristic 'tornado signature' i.e. winds in opposite directions on either side of the vortex can be seen clearly.

4.8 Duststorms ('Andhis') of northern India being essentially the same phenomenologically as thunderstorms, produce weak convective echoes on the PPI but since the precipitation evaporates before reaching ground, the tall columns are not exhibited on the RHI. A typical duststorm echo observed by a 3 cm radar at New Delhi is shown in Figs.28 and 29.

4.9 An important signature of severe convective storms is the quantity known as Vertically Integrated Liquid water content (VIL). Using reflectivity measured at various altitudes the Liquid Water Content (LWC) in a convective cell can be computed and integrated over height. This quantity and its rate of increase with time are taken as measures of severity of a thunderstorm. VIL can be computed and displayed by automated equipment. It is possible to compute it with manual isoecho systems but that is time consuming. See also section 9.2.3.

4.10 While using X-band (3 cm. wavelength) radar, the shape of a convective echo may be distorted due to radar beam attenuation in the heavy rain in the cell itself and its size shown smaller than it is. The centroid of the cell is shifted towards the radar. These effects may be kept in mind while judging the intensity or movement of the echo.

4.11 Most of the signatures of severe convective storms mentioned in the preceding paragraphs have been studied mainly in the U.S. Midwest. There can possibly be regional and climatic variability in these signatures and not all of them may be applicable to all regions.

4.12 Radars have been used as support systems for weather modification studies in two ways. One is to observe the growth and structure of clouds to decide which clouds are to be seeded. The other is to evaluate the rainfall produced by the seeded or 'control' clouds (see section 6 on estimation of rainfall by radar and section 9.4 regarding hail suppression).

5. APPLICATION OF RADAR TO AVIATION METEOROLOGY.

5.1 We can seek to get from weather radar the following information of interest to aviation :

(1) The location, extent and height of precipitating clouds especially of medium and large convective clouds and thunderstorms.

(2) The type and intensity of precipitation (rain, shower, snow, hail).

(3) The location and intensity of turbulence (in clouds and in clear air), air motion within clouds and wind shear.

(4) Conditions favourable for fog formation.

Groundbased radar is useful for judging the take-off, climb, descent and landing conditions. This is provided at the Airport Meteorological office, where the forecaster and the pilot can see and interpret the scope. In some places a remoted picture from a more distant installation is provided.

Information on conditions en route can be transmitted to aircraft from ground-based radar but as its range is limited it is better for the pilot in this phase of the flight to depend on an onboard radar.

5.2 Among the severe weather phenomena of particular interest to aviation are occurrence of hail, turbulence, windshear and icing. In section 4 the indications from radar echoes of likely presence of hail have been discussed.

5.3 Severe turbulence tends to occur in storms with the greatest reflectivities. High gradients of reflectivity are also believed to be associated with turbulence. Since ground-based radar is usually far removed from the thunderstorm location, the resolution is not sufficient to portray the reflectivity gradients correctly. In the case of large echoes it is necessary for the pilot to locate the regions of high reflectivity and high reflectivity gradients apart from the protrusions mentioned in section 4.5. This can best be done with onboard radar.

Moderate to severe turbulence often occurs in the clear air in the vicinity of a thunderstorm. Hence a pilot should try to remain at least 15 nautical miles away from the edge of the thunderstorm echo while flying within about 1.5 km. above general cloud level. Here a margin is allowed because errors in determination of the size of echo will play a part. When there is a large and intense echo its size will be underestimated by a 3 cm radar due to rain attenuation.

Turbulence can be directly detected by Doppler Radar (See section 9).

The structure of groups of convective cells or squall lines was discussed in section 4. Since there are areas of stratiform rain with low reflectivity and little vertical motion between convective cells, onboard radars will also enable the pilot to distinguish safe gaps in a convective formation.

Severe icing can occur on the aircraft surfaces if super-cooled water is present in convective clouds. Vertically oriented reflectivity contours (see Figs. 11 & 17) without any bright band are indicative of conditions when icing may occur.

5.4 Wind shear in a convective cloud can often be recognised on the RHI as already discussed. The presence of a spearhead echo (see section 4) or of other sharp protuberances may be associated with a 'downburst' which is very dangerous for landing of aircraft. See section 9 regarding detection of low level windshear by Doppler Radar.

5.5 As mentioned in section 4, the extrapolation of paths of convective echoes will enable short period forecast of thunderstorms over airports. Hence a continuous watch of the radar scope is very useful in aviation.

5.6 The conditions favourable for anomalous radiowave propagation are often similar to those needed for fog formation. Hence the appearance of extensive anomalous propagation echoes over land during winter nights can often be used to predict fog formation in the morning. This is an application of radar which is not widely recognised.

6. QUANTITATIVE ESTIMATION OF PRECIPITATION BY RADAR.

6.1 It was explained in section 2.10 that it is possible to compute the radar reflectivity factor Z from the measured received power Pr. We may recall that Z is the sum of the sixth powers of the particle diameters D. The rate of precipitation ($R\ mm.hr^{-1}$) falling to the ground is a function of the volume of liquid water and the fall velocity and hence is proportional to $D^{3.5}$. Hence Z should be related to R by a relation of the form

$$Z = AR^{b} \qquad \ldots (8)$$

where A is a constant and b is an exponent between 1 and 2 (ratio of 6 to 3.5). However a unique value for A and b cannot be obtained because the values will depend on the size distribution of the drops. Drop size distribution will depend on the type of rainfall (showery, stratiform) as well as season and place. Further complication will occur with nonspherical precipitation particles and especially solid precipitation. Experiments comparing radar-measured Z and raingauge measured R, have yielded values of A ranging from about 50 to 2000 and b from 1.0 to 2.0 for various types of rain or snow at various places. An equation

$$Z = 200R^{1.6} \qquad \ldots\ (9)$$

known as the Marshall-Palmer equation is taken as a standard relationship for temperate latitude rains.

6.2 If a reliable relationship is available, radar can provide an estimate of instantaneous precipitation rate at each point of its area of coverage which may be several thousand square kilometres. These estimates will be available in realtime instead of waiting for reports from individual raingauges. A radar is equivalent to a very dense raingauge network and can portray the spatial variations of rainfall much better than any practical raingauge network. Especially in situations of large spatial gradients in rainfall, a raingauge network has to be extremely dense to give a correct portrayal of precipitation distribution. By acquiring radar data at frequent intervals the total accumulated rainfall over any period for any small area can also be computed.

6.3 Although this capability looks attractive there are practical problems. The radar samples a large volume (see equation 2, section 2.4) the magnitude of which increases with range. This volume is aloft while a raingauge samples the rain falling in a very narrow column at the ground. The particles sampled by the radar may undergo modifications before they fall into the raingauge, due to melting, coalescence within the cloud, accretion with cloud droplets, coalescence between raindrops below cloud base and evaporation below cloud base. The sample may also fall at a different place due to wind. What radar measures is therefore not the same quantity as what a raingauge below the radar sample measures. Hence point rainfall estimates by radar using a fixed Z-R relationship do not compare well with raingauge data. Rainfall integrated over larger areas compares better.

As mentioned in section 2.7, the notional volume V is not often filled by precipitation particles especially at longer ranges. Also the beam height is too high at longer ranges to observe the low level precipitation. Further, if the beam intercepts the melting layer, the measured echo intensity will be high because of the bright band. For these reasons it is necessary to restrict quantitative measurements to a relatively short range (at the most 200 km. in flat terrain in the tropics and shorter distances in hilly or temperate regions).

6.4 Since it is not feasible to measure dropsize in routine operational work, several scientists have found it convenient to compare radar measurements with a small calibrating network of raingauges in a target area and thereby derive a mean Z - R relationship. For any individual occasion the rainfall computed from this relationship is further adjusted in magnitude using data from a few raingauges. If the average rainfall from the calibrating gauges is G, and the radar determined rainfall (using the mean Z-R relationship) is R, the ratio G/R is used as a multiplying factor to correct the radar estimates for the rest of the radar coverage area. For realtime estimation, these gauges will have to be of the telemetering type so that their data are immediately available. In computerised radars the raingauge data can be automatically incorporated to adjust the radar values.

6.5 To evaluate the Z-R relationship it would be ideal if the dropsize distribution is determined experimentally and both Z and R computed. In India the sizes of raindrops at the ground were measured and the following relationships obtained for Pune.

$$Z = 219 R^{1.41} \quad \text{for thunderstorms} \quad \ldots \quad (10)$$

$$Z = 67.6 R^{1.94} \quad \text{for steady rains} \quad \ldots \quad (11)$$

$$Z = 66.5 R^{1.92} \quad \text{for 'warm rains'} \quad \ldots \quad (12)$$

Another set of experiments gives the relationships

$$Z = 109 R^{1.64} \quad \text{for Khandala} \quad \ldots \quad (13)$$

$$Z = 342\ R^{1.42} \quad \text{for Delhi} \quad \ldots \quad (14)$$

More recently using the method outlined in para 6.4 a mean relationship

$$Z = 100\ R^{1.2} \quad \ldots \quad (15)$$

for Northeast Monsoon rains near Madras was obtained. For Southwest monsoon season rains near Madras the relationship

$$Z = 100\ R^{1.3} \quad \ldots \quad (16)$$

was obtained. But it is to be pointed out that there are appreciable variations from one rainspell to another.

6.6 For quantitative measurement of the received power and computation of Z and R therefrom the following steps are necessary:

(1) Sample the echo from a number of successive pulses and average them for each volume element (BIN) consisting of 1 or 2 km range and one beamwidth (1 to 2 degrees depending on the radar).

(2) Convert this voltage into received power using the known radar parameters and after applying certain corrections including those for attenuation of the radar beam due to range and atmospheric gases.

(3) Computing the Z value from the radar equation subject to the usual assumptions.

(4) Converting to rainfall rate values assuming a Z-R relationship.

(5) Integration as required to larger areas

(6) Computing cumulative rainfall for finite time periods using the rainfall rates already determined at short intervals of time.

6.7 It is necessary to use a digital processing system for digitizing the radar signal output and carrying out the above computations in realtime. The system can exhibit the results on a TV type of display on X-Y coordinates representing various rainfall rate levels in a grey scale or by colours. The data can also be printed out on a suitable printer.

The first such system developed in India known as Digital Video Integrator and Processor (DVIP) was in experimental operation at Cyclone Detection Radar, Madras for some years. A grey scale display and printout of rainfall in association with a cyclone are shown in Figs. 30 and 31. Fig. 31 shows an area of 200 km. radius around Madras divided into 10 km x 10 km. squares. Each square has a digit representing a particular rainfall rate at the time of observation. By adding successive observations at intervals of 15 minutes, a cumulative rainfall amount for selected grid squares is printed out at the bottom of the figure. Use of digital radar data is further discussed in section 9.

6.8 Realtime precipitation mapping by radar is particularly useful in heavy rainfall warnings and in flood forecasting, particularly flash floods. Other applications include evaluation of weather modification experiments. Radar estimates have also been used as ground truth to verify satellite estimates of areal precipitation over large areas. Radar measured rainfall data can also be used in climatology to interpolate into raingauge network data.

7. RADAR OBSERVATION OF TROPICAL CYCLONES.

7.1 One of the most important uses of weather radar is to observe tropical cyclones. In India there is a network of S band (i.e. 10 cm wavelength) radars primarily for this purpose. Radar can recognise and locate a tropical cyclone from the spiral pattern of rainbands and the eye (if formed). Continuous or frequent observation enables tracking of the storm to a good degree of accuracy. Besides this, radar can give operationally useful information such as likely intensity of the system, the precipitation distribution and the approximate radius of maximum winds. It also gives detailed information on storm structure.

The typical radar echo pattern associated with a well developed tropical cyclone is shown in Fig.32. As the system diameter is several hundred kilometres the entire pattern is rarely seen at the same time by any one landbased radar. But a time composite from one radar or a spatial composite from two or more radars may give the complete pattern of precipitation associated with a cyclone. The echoes identified in Fig.32 are:

(1) Precyclone squall lines

(2) Outer convective activity

(3) Spiral Bands and Rain shield

(4) Eyewall surrounding the eye

(5) Streamers.

7.2 Precyclone squall lines (See Fig.22) are lines of convective cells occurring about 500 km ahead of the cyclone centre. They are not part of the circulation around the system. But they are usually oriented perpendicular to the direction of the storm motion at that time and can therefore be used as fairly reliable predictors of storm motion. However they usually dissipate at the coast long before the landfall of the cyclone. They may produce heavy rain in coastal areas well ahead of the storm.

7.3 Outer convective activity, is a group of randomly oriented convective cells occurring some 300 km. ahead of a storm. These do not help in identifying the position or movement of the cyclone.

7.4 Spiral rain bands :

Precipitation cells in rain bands are organised approximately along logarithmic spirals defined by an equation of the form

$$r = Ae^{\theta \tan\alpha} \qquad \ldots \quad (17)$$

or

$$\log_e r = \log_e A + \theta \tan\alpha \qquad \ldots \quad (18)$$

where (r, θ) are polar coordinates of any point on the spiral with reference to the centre of the cyclone,

α called the crossing angle is the angle of incurvature of the spiral at the point (r, θ) i.e. the angle between the tangent to the spiral at this point and the tangent at the same point to a circle centred at the origin and of radius r,

and A is a constant.

Usually in steady state systems the crossing angle increases from near zero at the radius of maximum winds (R) to a maximum of about 30 degrees at 3 R and decreases gradually thereafter. In a nonsteady system there may be asymmetries i.e. different angles in different sectors. The spiral bands tend to distort in shape when they are close to land. Individual cells in these bands move anticlockwise along the band as part of the storm circulation but also often have a small component of motion radially outwards. The entire pattern of bands is subject to changes over a period of several hours.

Interspersed with these bands which are mainly convective are areas of lighter precipitation usually stratiform known as the rain shield. The orientation of the spiral bands may be masked by this shield, but can be delineated by observing at reduced radar receiver gain or by applying the isoecho system suppressing the weaker echoes. (see Figs.40, 41 & 42). After tracing the bands, transparent overlays with spirals of specified crossing angles drawn on them are superposed on the picture. Spirals of 5 to 30 degrees crossing angles are used. If any band can be seen over an appreciable arc (at least 90 degrees and preferably 180 degrees or more), the position of the centre of convergence of the band is estimated (see Fig.33) by fitting the overlay. If more than one band is seen successively larger angle spirals are used as one goes away from the storm centre. The mean position obtained from several bands can be taken as the storm centre. Thus the centre can be estimated even when the eye is not formed (as in marginal cyclonic storms) or is too far away to be seen by the radar. However, the procedure is highly subjective and prone to large errors. Any such determination must be checked for reasonable consistency with satellite or synoptic evidence relating to the storm's location. Curved area which are not genuine spiral bands may often form. In weak systems such as depressions or marginal cyclonic storms, there may be many curved arcs converging to more than one centre. These multiple vortices should not be confused with the real centre of the system which may not be apparent on radar. Location of centres of depressions by radar is not feasible.

An example of spiral bands in a developing cyclone without an eye is shown in Fig.34. Usually the bands are more tightly coiled and have smaller crossing angles in the more intense systems.

7.5 In cyclonic storms very often an 'eyewall' is partly formed usually as an extension of the innermost spiral band. As the storm intensifies further the eyewall may become more complete and may separate out from the spiral band and be seen as a distinct ring. The area inside the eyewall is echofree or nearly so and may be circular, elliptical or sometimes of irregular shape. The more intense the cyclone, the more symmetrical and complete the eye is likely to be. Radar pictures of severe cyclonic storms with a core of hurricane winds are shown in Figs.35 to 45.

In deep systems an additional eyewall sometimes forms outside the original one. After sometime one of the walls may disappear. This double wall configuration can be seen in Figs.38, 44 and 45. In these cases the walls are not quite concentric. These are called "asymmetric double eyes". Cases of symmetric double walls have been reported in the Atlantic and Pacific. It is believed that an asymmetric double eye is only a case of the innermost spiral band curving into a complete circle. The symmetric double eye is however considered to be the result of a process of repeated cycles of intensification and weakening. In either case the appearance of a double wall is an indication of high intensity of the system.

When an appreciable part of the arc of the eyewall is seen and can be identified as such, its geometric centre can be determined fairly accurately and is taken as the centre of the cyclone in preference to all other data sources. Accuracy of about 0.1 degree latitude is possible. The radar centre however may not quite coincide with the pressure or wind centre ^ in some cases. When a small arc of the eyewall is seen (Fig.43) either because the rest is beyond range or is not formed the meteorologist should decide whether it is really the eyewall. Once it is identified as eyewall, the centre of the system can be estimated with a fair degree of accuracy (say within 30 km).

The radius of maximum winds (RMW) of the storm is usually in the eyewall region a little outside the inner echofree area of the eye. It has been established by aircraft observations in the US and by post-cyclone damage surveys in India that the radius of maximum winds (RMW) approximately coincides (within a few kilometres) with the radius at which maximum radar reflectivity occurs in the eyewall (Fig.46). Utilising this finding, the Radius of Maximum Reflectivity (RMR) is observed and reported by

^ or the centre determined from Satellite imagery.

radar stations in India when an eyewall is clearly observed. The RMR is taken as equal to the RMW and the information is used in the nomograms for computation of maximum height of storm surge in which RMW is one input parameter. The knowledge of RMW also enables determination of the point at which the peak surge will occur.

It has been statistically shown in the Pacific that smaller eyes are associated with deeper systems. However this finding cannot be used to compare intensities of two individual storms based on eye diameters. In a given storm if there is a gradual decrease of eye diameter with time it can be invariably associated with intensification of the storm. The variation of RMR is probably better correlated with intensity changes. The converse phenomenon i.e. increase of eye diameter or RMR with time should theoretically mean weakening of the system. However, operationally extreme caution should be exercised in coming to such a conclusion as apparent widening out of the eye may sometimes be due to poor seeing conditions of the radar.

Radar reflectivity in the eyewall is often unsymmetrical around the centre. There are corresponding asymmetries in the rainfall and wind speed in the core region. In southern Bay of Bengal storms the highest rain rates and wind speeds in the eyewall appear to occur immediately to the left of the track.

7.6 The spiral bands in the rear often extend into nearly straight lines of convective cells in the right rear sector well separated from the central echo mass of the eyewall area. These cells are intense and capable of giving heavy rainfall over the areas they move over. These lines known as 'streamers' should therefore be considered while forecasting precipitation. For instance, when a storm is crossing the Saurashtra coast, the streamers appear over Bombay. Hence Bombay may get heavy rainfall with relatively little rain in South Gujarat and North Maharashtra coasts.

7.7 Successive hourly positions obtained by radar are plotted to obtain a track. It is usually seen that the track meanders considerably around a mean path even when there is no general change of direction of motion of the cyclone. The oscillation of the track is partly due to errors in radar fixes but partly real. Some scientists have established a trochoidal motion in many cyclones. If fixes of good accuracy are available for some hours a smoothened track can be constructed and extrapolated to predict the likely point of landfall of the storm. This extrapolation usually gives good results provided there are no synoptic indications for major change in the track of the system e.g. recurvature. To allow for short period meandering and for radar fix errors it is desirable to draw an envelope around available fixes taking into account the reported margin of error, while attempting extrapolation of track. Some examples of radar track extrapolation in various circumstances are given in Figs 47 & 49.

7.8 It is seen from experience that the tightness of banding of the spiral bands, the number of bands seen, the completeness of the eyewall, the decrease of the eye-diameter or of the RMR and the occurrence of double walled eye are all positively correlated with the intensity of the system. However there is considerable subjectivity in estimating intensity from these parameters. The most important problem is that unless the cyclone is very close to the radar, the latter may not see all the features sufficiently well to be able to assess them in relation to cyclone intensity. There may also be time lag between the appearance of any of these radar features and the intensification or weakening of the storm.

7.9 When a storm comes over land the eyewall seen on the radar tends to break up, but in some cases a clear eye can be seen over land also (Fig. 35).

7.10 Fig. 50 shows a satellite (INSAT-1B, visible) imagery of a cyclone the radar picture of which is shown in Fig. 44. The total cloud coverage shown by satellite is typically about 10 times the total radar echo area. The outflow seen by the satellite cannot be seen by radar as it senses only the precipitation. However the radar can usually see the core structure of a nearby cyclone in greater detail than the satellite can.

Recent studies show that in the case of cyclones with well defined centres, the satellite and radar fixes generally agree to within about 20 Km. The differences may be much more if a well formed eye cannot be seen. Moreover, as the track of a cyclone oscillates around a mean path, the track (radar-observed) is smoothened out by the forecaster, before giving centre positions for the public or outside agencies.

7.11 The total echo area seen by radar is roughly equal to the total area of significant precipitation (say 2 cm/day) or more). From experience it is also seen that the diameter of the area of gale force winds (15 m. sec^{-1} or more i.e. the size of a severe cyclone is about 1.5 times the radar echo dimension.

7.12 For areas of the cyclone which are within about 200 km. of the radar, the latter can estimate rainfall rates and amounts approximately (see section 6) and in any case portray the spatial distribution of rainfall. The rain rate distribution can be converted into a Latent Heat Release (LHR) distrubtion. Some satellite studies have shown that changes in core area LHR are positively correlated with changes in cyclone intensity. As the rainfall pattern can be extrapolated for some hours, the rainfall distribution over land can also be predicted for short periods (see section 9 for a further discussion).

7.13 The main limitation of landbased radar in observation of cyclones, is the range limitation. Radars mounted on reconnaissance aircraft although they have a short range, can go to any part of the cyclone and can thus yield valuable data (see section 9).

7.14 Operational procedures in IMD relating to radar observations of tropical cyclones are given in the IMD cyclone Manual and amended from time to time according to the decisions of the Annual Cyclone Review (ACR) meetings. Some important guidelines are reproduced below.

7.14.1 When a cyclone is tracked by more than one radar, greater weightage may be given to the positions reported by the radar nearest to the cyclone. However, the centre fix based on observations of the 'eye' should be preferred to that based on spiral band observation.

7.14.2 The distances reported by radar may be rounded off to the nearest 10 Km and the direction of movement to the nearest of the ~~10~~ 16 points of the compass on a smoothened track in cyclone bulletins for public dissemination.

7.14.3 RMR should be reported only when the cyclone centre is within 200 km of the radar.

8. OPERATIONAL PROCEDURES.

8.1 Recording of radar information :

In India at present the radar picture is traced on a transparent overlay and transferred to a polar diagram. The overlay may be a thin transparent plastic sheet or film on which the map of the area is drawn to the same scale as the radar scope. It is important that the range ring diameters be adjusted during maintenance to correspond exactly to the scale of the map. While tracing the picture there will be some parallax error as the overlay is not in the same plane as the CRT face. To avoid this a "reflection plotter" is used in some radars. It is also possible to feed the map information electronically to the CRT display but this is generally not done in IMD radars. The overlays are again traced on paper polar diagrams for keeping as a permanent record.

Photographs of the radarscope are also taken for a permanent and accurate record. Unless a polaroid camera and film are used it is not possible to get the photograph in realtime. Generally a 35 mm still camera is mounted in front of the radarscope and black and white pictures are taken in various modes of operation as required. The Cyclone Detection Radars are usually provided in addition with a camera which can use a 30 m x 35m film roll to enable a large number of pictures to be taken at frequent intervals. When the film is developed positive paper copies or contact 35 mm positive film copies can be taken. The latter can be projected on a microfilm reader or projector for any subsequent analysis. If the pictures on the 30 metre roll are taken at the same radar settings it is possible to run the film later as a time-lapse movie. This latter purpose can however be better achieved by using a video camera.

8.2 Transmission of radar information :

For supplying realtime information to forecasters the essential details of the picture are coded in a semiplain language message called RAREP (RAdar REPort). This gives the boundaries of the area(s) containing echoes, the distribution in that area (Broken, Scattered etc.), the orientation of line echoes, the intensity, tendency and heights of tops of selected echoes and movement of groups of echoes when it is possible to evaluate it. Any additional information can be added in plain language. A copy of the Radar code used in IMD is at Appendix to this Chapter. These coded messages are transmitted by T/P or W/T to the forecasting offices. Decoding of these messages, does not however give the forecaster a complete picture of the echoes as they appear on the scope.

WMO has adopted a new general format for data transmission the FM 94 BUFR. This format is being extended for international exchange of digital radar data in Europe.

It would be ideal for the forecaster to be able to see the radar scope for himself at frequent intervals. This is possible at airport installations where the scope is close to the forecaster's room. In some installations 'slave' PPI displays are provided in the meteorological briefing room and in the air traffic control room. For transmission to more distant locations of the complete radar picture, a relatively less expensive method is to make an interpreted sketch of the scope at the radar station and transmit it by facsimile. Dedicated telephone line facsimile is provided for this purpose between some radar stations and the nearest cyclone warning centres. Telefax equipment attached to STD telephones can enable sending the sketches to any forecast centre subject only to the vulnerability of telephone lines in severe weather situations. While direct transmission of the analog radar picture requires very expensive equipment, digitized data can be transmitted on low bandwidth transmission lines over long distances and a TV type display can be provided at the forecast centre (see Section 9). Wherever and whenever possible the meteorologist should see the radar picture for himself for a correct appraisal of the situation.

8.3 In the case of tropical cyclones the radar report is divided into two parts. Part A contains information on the position (latitude and longitude) of the cyclone determined by radar, its movement over the preceding three or six hours, the degree of confidence of the fix and the characteristics of the eye (if seen). This part of the message is transmitted only if the radar is able to give a fix and is sent as an addressed message of high priority to concerned forecast centres. Part B gives a description of all the echoes observed, as in any other situation and is transmitted whether or not the radar is able to locate the cyclone.

8.4 Weather radars at airport locations are normally operated hourly during the active season. These observations are used mainly in preparation of terminal forecasts and air field warnings. The messages are also exchanged with other aeronautical meteorological offices. In the case of 'cyclone detection radars', observations are taken only at certain fixed hours. In case of severe weather or a tropical cyclone, observations are taken three hourly, hourly or at shorter intervals as necessary. When a cyclone is on the radarscope continuous operation is desirable.

8.5 A high standard of maintenance and periodical calibration of the radar is necessary to get reliable and accurate information from it. Deterioration in performance (e.g. poor receiver sensitivity, reduction in transmitted power, errors in elevation or azimuth readings) may occur gradually and may go unnoticed if periodical checks are not made. Such deterioration may result in the radar not seeing significant echoes or underestimating their height or intensity. It is therefore necessary for the meteorologist to satisfy himself/herself that the radar performance is normal. There are routine procedures prescribed for periodical maintenance checks by the radar stations. The Cyclone Detection Radars are also provided with test equipment for monitoring the power transmitted, receiver sensitivity and other radar parameters and for calibrating the isoecho system at frequent intervals.

8.6 In the use of radar as an operational tool, it is important for the forecaster to bear in mind that while radar is a versatile instrument, it has its limitations. Also just as in the case of every instrument there are errors associated with radar observations and their interpretation have been dealt with in the relevant sections. It may be useful to recapitulate the major ones here.

8.6.1 Radar at the wavelengths commonly used can detect only precipitation particles and not cloud drops (see section 2.5)

8.6.2 At some wavelengths (particularly with 3 cm. radar) attenuation by rainfall is a serious problem. Intervening precipitation may prevent precipitation further away from being detected. Attenuation can also result in depiction of a smaller areal extent or a distorted shape of echoes. With 10 cm. radar these problems are not serious (see section 2.3).

8.6.3 The range up to which a ground based radar can see precipitation is limited mainly by the earth's curvature and varies with radio wave propagation conditions. Only the upper portions of distant precipitating clouds are seen. Hence the effective range of radar for qualitative use is between 300 to 400 Km and for quantitative measurements of echo intensity and precipitation about 200 Km. in flat terrain. Heights of echoes determined by radar may also be in error because of propagation conditions and because of finite width of the radar beam. Resolution is also limited by beam width (see sections 2.6 to 2.9).

8.6.4 Since radar signals fluctuate, measurements of echo intensities have to be made by sampling and averaging several pulses. Not all radars have this facility. There is also no unique relationship between echo intensity and rainfall. For radar estimation of precipitation, reflectivity rainfall relationships have to be validated by calibration with raingauges (see section 2.10, 6.3, 6.5).

8.6.5 Many spurious echoes due to anomalous propagation, refractive index discontinuities, sea clutter, ground clutter etc. need to be distinguished carefully from precipitation echoes. (see sections 3.6, 3.7).

8.6.6 With conventional radar, only rough subjective guidelines are available for identifying or inferring hail, turbulence, tornadoes etc. (See section 4.3, 4.5, 4.7).

8.6.7 A single ground- based radar can usually see only a part of a tropical cyclone at a time. Radar cannot locate the centre of depressions. In the case of weak cyclones, the rain bands may not be sufficiently well organised to yield reliable centre positions. Radar positions of cyclones are more accurate in intense cyclones but could differ to some extent from satellite or synoptic ~~fixations~~ [indications]. (see sections 7.1, 7.4, 7.5).

8.6.8 While radar can give some measures of intensification of cyclones, such as tighter organisation of bands, decrease of eye diameter or RMR, these are not decisive. Particularly it is not desirable to interpret the increase of eye diameter or RMR as weakening of the cyclone in operational decision making. RMR is not reported when the cyclone is over 200 Km. from the radar. Radar errors also contribute to cyclone track oscillations. Radar observed positions need to be checked with satellite or synoptic evidence and the track smoothened when necessary. Extrapolation of radar track should be done with care and is not applicable as a forecast procedure in cases where recurvature or other sharp changes in track are to be expected. (see sections 7.5 to 7.8, 7.13).

8.6.9 Lastly the need for proper maintenance and calibration of the radar and use of careful operational procedures cannot be overemphasised. (see sections 8.1 to 8.5).

8.6.10 Radar should therefore be considered as only one of the tools in the armoury of the meteorologist whose expertise is the primary factor in the success of his forecast.

9. RECENT DEVELOPMENTS.

9.1 In the previous sections we have considered weather radar in its primary function of remote detection of precipitation. With many recent advances radar is now capable of contributing quantitative information to a variety of atmospheric inquiries with spatial and temporal resolution unequalled by other instruments. Investigation concerned with precipitation physics, mesoscale dynamics, the planetary boundary layer and kinematic structures of the stratosphere and mesosphere are being undertaken using radar. In this section we shall briefly consider these developments which are not yet in operational use in India. Indeed some of the techniques mentioned here are only in a research mode in other countries too. Only a sketchy account is given here and the interested reader should consult the references listed.

9.2 Digital Radar :

The radar yields an immense amount of data which a meteorologist cannot assimilate in realtime without some form of processing. Computer processing and computer control have therefore become the bases for most of the recent techniques to be described. In section 6, the digital processing of data from a conventional radar was mentioned in connection with quantitative estimation of precipitation. Digital processing has numerous other applications.

9.2.1 The video voltage output at each range azimuth bin (illustrated in Fig.5) is converted into a digital quantity, by a processor which works in synchronisation with a programmed scanning of the radar antenna. The antenna rotates in the azimuthal plane at one elevation (say zero degree) and then is stepped up in small steps of elevation in successive scans. Thus data are collected in 3 Dimensions over the entire quantitative range of the radar. Echo returns from a number of pulses of the radar are averaged for each bin. These are corrected through software for attenuation of the radar beam due to range and atmospheric gases and for variations in radar constants and converted to Z values. Using a Z-R relationship a rate of rainfall is calculated for each bin. Further integration over larger areas can also be performed (at the expense of resolution) and the output presented on a TV display in grey shades or in colour code of ranges of reflectivity or rate of rainfall. The digitised data can be transmitted to a remote terminal through telephone lines; or a radio link. Since most of the operations are by software the system is highly flexible. Computer control of the radar operation even from a remote position has been achieved.

Successive scans at frequent intervals enable time integration of rainfall rates and a map of cumulative rainfall at various points can be printed out.

9.2.2 The ordinary PPI gives a quasi-horizontal section of the three dimensional reflectivity field because the height of the radar beam increases with range. If we construct a series of PPI's by scanning at various elevations, we can cut out annuli corresponding to any given altitude say 3 km. from the various PPI's and synthesise a Constant Altitude PPI (CAPPI). While it is possible to do this without a computer it would be laborious and time consuming. With a computerised radar system several such maps for different altitudes can be constructed quickly.

9.2.3 Just as we can relate the reflectivity factor (Z) to the rainfall rate, we can also have equations of the same form relating it to the liquid water content M (LWC expressed in grams.metre^{-3}). The LWC here refers only to the precipitation size particles and not cloud droplets. With such a relationship the LWC at various levels can be computed *in realtime*. It is also possible to compute in the case of convective clouds the Vertically Integrated LWC (VIL) for the whole cell. Several workers have found that the VIL and its rate of growth are related to the severity of a thunderstorm and this quantity can therefore be used for identifying several local storms.

9.2.4 Since the 3-D reflectivity data are available, it is possible to determine the heights of echotops (upto a specified threshold of reflectivity) by suitably designed software instead of having to make RHI scans at numerous azimuths and correct them manually.

9.2.5 Computerization also makes it possible to reject unwanted clutter echo and present a 'clean' picture. Stored data of permanent echoes can be subtracted from the output. This however will not reject anomalous propagation and similar nonprecipitation echoes. For this it is possible to compute the variance of the signal which is small for AP and clutter echoes and large for precipitation echoes and thereby distinguish and reject the former.

9.2.6 Pattern recognition techniques have been employed with computerized data to compare the radar echo at time t_1 with the echo at time t_2. Thus the motion of the echo can be determined and it can also be extrapolated in time. The use of an interactive display system makes it possible for the meteorologist to 'see' the echo in the predicted position. The meteorologist can at this stage incorporate the expected effects of any other feature e.g. topography. In recent years pattern recognition techniques have been extended to study motions of particles within the echo. This involves high resolution and large computer capacity. It may help in locating areas of turbulence and in identifying tornadic storms. The method however suffers from the fact that it is actually monitoring changes in reflectivity which may not necessarily be due to motion.

Pattern recognition methods hold great promise in NOWCASTING, that is, forecasting for short periods of a few hours using, mainly, frequently updated radar and satellite pictures. This can be the basis for very short period forecasts over radio or TV for a city or other small regions. In India, this should be particularly successful in well-defined weather systems such as depressions and cyclones where the precipitation distribution may be extrapolated in time with greater confidence than shortlived phenomena such as local severe storms.

9.2.7 Digital radar output is relatively easy to transmit over long distances. Hence semiprocessed digitized radar data from various stations can be transmitted to a central computer where a composite picture can be displayed after further processing. Such a system can obtain calibration data from telemetering raingauges in realtime and use them to correct the display. Its output can again be transmitted to any remote location such as a water authority who may need the precipitation data for flood assessment and water management. The computer display can also superimpose a satellite picture on the radar picture. Such a system has been implemented in the UK. Recently "Radar Networking" has covered several European countries, so that an almost unbroken radar data coverage over a large part of Europe is available in realtime. In the United States it is possible for many users to obtain the digitized radar imagery over telefax type of equipment.

9.3 Doppler radar :

9.3.1 The radar echo from an object which has a component of motion towards or away from the radar, suffers a Doppler shift in frequency. This phenomenon has been made use of in military and aviation radars to detect moving targets (and distinguish them from fixed clutter) and evaluate their speed. In weather radar, pulsed Doppler systems have been developed especially in the past twenty years and are coming into operational use in some countries. Their use is still limited because they require 'coherent' transmitter - receivers and elaborate signal processing facilities which are all expensive.

9.3.2 Since a Doppler radar can detect only the radial component of motion towards or away from the radar, ideally there should be three such radars in a small area to get the three components of motion. It is possible to use only two Doppler radars and obtain the horizontal wind by neglecting the vertical component of motion. Such multiple Doppler systems however are not considered suitable for operational work. Hence techniques have been developed to get these outputs from a single Doppler radar.

9.3.3 On a colour PPI display different velocity intervals of the precipitation particles can be displayed in different colours (instead of reflectivity values). The maximum velocity that can be unambiguously displayed increases with the pulse repetition frequency (p.r.f). Any velocity beyond this maximum value will be 'folded over' to coincide with a low velocity value. This is analogous to the multiple-time-around echo mentioned in section 3.7.4, where the maximum unambiguous range increases with decreasing p.r.f. A compromise between the two conflicting requirements can be made by choosing a p.r.f. suitable for the purpose in view. Even if there is a foldover identification of velocity intervals can be made from continuity considerations. Such a colour display will indicate precipitation particle motion pattern in small scales directly. Alternatively what is known as a Velocity-Azimuth Display (VAD) can be used on which the maximum positive and negative velocities will be displayed at the azimuths corresponding to the prevailing direction of particle motion and zero velocities in the orthogonal directions. Hence it is possible to determine both the direction and speed of the motion. It is possible to interpret these two types of displays to determine wind variation with height, i.e. wind shear, the vertical motion and even the rainfall rate from the vertical motion. In the case of severe storms such as tornadoes a 'signature' consisting of opposite velocities on either side of the vortex can be seen. This is a more positive identification than looking for a hook echo in the reflectivity display. 'Downbursts' can also be identified by the divergence which can be detected.

9.3.4 The use of Doppler radar is particularly considered useful for low level wind shear alerts at airports. Since the downburst or microburst starts as a downdraught within the lowest one kilometre from the ground and takes upto five minutes to spread on the ground, it can be detected by a Doppler radar to give a warning at least one minute in advance which is the requirement specified by the U.S. Federal Aviation Administration. A network of 'Terminal Doppler Weather Radars' is being established in the USA for this purpose. A sensitive Doppler radar can also detect the clear air echo from thunderstorm gust fronts which also cause low level windshear.

9.3.5 The utility of Doppler radar in observation of mesoscale phenomena has been proved. In the case of tropical cyclones which are larger in extent it is considered feasible to obtain the wind field directly from a suitably designed single land-based Doppler radar upto a range of about 300 km. Here again although only radial (with respect to the radar, not the cyclone) velocities are directly obtainable the total wind field can be computed from various considerations. However land-based radar has not been used in this fashion in the past. The new NEXRAD (WSR 88D) network being set up in the USA is expected to perform in this manner. Airborne Doppler radar however has been used very successfully in a number of hurricanes.

9.3.6 The Doppler facility can be combined with the various other techniques to be described in the subsequent sections, sothat radars of great versatility are created. A high degree of computerization and automation is involved. The software for various applications has however not yet been standardised and we may expect this to happen in the next few years.

9.4 Dual wavelength radars :

The simultaneous use of radar at two wavelengths enables the reflectivities at the two wavelengths to be compared. In the case of hail of sizes 1 to 4 cm, the reflectivity factor at 10 cm is higher than that at 3 cm (due to the departure from the Rayleigh law at the latter wavelength). Hence determination of the ratio of the reflectivities should help detect hail and distinguish it from rain showers of high reflectivity. This technique has been successfully applied in the USSR. Usually a single antenna with dual primary feeds for the two wavelengths, can be used for the purpose.

In the USSR, Yugoslavia and Bulgaria hail suppression is carried out by seeding rockets fired from ground, after identifying zones of hail or likely hail formation from radar.

Comparison of reflectivities at two wavelengths has research uses such as determination of drop size distribution and the study of clear air echoes.

9.5 Millimetre wave radars :

Radars of frequencies higher than 10 GHz (wavelength shorter than 3 cm) are not used operationally because they are subject to heavy attenuation due to rain and therefore their range of operation is severely limited. However because of the Rayleigh fourth power law (see section 2.3), it is possible to get echo return even from cloud droplets. Millimetre wave radars are therefore ideal for cloud physics studies. By using vertically pointing radars, dropsize and vertical motion studies have been carried out. They have also been tried as ceilometers but have not been very successful because the cloud boundaries as seen by radar do not coincide with the visual cloud base. Also it is difficult to relate the radar echo to the international cloud classification system.

Millimetre radar being sensitive to light precipitation will probably be used in automated weather systems to distinguish between various present weather (ww) code figures such as drizzle (50 to 59), rain (21, 60 to 65) snow (22, 23, 70 to 75) and forms of transition.

9.6 Polarization Diversity Radars :

In conventional weather radar the radiation is linearly polarized (usually horizontally). If a circularly polarized signal is used, spherical raindrops will return a signal circularly polarized in the opposite sense which the radar receiver will not recognise. Hence echo from rain is suppressed in such radars which are used for non-meteorological purposes where rain echo is unwanted clutter.

However in the case of a non-spherical precipitation particle, if the incident radiation is polarized in one plane, a cross-polarized component is also scattered back. Solid precipitation particles as well as large liquid drops are non-spherical and hence unsymmetric targets which can return echo with two polarizations. This property has been sought to be used to distinguish between solid and liquid precipitation and also provide direct measurement of drop sizes. A recently developed instrument is the dual polarization radar in which the polarization is changed in alternate pulses to horizontal and vertical. There are two channels in the receiver to receive the two components in the echo and derive their ratio which is called the differential reflectivity. It is claimed that from this the rain rate can also be derived more accurately than by the conventional methods. It is also claimed that conventional radars can be modified to provide this facility at modest cost.

9.7 VHF and UHF radars for clear air observations :

In recent years powerful radars operating at much lower frequencies than conventional radars i.e. in the ultrahigh frequency and very high frequency ranges have been developed. They use a fixed array of antenna elements whose beam is vertical but which can be electronically switched (without moving parts) to off-vertical directions. These also have a Doppler facility and can observe wind, turbulence, atmospheric waves and stable atmospheric layers in the troposphere and stratosphere via scattering from clear air irregularities in radio refractive index. They can also be used for the mesosphere where an ionized medium is available to give echoes. Hence these are often known as MST (Mesosphere Stratosphere Troposphere) radars. Their main advantage is that they can operate in the optically clear atmosphere (no precipitation particles are needed to provide echoes). Lower power versions are commercially available for use in the troposphere or in the troposphere and lower stratosphere. Near-continuous monitoring of upper winds is possible with these radars which may perhaps one day replace the conventional balloonborne radiosonde.

An indigenously developed MST Radar has recently been installed near Tirupathi in Andhra Pradesh for research purposes.

9.8 Satellite borne Radar :

Radar has been used on satellites primarily for non-meteorological purposes. But these have been used also for mapping ocean surface wind fields. There are many limitations such as large beamspread, sidelobes, difficulty in discrimination of targets from ground and sea clutter and noise problems. These can be overcome by using large antennas and high power. It may be expected that meteorological radars may be flown in satellites soon for precipitation measurements also. These may have advantages over present methods of satellite rainfall estimation using passive radiometers inthe visible/infrared and microwave bands.

9.9 Use of Radar in conjunction with other observational platforms :

Use of modern radar in conjunction with various other observational systems e.g. lightning detection systems, microwave radiometers and sodars may increase its capabilities in severe storm detection, icing detection, flash flood forecasting and the like. The most important and successful joint use of observational tools is the combination of radar and satellite imagery.

9.10 To conclude we must emphasize that in the midst of rapid developments in the versatility of radar and increase in automation, the importance of intelligent human interpretation of its outputs is increasing. The greatest contribution is therefore that of the human meteorologist.

10. APPENDIX.

CODE FOR REPORTING RADAR OBSERVATIONS

Part 'A' (to be reported when centre of a cyclone can be determined).

CYREP FFAA STATION IIiii

YYGGg $4R_wL_aL_aL_a$ $1L_oL_oL_oL_o$

EYE or SPIRAL 6CSDT $Pd_sd_sf_sf_s$

Explanatory Notes :

CYREP FFAA : Radar Report giving centre of a cyclone.

STATION : Name of Station in plain language.

IIiii : Station Index Number.

YY : GMT date.

GGg : Time of observation in hrs and tens of minutes GMT.

4 : Indicator figure.

1 : Quadrant of globe ________'1' for our area as per WMO definition.

R_w : Wavelength of radar
3 for 3 cm radar
8 for 10 cm radar

$L_aL_aL_a$: Latitude) In tenths of a degree. Tenths are obtained by dividing the number of

$L_oL_oL_oL_o$: Longitude) minutes by six and discarding the remainder.

EYE or SPIRAL : Either the word 'EYE' or the word 'SPIRAL will be reported, but not both.

The word 'EYE' will be reported if a partial or complete eye is seen by the radar.

If a double walled eye is seen "DOUBLE EYE" will be reported instead of "EYE".

If the storm centre is estimated using only Spiral bands the word 'SPIRAL' will be reported.

6 : Indicator figure to show that eye characteristics and/or confidence of fix follow.

C : Confidence of fix (Vide Table 1).

S : Shape of eye and length of arc of eyewall seen (Vide Table 2).

D : Diameter or length of major axis of the eye (Vide Table 3).

T : Tendency of the eye determined over the period since the last observation (Vide Table 4).

<u>NOTE</u> : S, D and T will be reported as solidus (/) if the storm centre is fixed from spiral bands only.

P : Period over which the movement of the storm centre has been determined (Vide Table 5).

$d_s d_s$: Direction in tens of degrees towards which the storm centre is moving.

$f_s f_s$: Speed of movement of storm centre in <u>kilometres per hour</u>.

If movement over a period of 3 hours or more cannot be estimated, the group $Pd_s d_s f_s f_s$ will be dropped.

<u>NOTE</u> : The radar Meteorologist may at his discretion add any other operationally useful information not covered above, in plain language at the end of Part A of the message.

Table 1

Confidence of Fix (C)

Code Figure	Category	Radar echo pattern	Likely accuracy about
1	Very poor	Spiral bands, ill-defined or too few or too short.	100 km
2	Poor	Centre estimated from well-defined spiral bands ____ eye not visible.	50 km
3	Fair	Partial eye wall seen.	30 km
4	Good	Closed or nearly closed eye whose geometric centre can be located with confidence.	10 km

NOTE : The accuracy and criteria as given above are only illustrative and not definitive.

Table 2

Shape of Eye and length of arc of eyewall seen (S)

Code Figure	Length of arc	Shape
0	-	Ill-defined
1	Less than 180°	Shape other than circular or elliptical
2	More than 180°	Shape other than circular or elliptical
3	Closed.	Shape other than circular or elliptical
4	Less than 180°	Elliptical
5	More than 180°	Elliptical
6	Closed.	Elliptical
7	Less than 180°	Circular
8	More than 180°	Circular
9	Closed.	Circular

Table 3

D - Diameter or length of major axis of the eye of the tropical cyclone.

Code Figure		Code Figure	
0	less than 10 km	6	60 to 69 km
1	10 to 19 km	7	70 to 79 km
2	20 to 29 km	8	80 to 89 km
3	30 to 39 km	9	90 km and greater
4	40 to 49 km	/	Undetermined.
5	50 to 59 km		

Table 4

T - Tendency of the eye, determined over the period since the last observation.

Code Figure	
0	Eye has first become visible since the last observation.
1	No significant change in the characteristics or size of the eye.
2	Eye has become smaller with no other significant change in characteristics.
3	Eye has become larger with no other significant change in characteristics.
4	Eye has become less distinct with no significant change in size.
5	Eye has become less distinct and decreased in size.
6	Eye has become less distinct and increased in size.
7	Eye has become more distinct with no significant change in size.
8	Eye has become more distinct and decreased in size.
9	Eye has become more distinct and increased in size.
/	Change in character and size of eye cannot be determined.

Table 5

P - Period over which the movement of the storm centre has been determined.

Code Figure	Period
7	During the preceding 3 hours
8	During the preceding 6 hours
9	During a period more than 6 hours

Part B

(to be reported whenever any radar echo is seen)

RAREP ffBB IIiii YYGGg

CHARACTER { $b_1 b_1 b_1 / r_1 r_1 r_1$ ....

$b_n b_n b_n / r_n r_n r_n$ } INTENSITY

TENDENCY $d_s d_s f_s f_s$ ALTD { $bbb/H_t H_t/rrr$ }

[NOTE : In the case of cyclones, Part B will normally be reported only at synoptic hours. In the case of any break in observations or rapid development, additional Part B messages may be transmitted as necessary.

2. Part A messages are to be prepared and transmitted as close to the observation time as possible. Part B can be transmitted separately, after Part A has been sent. When Part A and Part B are transmitted together, the code groups RAREP, IIiii, YYGGg need not be included in Part B.]

Character :

EYE	: An echo identified definitely as the eyewall of a tropical cyclone.
SPRL BND	: A continuous or broken curved line of echoes recognisable as a spiral band associated with a cyclonic system.
SQL LN	: This pattern should normally have a length to width ratio of about 10 to 1 and length about 60 km or more.
BRKN LN	: A broken line of echoes.
SLD	: An area fully covered with echoes.
BRKN	: An area 4/8 to 7/8 covered with echoes.
SCT	: An area 1/8 to 4/8 covered with echoes.
WDLY SCT	: An area less than 1/8 covered with echoes.
ISLTD	: Isolated solid mass of echo.

ECHO ALOFT : Echo seen only at elevations higher than half the beamwidth.

bbb : Azimuth in three digits (degrees) of points on the periphery of an echo area.

rrr : Range (three digits) in units of kilometres.

NOTES : (1) The groups within the brackets ( ) may be repeated as many times as necessary.

(2) In the case of line echoes, in spiral bands and eyewall, as many bbb/rrr points along the line as necessary may be given to define the shape of the line. The points should preferably be given along the line in the anticlockwise direction.

(3) In the case of areas, as many bbb/rrr points as necessary to define the shape may preferably be given in the anticlockwise order starting from the northernmost point. The first point should be repeated as the last point to indicate that it is a closed area.

(4) In any one RAREP message, the character of echoes .... will be reported in the order given in the group description above.

(5) If any echo system with a distinct characteristic is partly or wholly embedded in another, the two systems should be reported in separate groups. For example, a SPRL BND, or BRKN LN (which may be distinguished as such by using the attenuator or isoecho system) embedded in a larger area of echoes will be reported as SPRL BND or BRKN LN in addition to the area reported separately.

(6) The number of features or groups should be as few as possible, and should be just sufficient to convey an overall picture of the system.

Intensity :

Code	For radars having facility for quantitative measurement		Other radars
	dBZ	Approximate rainfall rate mm/hr.	
WK	23 to 32	less than 4	Qualitatively determined as in draft Weather Radar Manual
MDT	33 to 42	4 to 15	
STG	43 to 52	16 to 63	
VRY STG	53 or more	64 and above	

NOTES : (1) The intensity of the strongest echo in the group is to be reported.

(2) The rainfall rates indicated are based on the relationship $Z = 200\ R^{1.6}$ and may be taken only as a rough guide.

(3) Intensity is to be reported only of echoes within 200 km range.

Tendency :

INCG : Increasing
DCG : Decreasing
NO CHG : No change

In view of the difficulties in finding out the tendency of echoes of large areal extent as in a depression or cyclone, tendency should be reported only in case of isolated cells or groups of cells or a line mainly for aviation purposes. The radar meteorologist will take into consideration the change in height area, length and intensity of echoes over a period of time in judging the tendency.

$d_s d_s$: Direction in tens of degrees towards which the echo or group of echoes is moving.

$f_s f_s$: Speed in kilometres per hour of the echo or group of echoes.

NOTE : (1) In case of a group of echoes or of a line, only the overall movement of the group of echoes will be reported.

(2) The movement will be observed over a period of, say 30 to 60 minutes.

ALTD : Indicator for echo height information.

H_tH_t : Height of top of echo above mean sea level in kilometres.

NOTE : (1) Reports of heights should be restricted to a maximum range of 200 km from the station.

(2) In the case of echoes of large area, the height group may be repeated as necessary for including a number of prominent echoes.

The radar meteorologist will have discretion to report any other special phenomena such as Bright Band and Anomalous Propagation in plain language at the end of the message.

From DDGM(WF) UOI No.w-72010/ dt. Pune-5; the April 1989.

"As per the decision taken in the ACR meeting, 1989 held at Madras RMR (Radius of maximum radar reflectivity) will be reported by adding the word "RMR" followed by the radius in digits in kms at the end of CYREP message".

The following limitations which were pointed out by the Working Group on Reporting of Radius of Maximum Reflectivity are given below:

1. Radius of maximum reflectivity is only approximately equal to the radius of maximum winds and there could be a difference of a few kilometres.

2. In view of various sources of error in the determination of the radius of maximum reflectivity, it should be taken only as an approximate figure and not as an absolute value. These aspects may be kept in view by all forecasting offices.

3. RMR should be reported only when cyclone centre is within 200 km of the radar

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139.	Thomas S.I.T.	1973	"Heights of cumulonimbus cloud tops over the Deccan Plateau and adjoining plains of Andhra Pradesh and east Maharashtra - A preliminary radar study." Ind. J. Met. Geophys., 24, 2, 163-164.
140.	Thomas S.I.T. and Raghavendra V.K.	1977	"Heights of cumulonimbus cloud tops over the Deccan Plateau and adjoining plains of Andhra Pradesh and east Maharashtra - A radar study." Ind. J. Met. Hydrol. Geophys., 28, 4, 479-482.

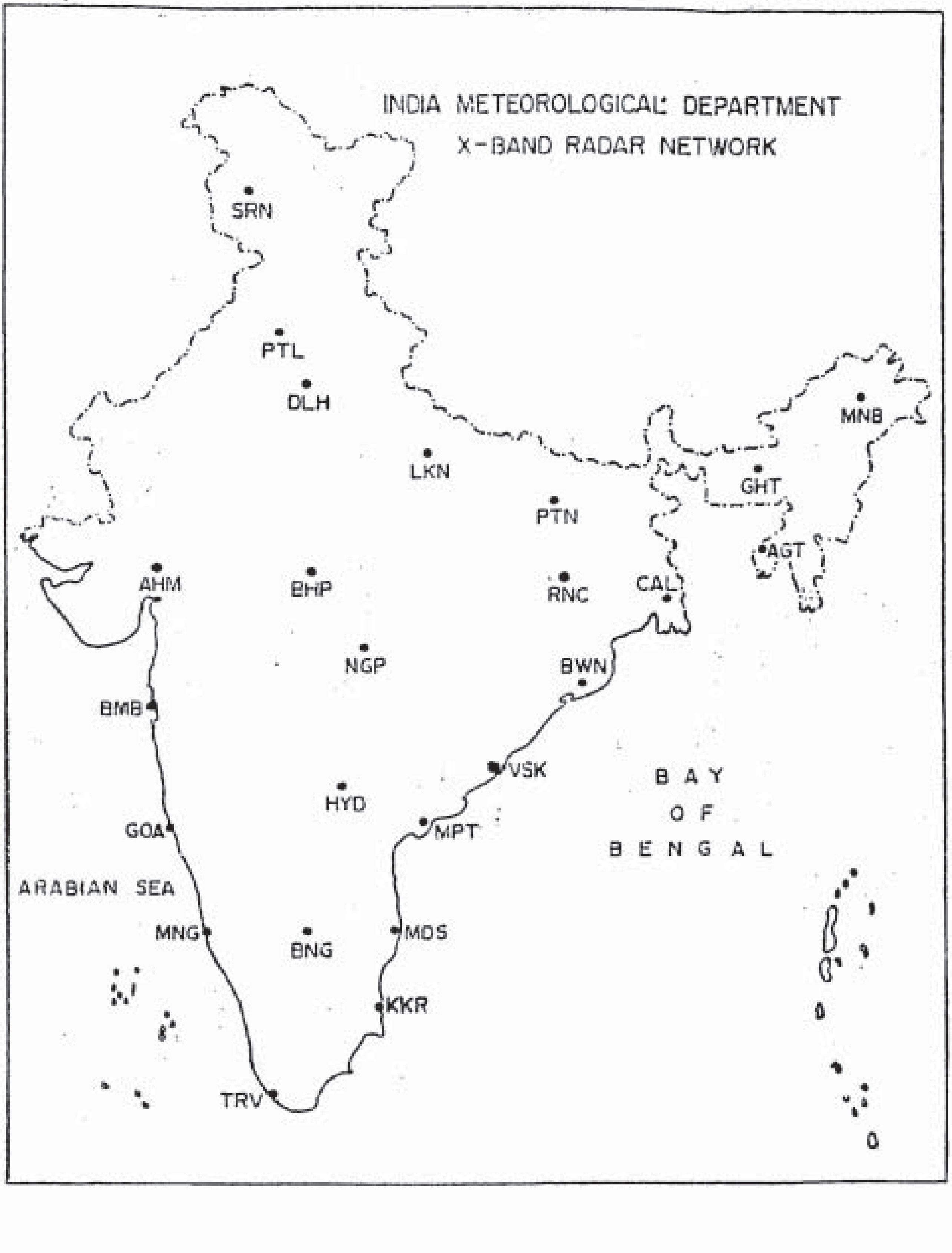
12. LEGEND FOR FIGURES

Fig. no.	Referred to in sections	Legend
1	1.3	Network of Weather Radars of IMD other than Cyclone Detection Radars
2	1.3	Network of Cyclone Detection Radars
3	2.1	Principle of Radar
4	2.1 2.2	Radar Displays
5	2.4 2.10.3 6.5	Sampling Volume and Averaging
6	2.6	Range-Height Diagram
7	2.7 2.9.1	Interception of Radar Beam by Precipitating Clouds at Various distances
8	2.8 3.7.2 3.7.6	Echoes from Ships and their reflection from a building
9	2.8	RHI echo of a Hill
10	3.2 4.2	PPI echoes from convective cells
11	2.10.3 3.2 4.2 5.3	RHI of convective cell (Grey shades correspond to 53, 43 and 23 dBZ)
12	3.3	PPI - Echoes from stratiform Precipitation
13	3.3 3.4	RHI - Echoes from stratiform Precipitation
14	3.4	As in Fig. 13 but with attenuation of 15 dB. Exhibiting Bright Band
15	2.10.3 3.5 4.4	Reflectivity Contours on PPI of cluster of echoes with convective and stratiform parts

16	3.4	RHI of a stratiform echo of Fig.15, showing bright band
17	2.10.3 3.2 3.5 5.3	RHI Grey scale range normalised picture showing horizontally oriented reflectivity contours in stratiform precipitation and vertically oriented reflectivity contours in convective precipitation
18	3.6.1 3.7.4	Offcentred PPI picture showing Anomalous Propagation. Andhra Pradesh and Orissa coasts and second time around echo of Burma coast can be seen
19	3.6.2	Seabreeze front seen as a thin line echo parallel to the coast
20	3.6.3	Sea clutter southeast of the radar (Surface winds were southeasterly)
21	3.7.1	Ground clutter. The echoes to the northwest are hills
22	4.4 7.2	Squall line about 400 km long
23	4.4	Line of convective cells
24	4.4	As in Fig.23 but at isoecho level 1 (threshold about 28 dBZ)
25	4.4	As in Fig.23 but half an hour later
26	4.4	As in Fig.24 but half an hour later
27	4.5	Hook echo from a hailstorm southwest of Delhi
28	4.8	PPI echo from a Duststorm
29	4.8	RHI corresponding to Fig.28
30	2.10.3 6.7	Digital Video Display during a cyclone. (The radar site is at the centre. Each square is 10 km x 10km. 8 shades of grey correspond to rainfall rates from 2 to over 128 $mm.hr^{-1}$.

31	6.7	Digital Print out of rainfall rates corresponding to Fig.30. The numbers (2 to 8) in each square (10km x 10km) represent rainfall rates of 1, 2, 4, 8, 16, 32, 64 $mm.hr^{-1}$. The blank squares on the southern eyewall depict rainfall over 128 $mm.hr^{-1}$ Dots represent 0 to 1 $mm.hr^{-1}$. Blank squares at centre contain ground clutter and rainfall is not computed. Listing below map shows cumulative rainfall in mm. over selected squares.
32	7.1	Radar echoes from a tropical cyclone (This is a composite of several cyclones)
33	7.4	Estimation of Cyclone Centre by Spiral Overlay - Example
34	7.4	Spiral bands in a developing cyclone before eye formation
35	7.5 7.9	Cyclone over land showing eye (15 August 1974 Calcutta Radar)
36	7.5	Cyclone 11 November 1977 showing eyewall as an extension of a spiral rainband
37	7.5	Cyclone of Fig.36 about 6 hours later showing small eye distinct from the spiral bands
38	7.5	Cyclone 18 November 1977 exhibiting double walled eye
39	7.5	Cyclone 13 November 1984
40	2.10.3 7.4 7.5	Same cyclone as Fig.39 Iso echo picture threshold level 42 dBZ
41	2.10.3 7.4 7.5	Same as Fig.40 but threshold level 37 dBZ

FIG. I



INDIA METEOROLOGICAL DEPARTMENT
X-BAND RADAR NETWORK
SRN
PTL
DLH
LKN
PTN
MNB
GHT
AGT
AHM
BHP
RNC
CAL
NGP
BWN
BMB
VSK
HYD
MPT
GOA
BAY OF BENGAL
ARABIAN SEA
MNG
BNG
MDS
KKR
TRV

INDIA METEOROLOGICAL DEPARTMENT

CYCLONE DETECTION RADAR NETWORK

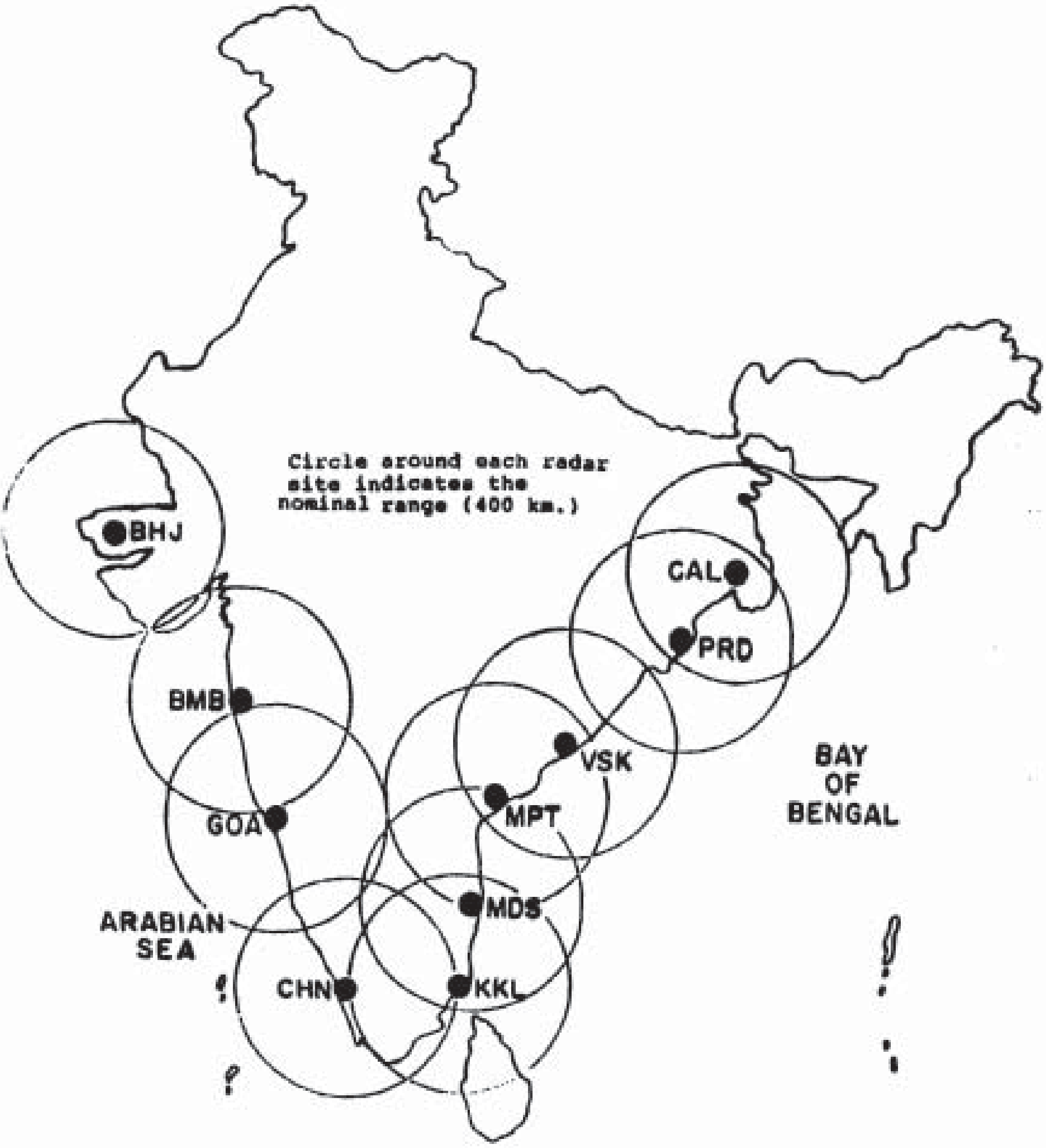


FIG. 7

PRINCIPLE OF RADAR

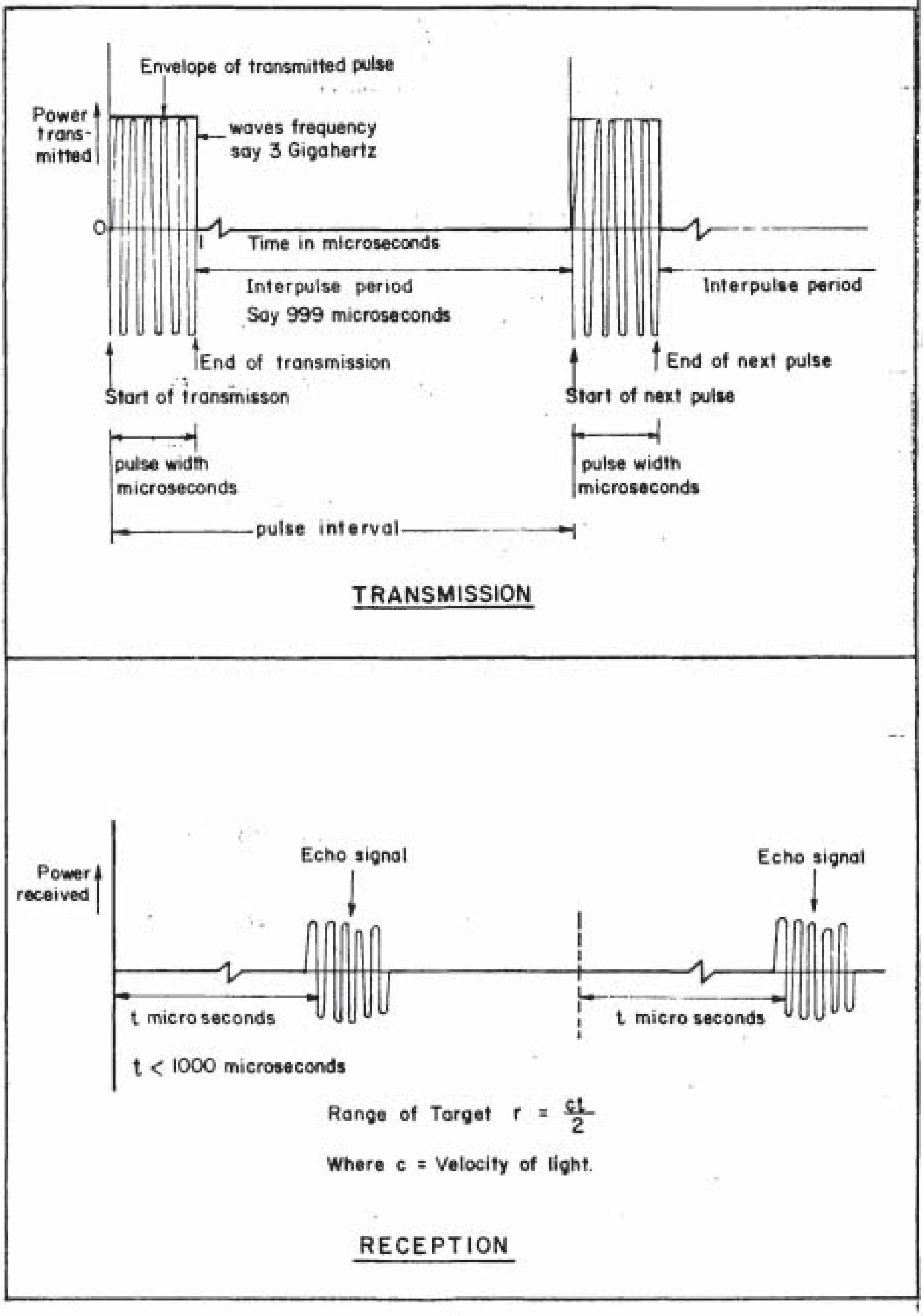
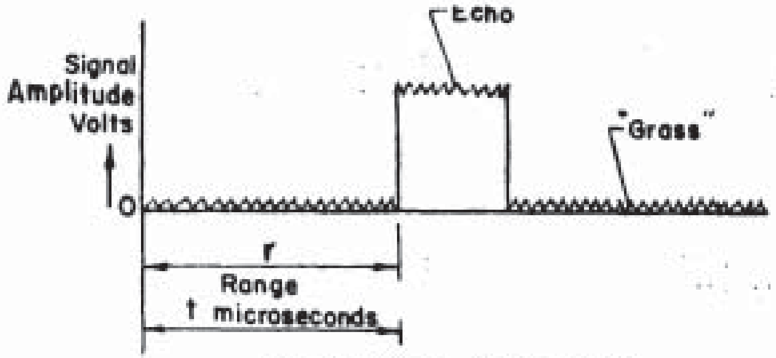
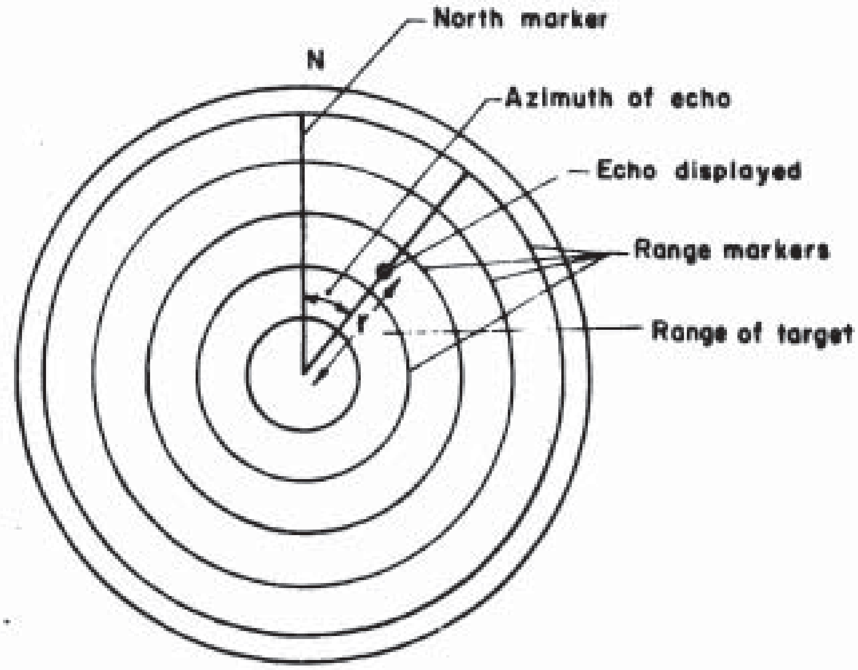


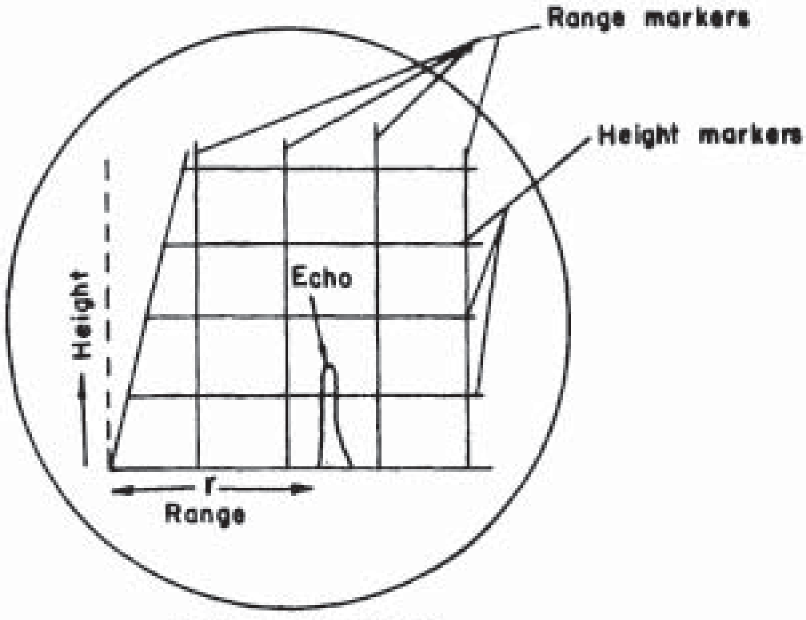
FIG. 3.



A - SCOPE DISPLAY

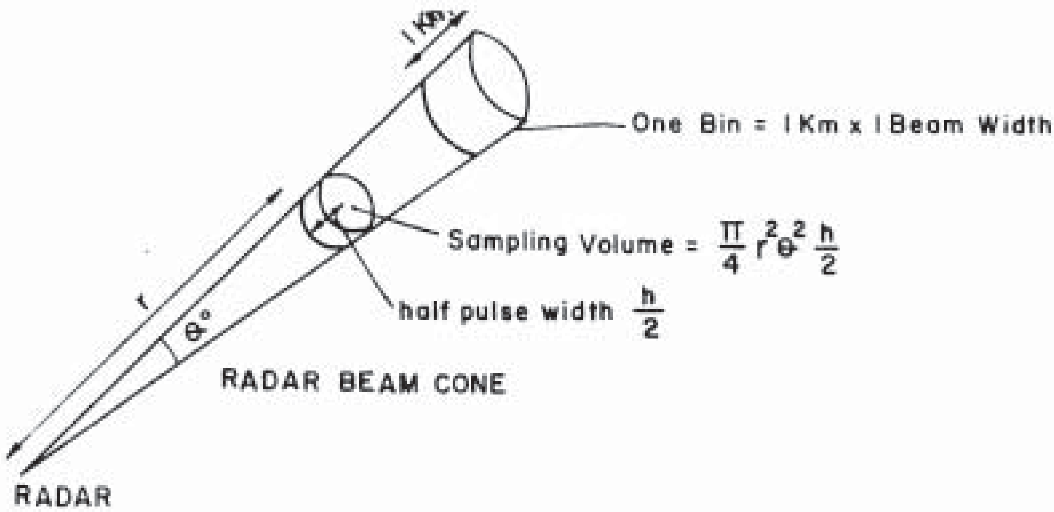


PPI DISPLAY



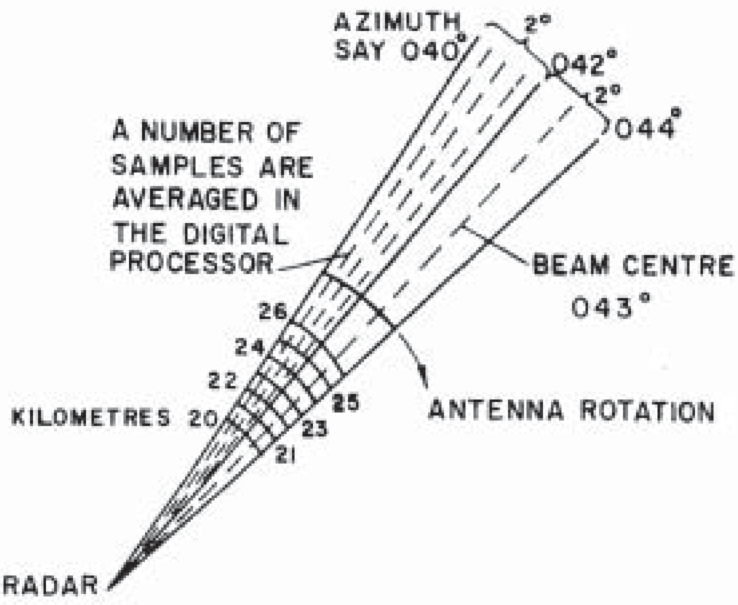
RHI DISPLAY

FIG. 4.



LET

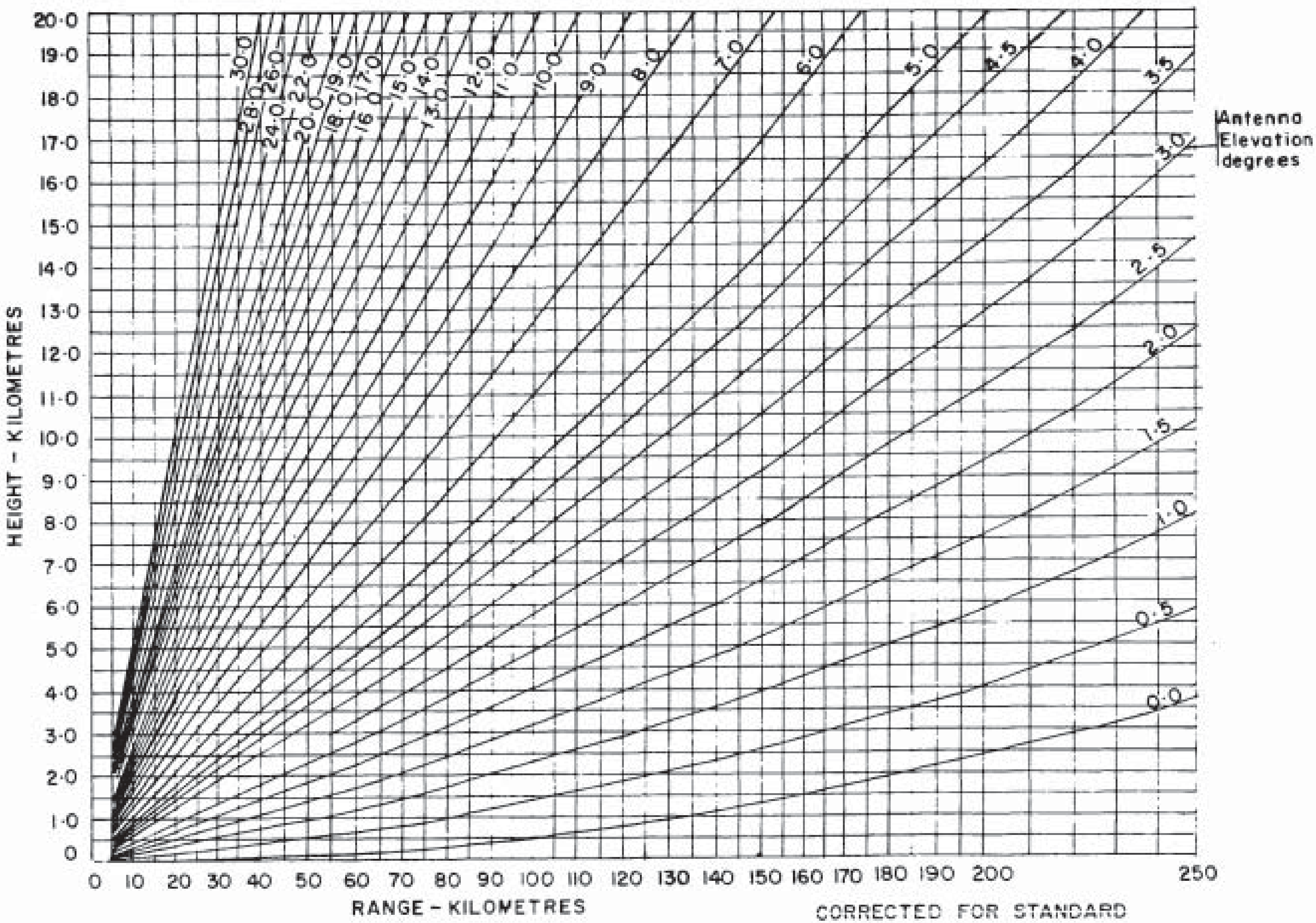
p.r.f . . . . = 900 per sec.
rate of revolution of antenna = 3 revolutions per minute
i.e. 20 seconds per revolution
Radar beam width θ . . . . = 2°
Antenna traverses one beamwidth in $\frac{2}{360} \times 20$ sec.
In this period $\frac{2}{360} \times 20 \times 900$ = 100 pulses are transmitted



Hence it is possible to get several samples (100 in this case) of the echo from each sampling volume and average these in the radar receiver by hardware circuits or better through software in computerised equipment. This average gives a more representative value of the signal than taking a single sample. Averaging is necessary because the radar signal from precipitation fluctuates considerably.

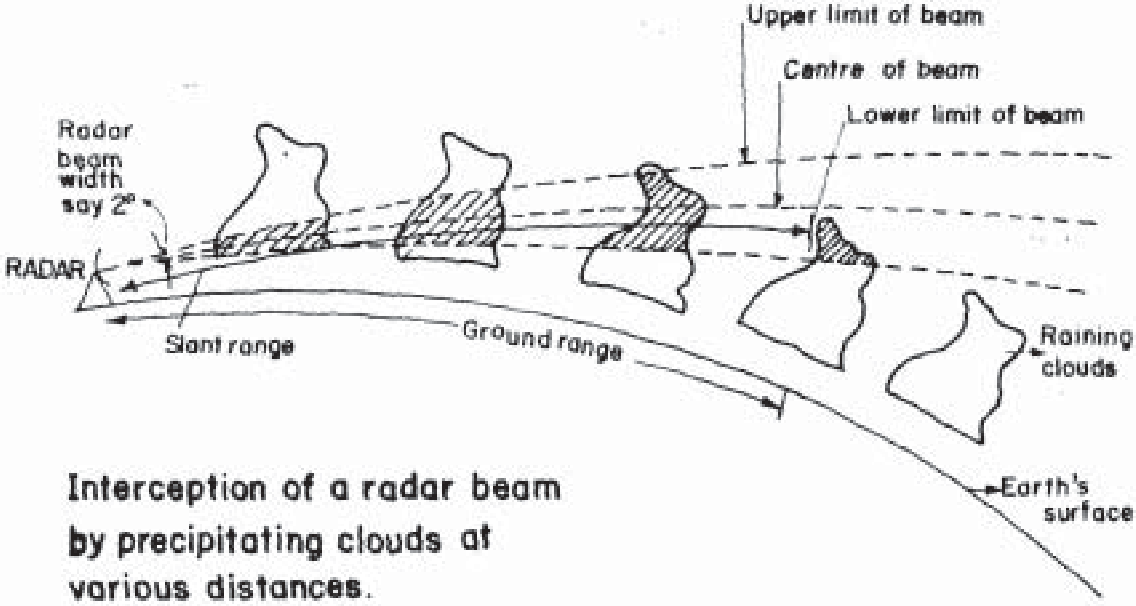
In digital equipment averaging is done in range also over a range interval of 1 or 2 Km. Thus if 1 Km. covers say 2 sampling volumes the total number of samples averaged over one range-azimuth BIN is 2 x 100 = 200

SAMPLING VOLUME AND AVERAGING



CORRECTED FOR STANDARD REFRACTION BY TAKING EFFECTIVE EARTH RADIUS = $\frac{4}{3} \times 6371$ KM

Fig. 6.



Interception of a radar beam by precipitating clouds at various distances.

FIG.7.

ECHOES FROM SHIPS AND THEIR REFLECTIONS FROM A BUILDING

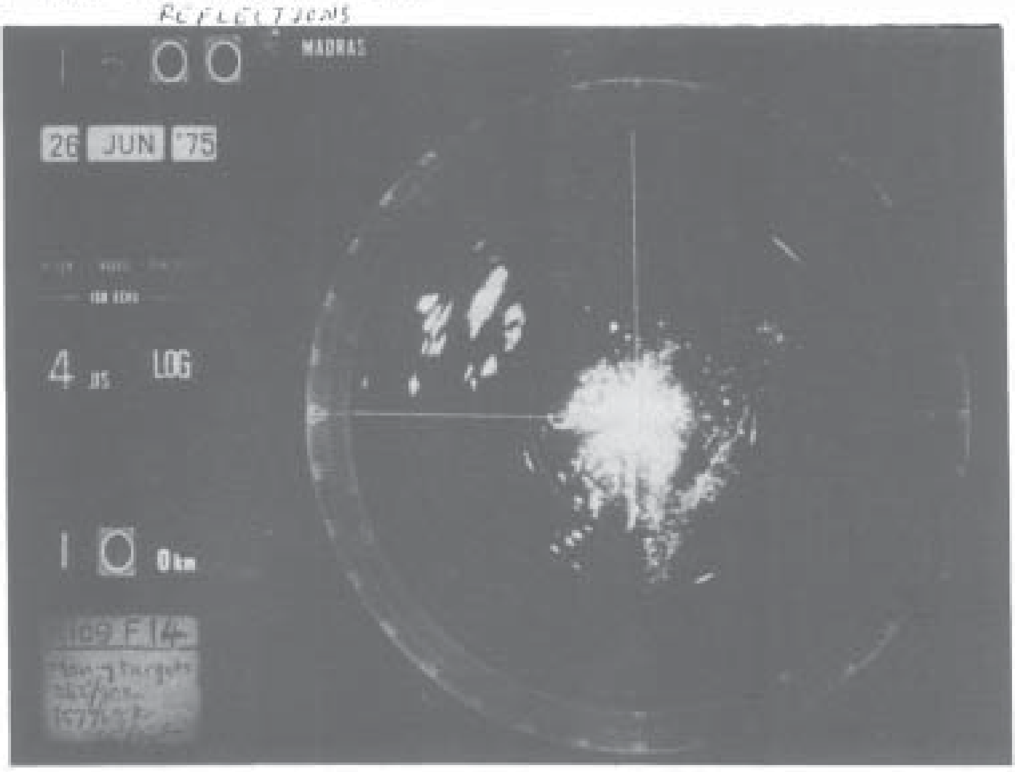


Fig.8.

RHI ECHO OF A HILL

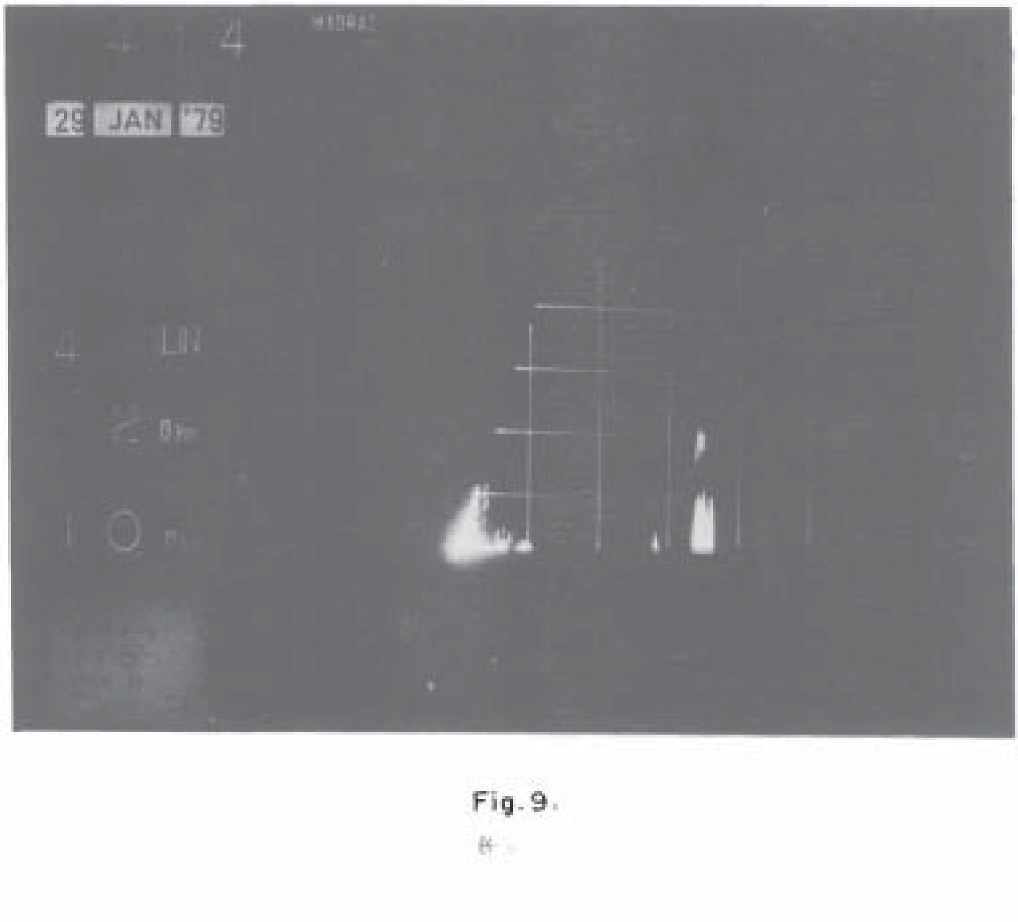


Fig.9.

PPI CONVECTIVE CELLS

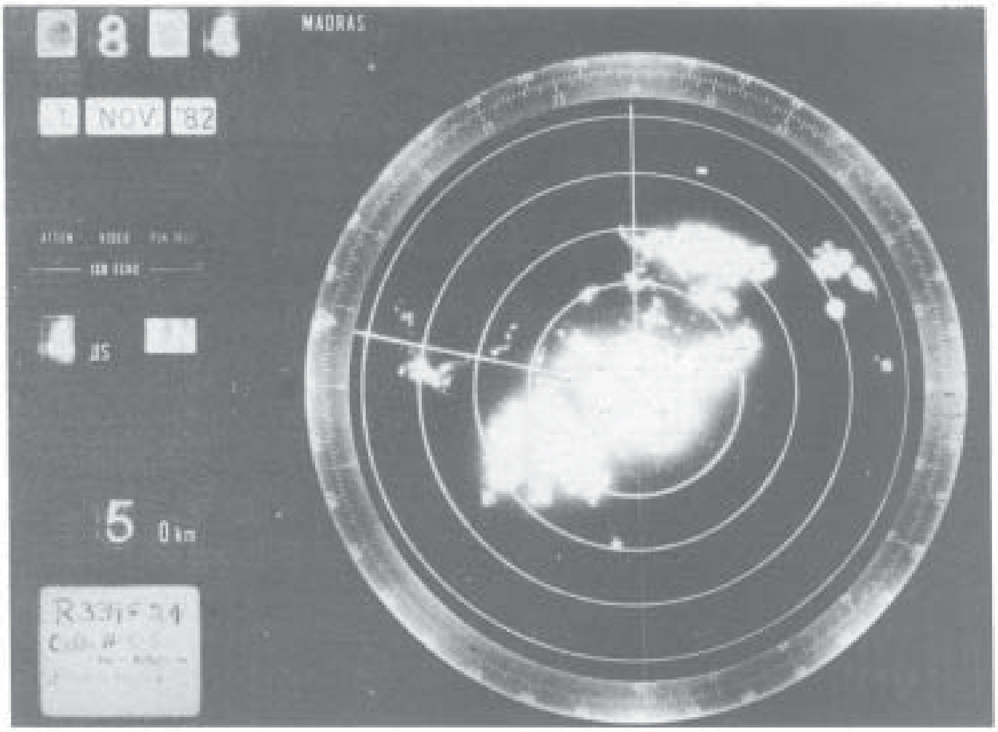


Fig.10.

RHI CONVECTIVE CELL

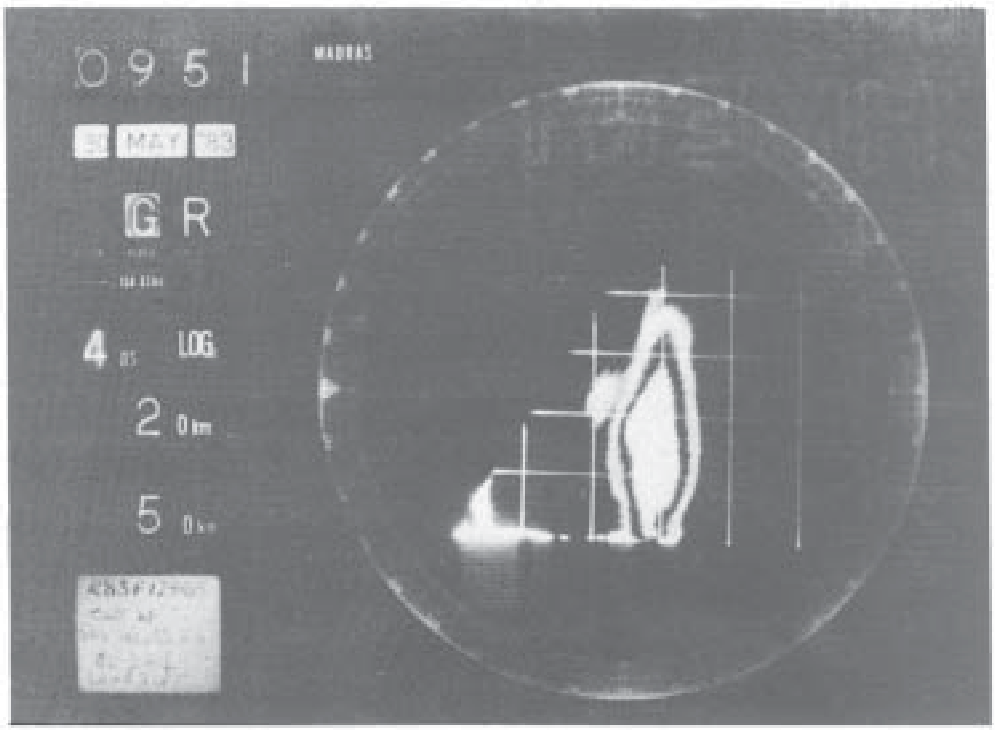


Fig.11.

PPI STRATIFORM PRECIPITATION

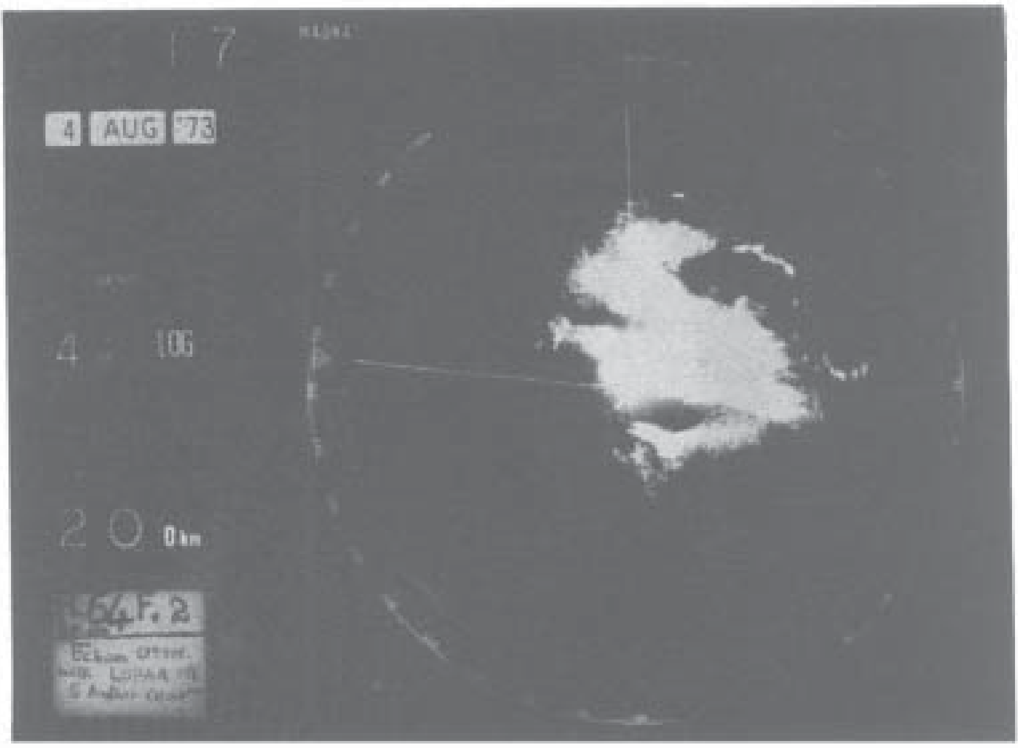


Fig.12.

RHI STRATIFORM PRECIPITATION

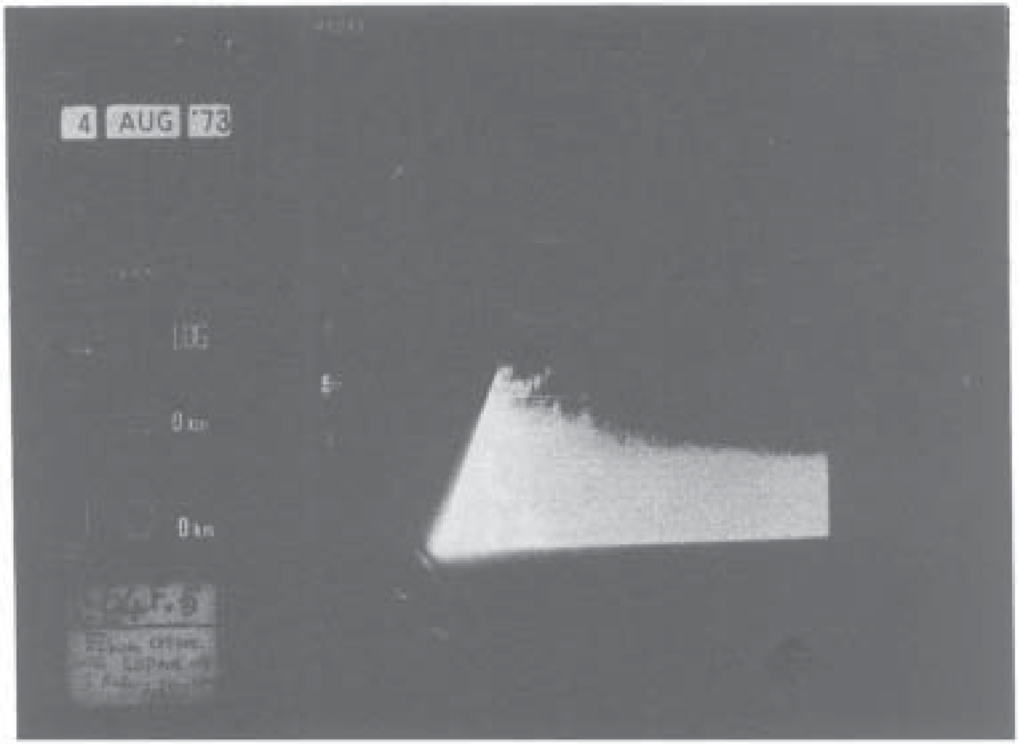


Fig.13.

RHI STRATIFORM BRIGHTBAND

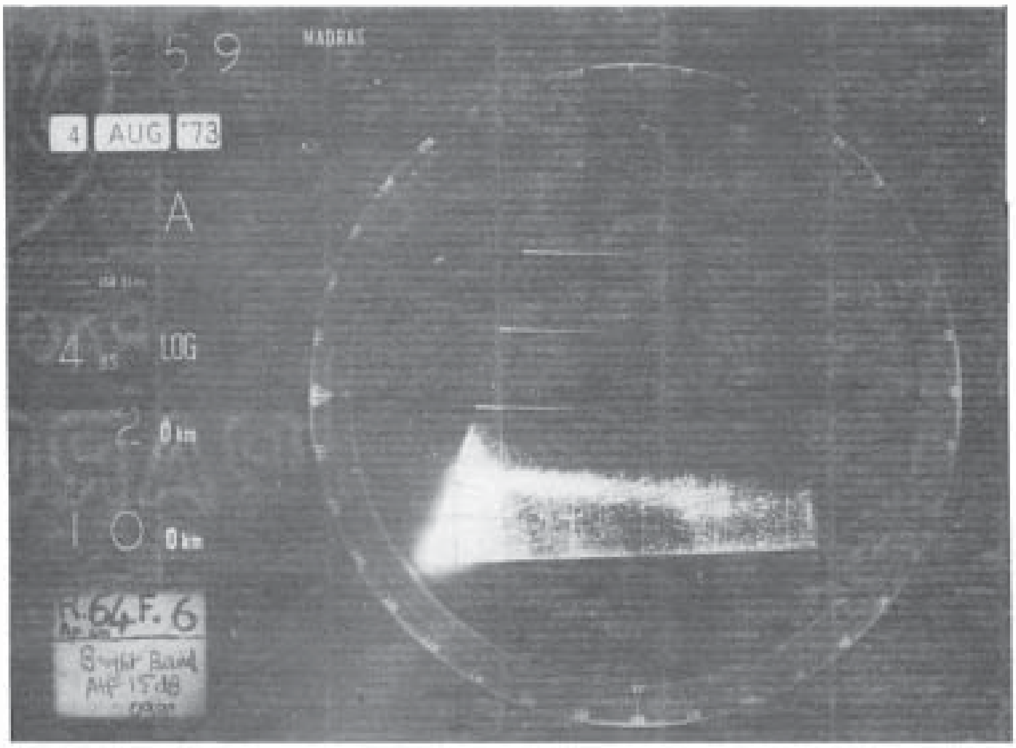


Fig. 14.

RHI STRATIFORM BRIGHT BAND

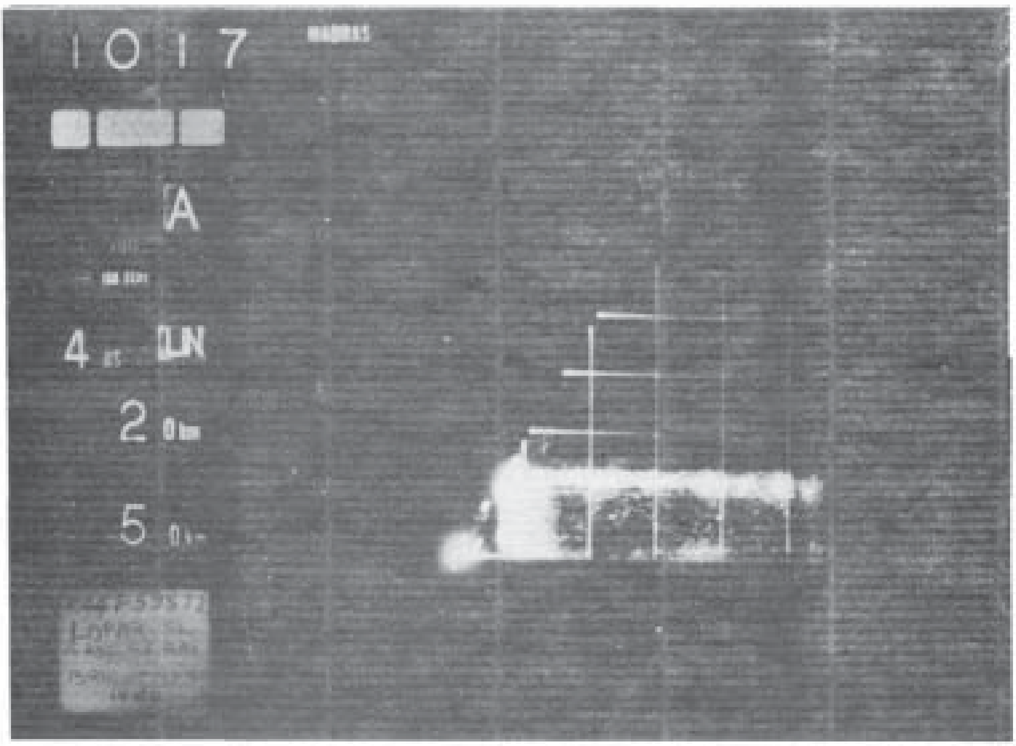


Fig. 16.

REFLECTIVITY CONTOURS OF A CLUSTER OF ECHOES WITH CONVECTIVE AND STRATIFORM PARTS

MADRAS RADAR

DATE : 15-11-79. RANGE : 500 Km.

TIME IST : 1039.

○ REFLECTIVITY THRESHOLD ~ 20 dBZ.

● REFLECTIVITY THRESHOLD 44 dBZ.

⊘ REFLECTIVITY THRESHOLD 34 dBZ.

BRIGHT BAND WAS OBSERVED IN DIRECTIONS A, B, C UPTO 50KM RANGE.

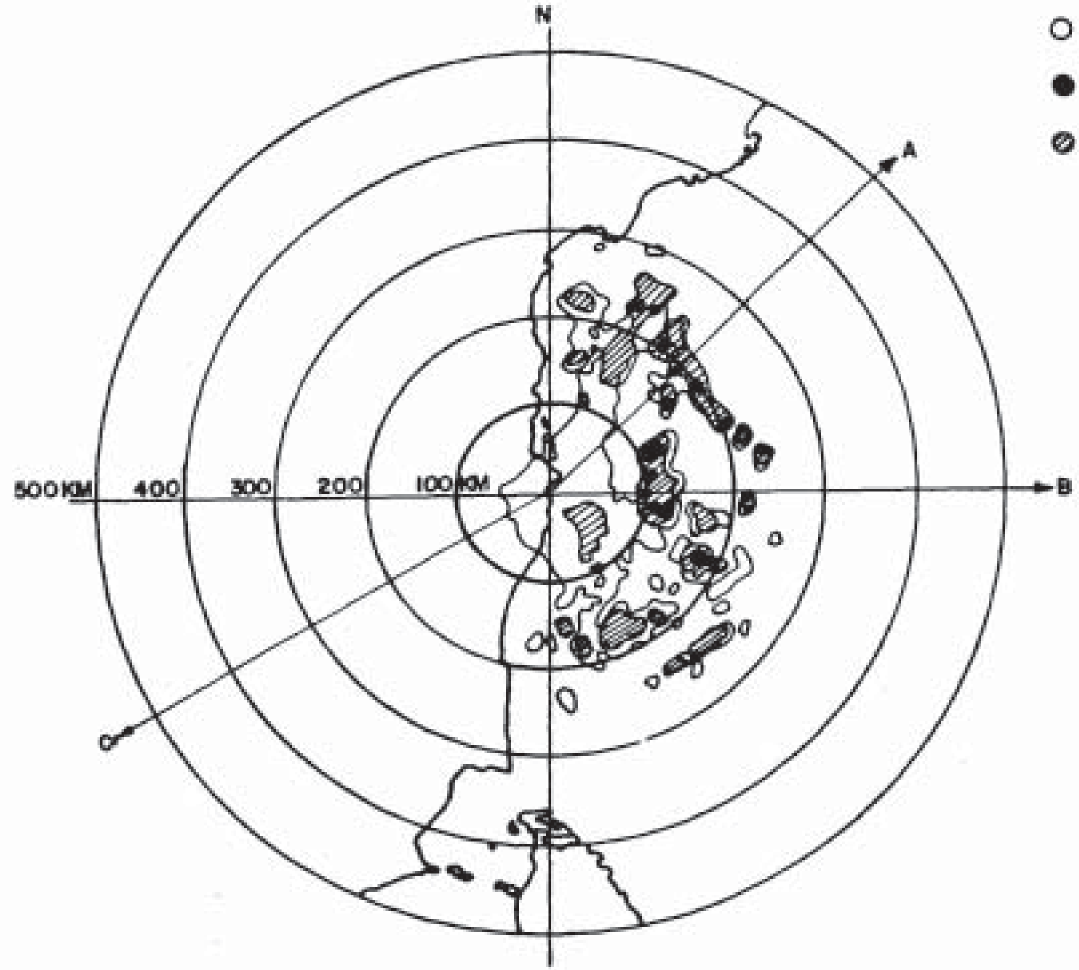


FIG. 15.

RHI _ GREY SCALE STRATIFORM AND CUMULIFORM CLOUDS

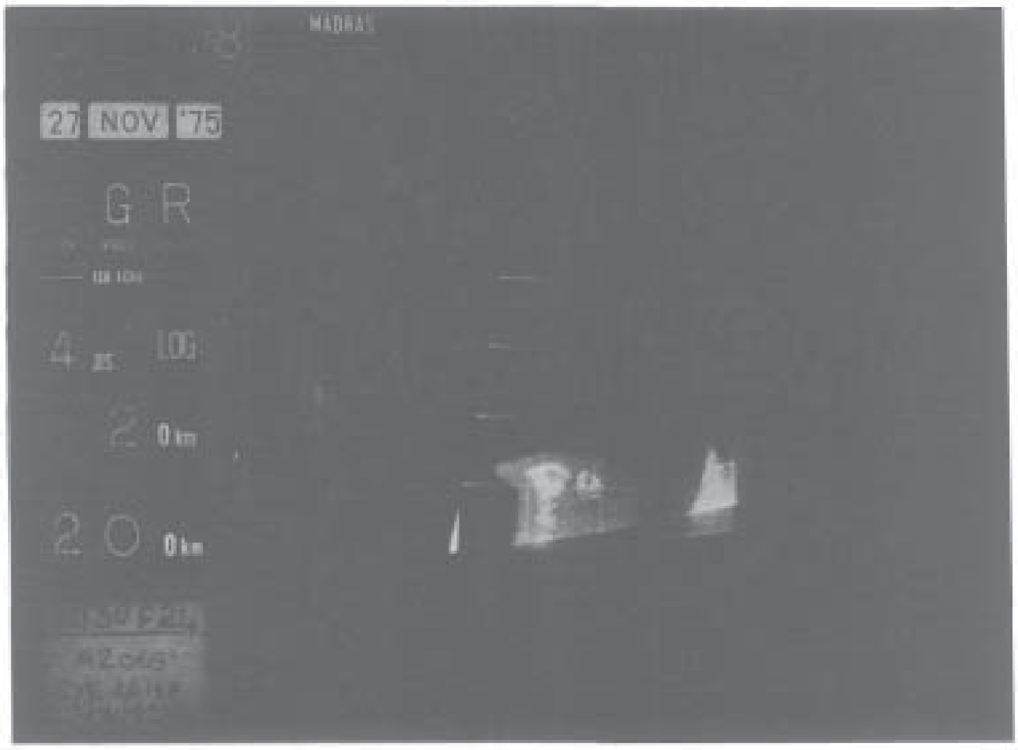


Fig. 17.

ANOMALOUS PROPAGATION ! ANDHRA, ORISSA AND SECOND TIME AROUND ECHO OF BURMA COAST

OFF CENTRED PPI

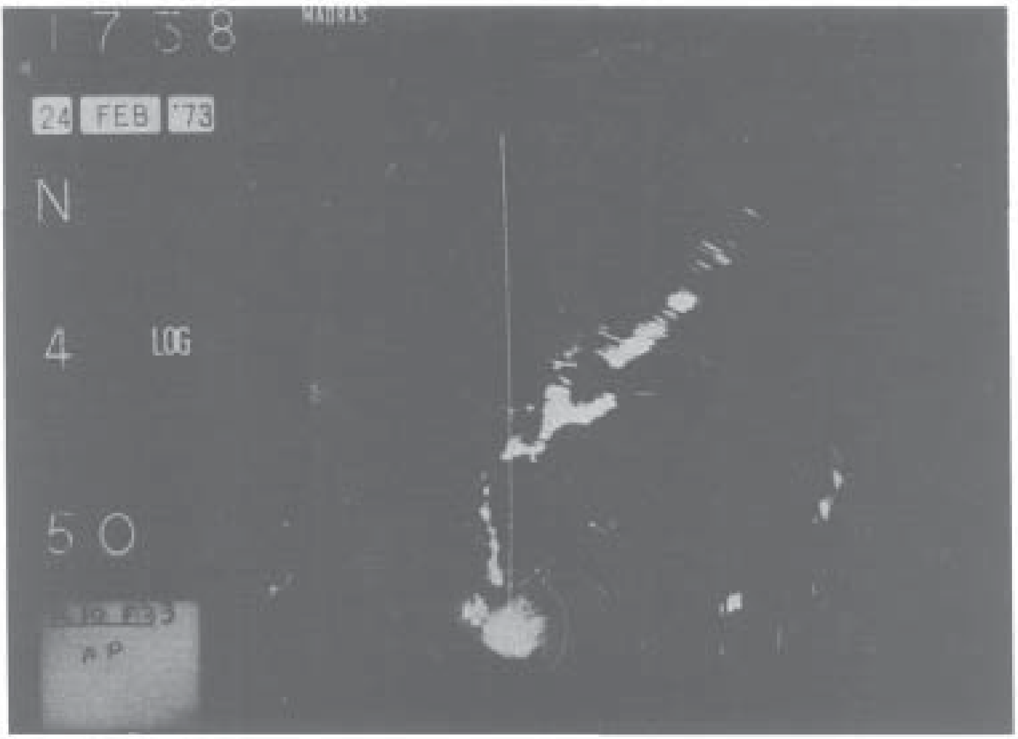


Fig. 18.

SEA BREEZE FRONT SEEN AS THIN LINE ECHO
PARALLEL TO THE COAST

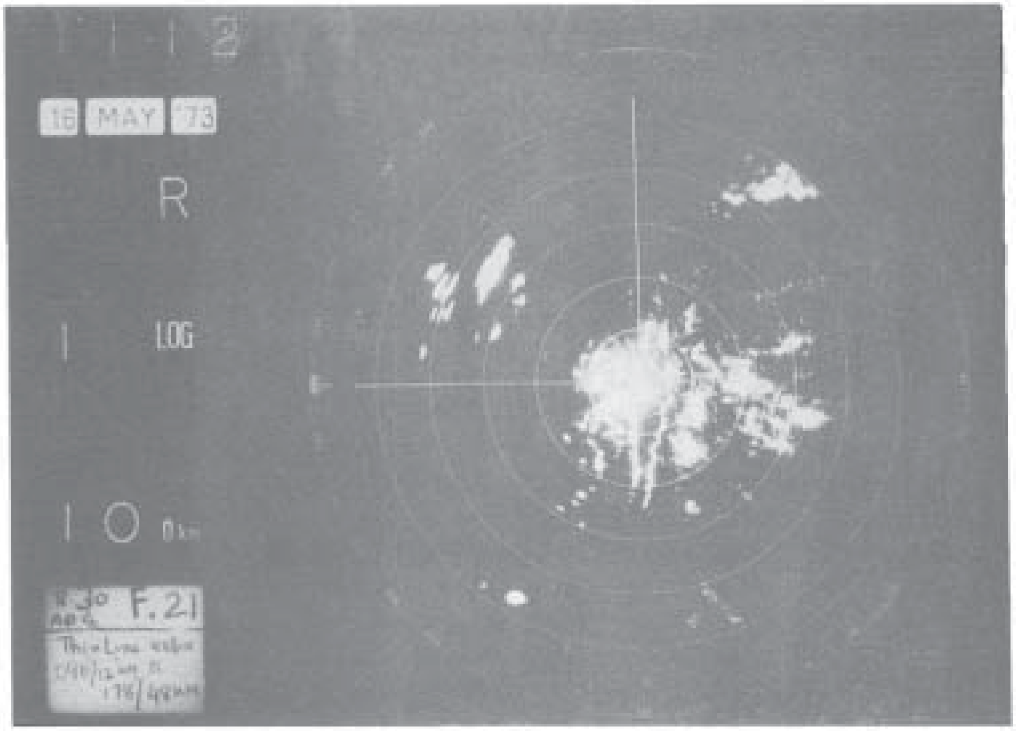


Fig.19.

SEA CLUTTER SOUTHEAST OF THE RADAR

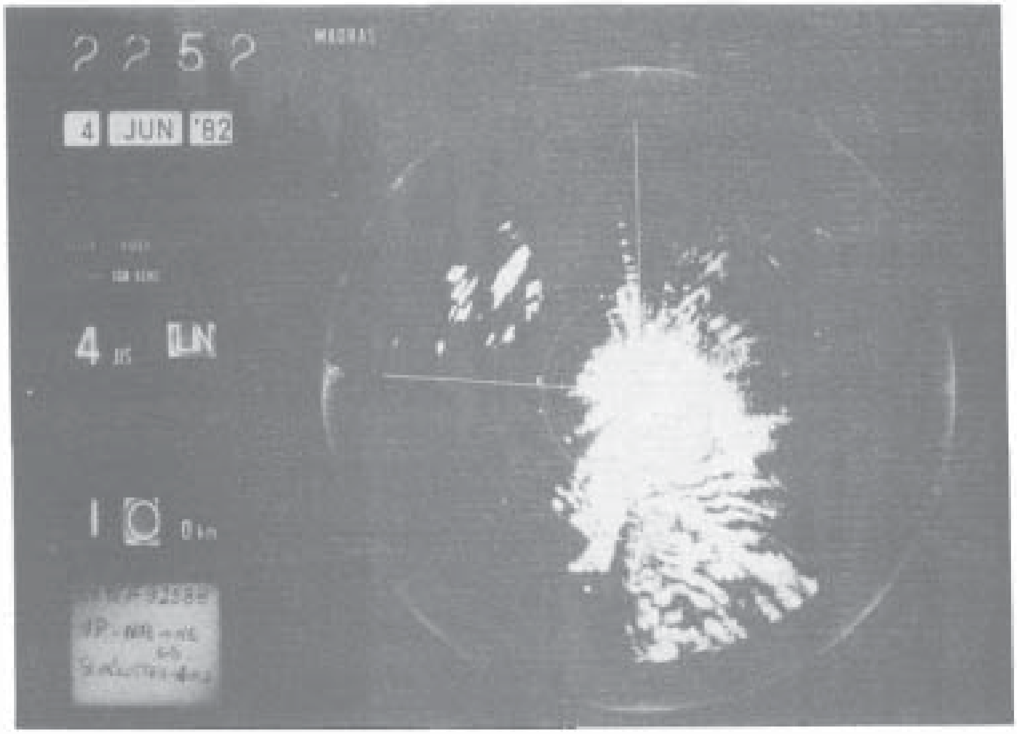


Fig.20.

GROUND CLUTTER; ECHOES TO THE NORTHWEST ARE HILLS

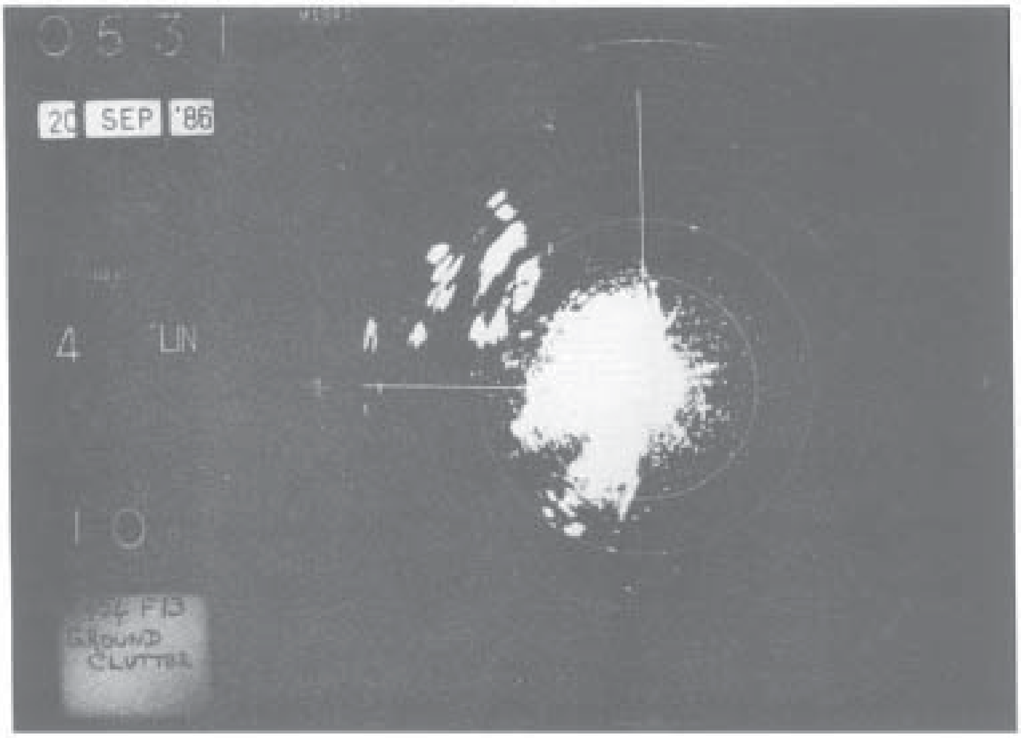


Fig.21.

SQUALL LINE ABOUT 400 km LONG

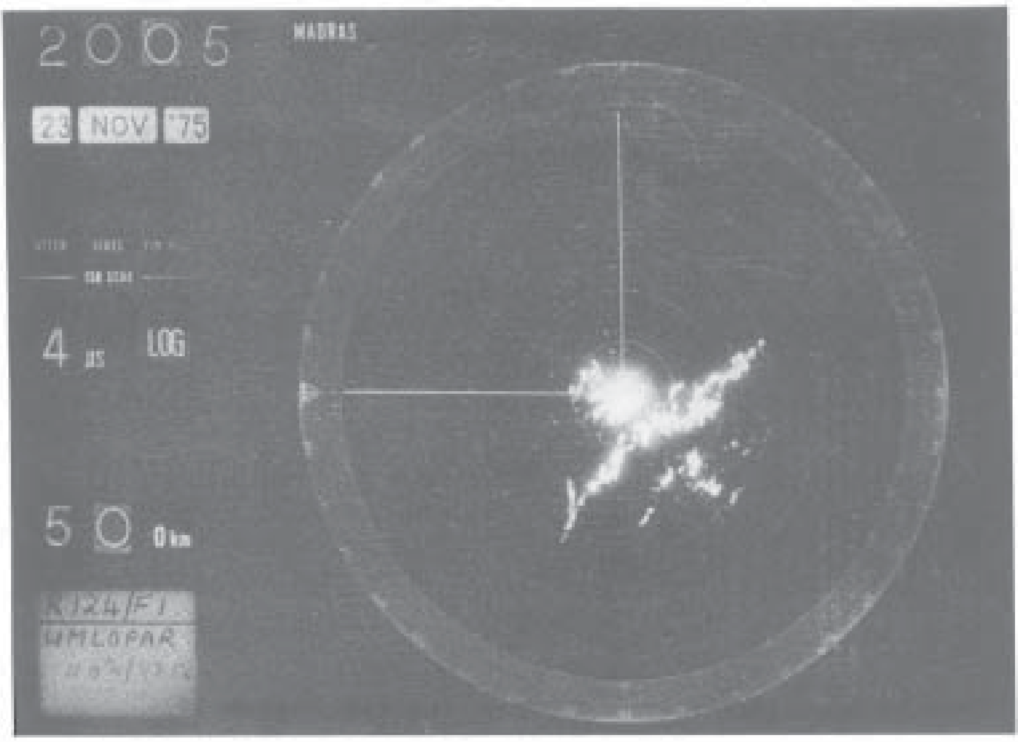


Fig.22.

LINE OF CONVECTIVE CELLS

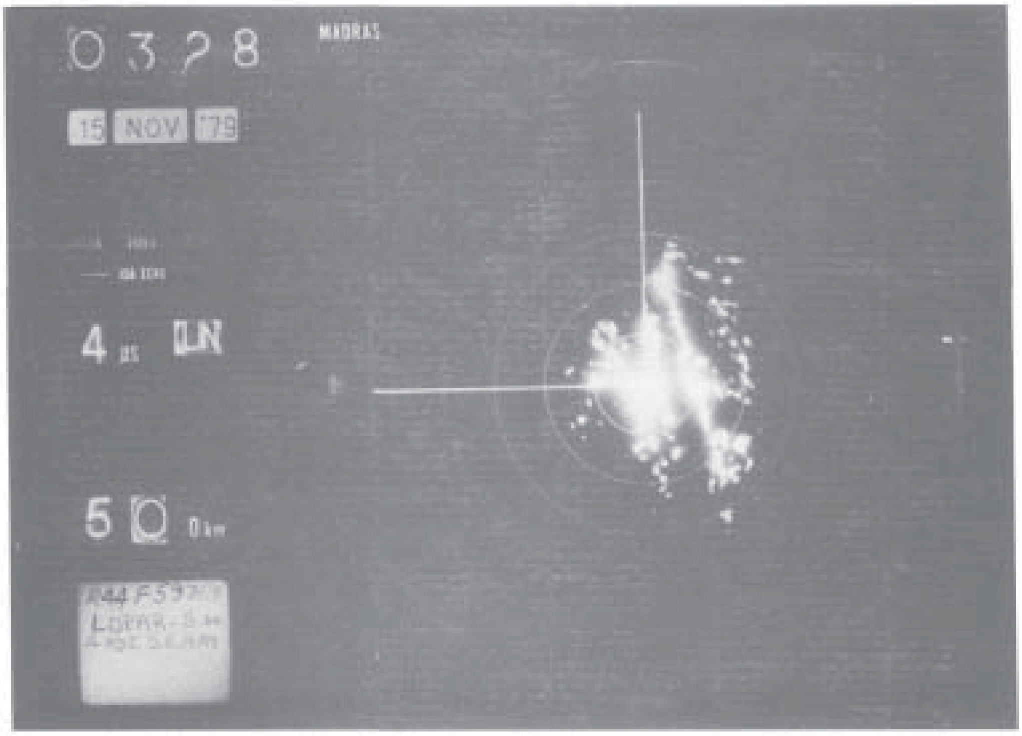


Fig.23.

LINE OF CONVECTIVE CELLS AT ISOECHOLEVEL
1 (Threshold about 28 dBZ)

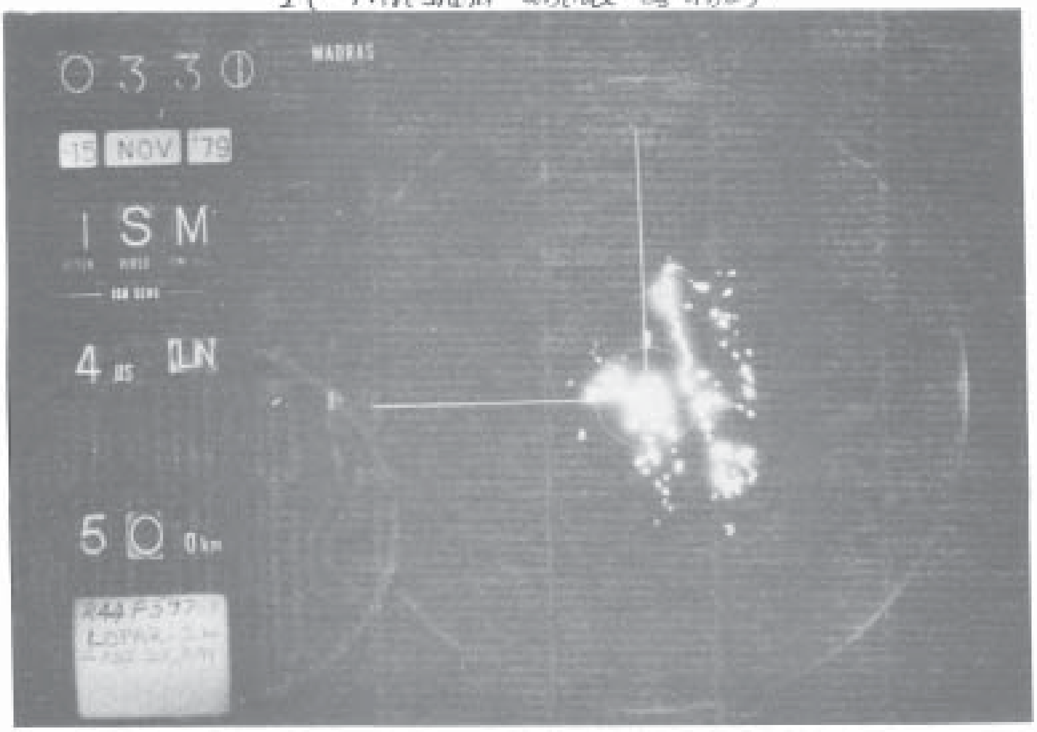


Fig.24

LINE OF CONVECTIVE CELLS - HALF AN HOUR
AFTER THE TIME OF FIG 23

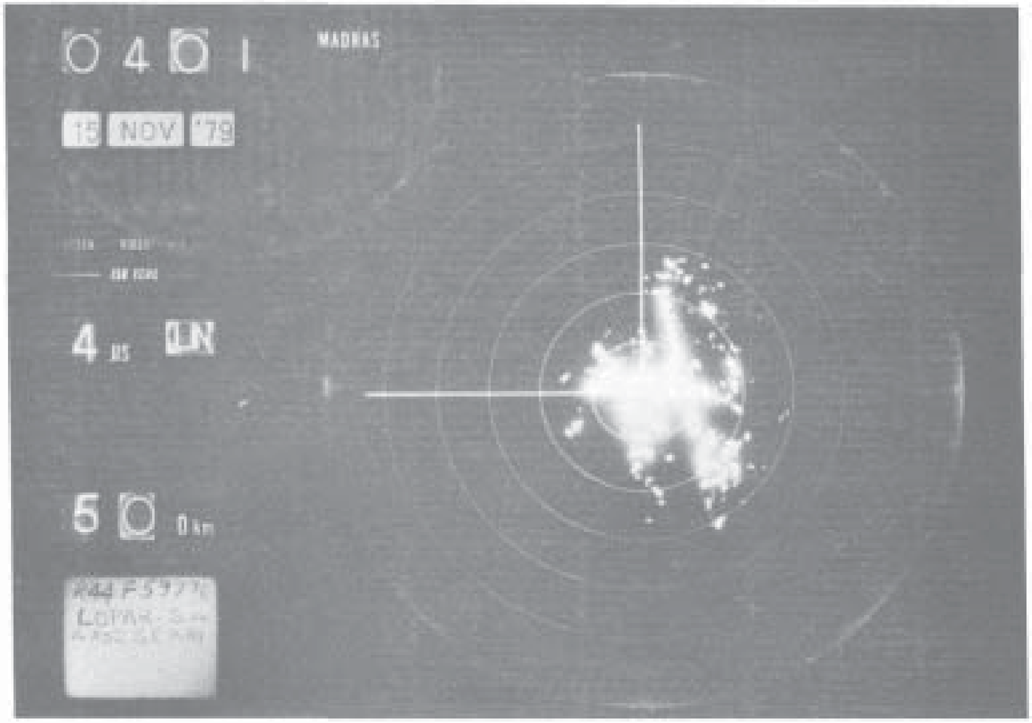


Fig.25.

AS IN FIG ~~25~~ 24 BUT ~~AT ISOECHO LEVEL~~ HALF AN HOUR LATER

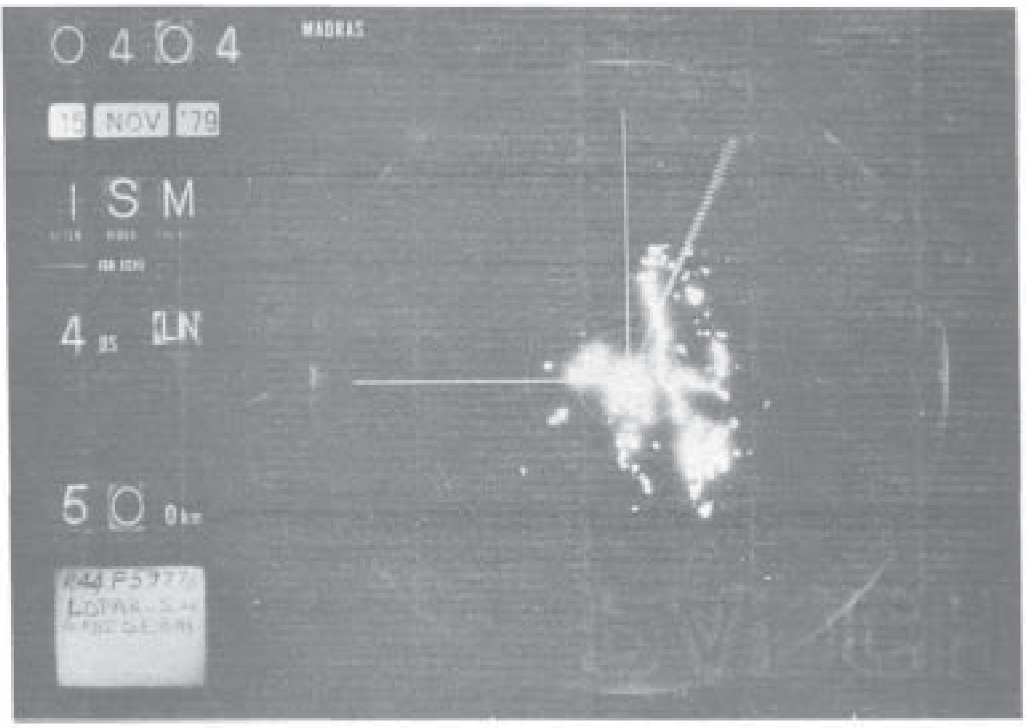


Fig.26.

HOOK ECHO FROM A HAILSTORM SOUTH~~EAST~~WEST OF DELHI

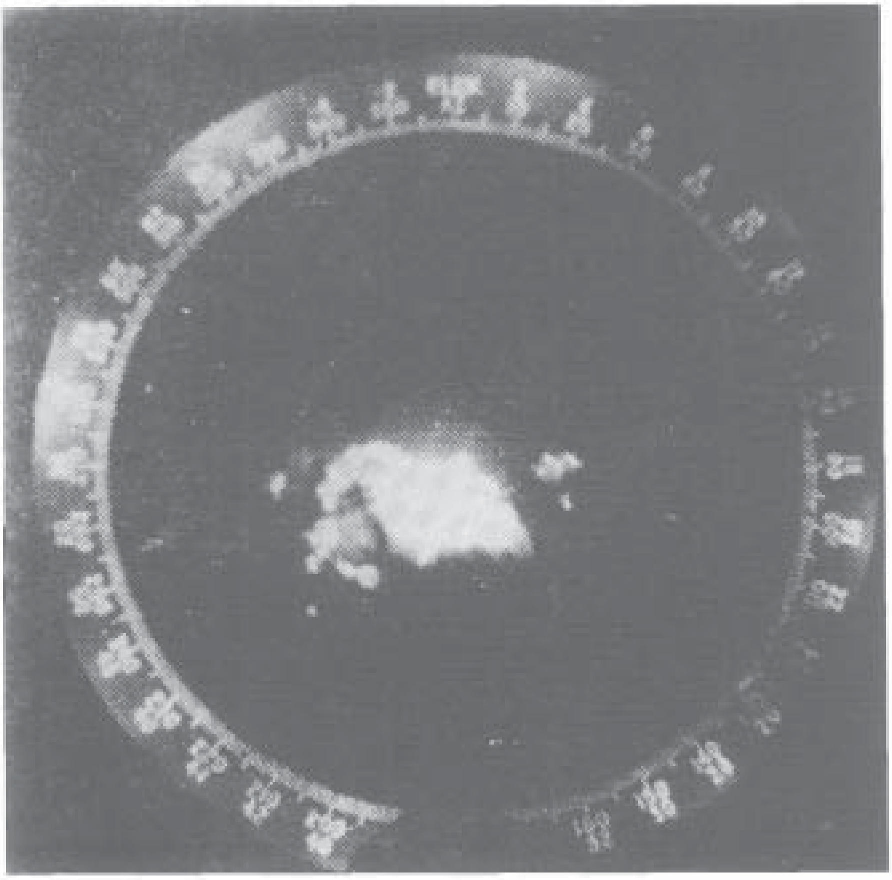


Fig.27.

PPI ECHO FROM A DUSTSTORM

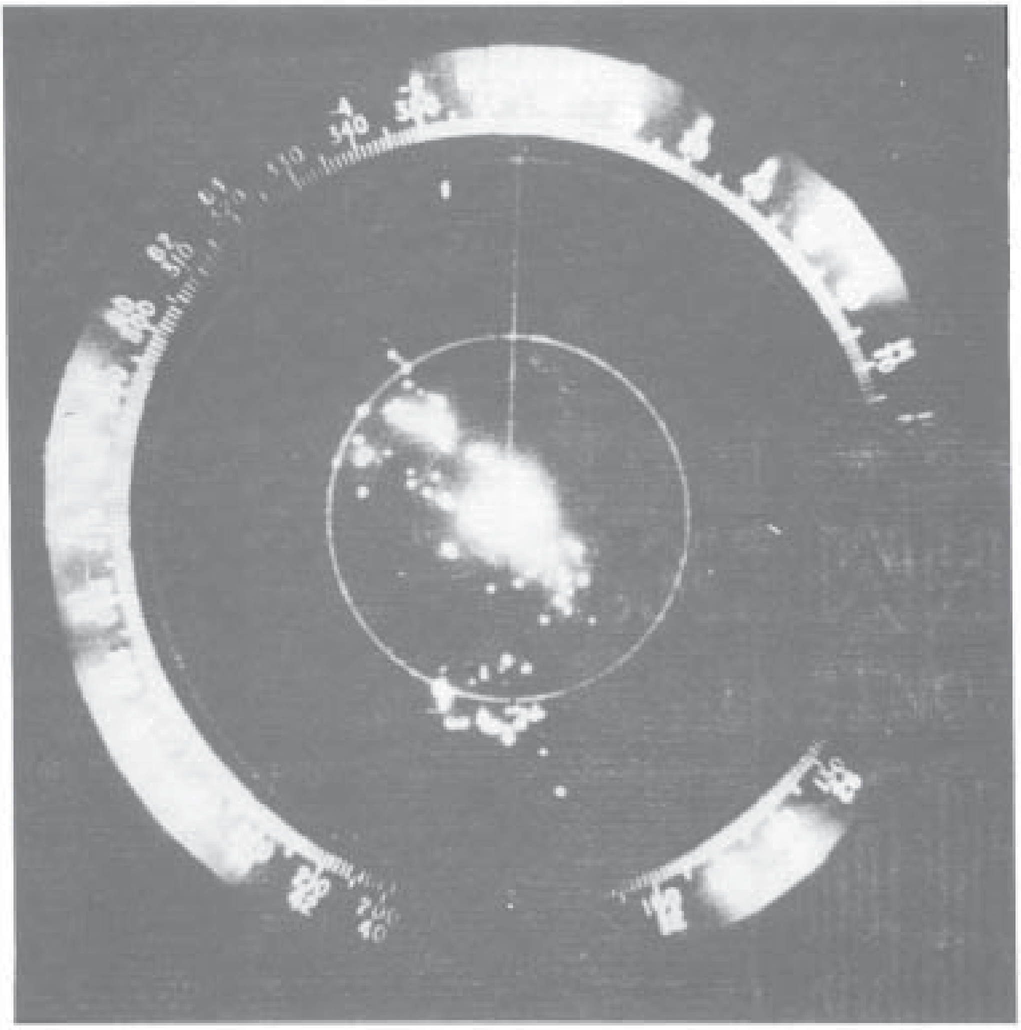


Fig. 28.

RHI CORRESPONDING TO FIG. 28 DUSTSTORM

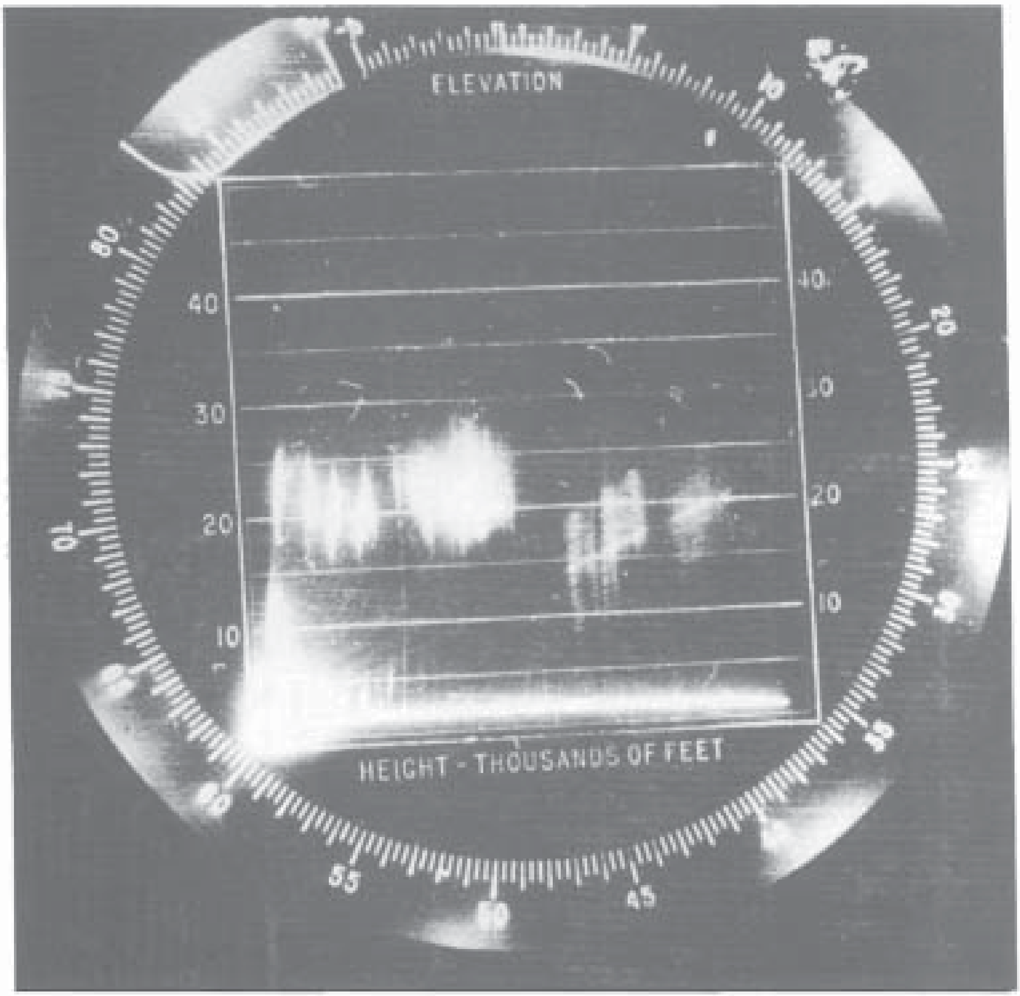


Fig.29

DIGITAL VIDEO DISPLAY DURING A CYCLONE

RADAR ~~16~~ IS AT THE CENTRE EACH SQUARE = 10 ~~Rm~~ km x 10 km

8 SHADES OF GREY CORRESPONDING TO RAINFALL RATES 2 ~~TO 128~~ TO OVER ~~min~~ mm/hr.

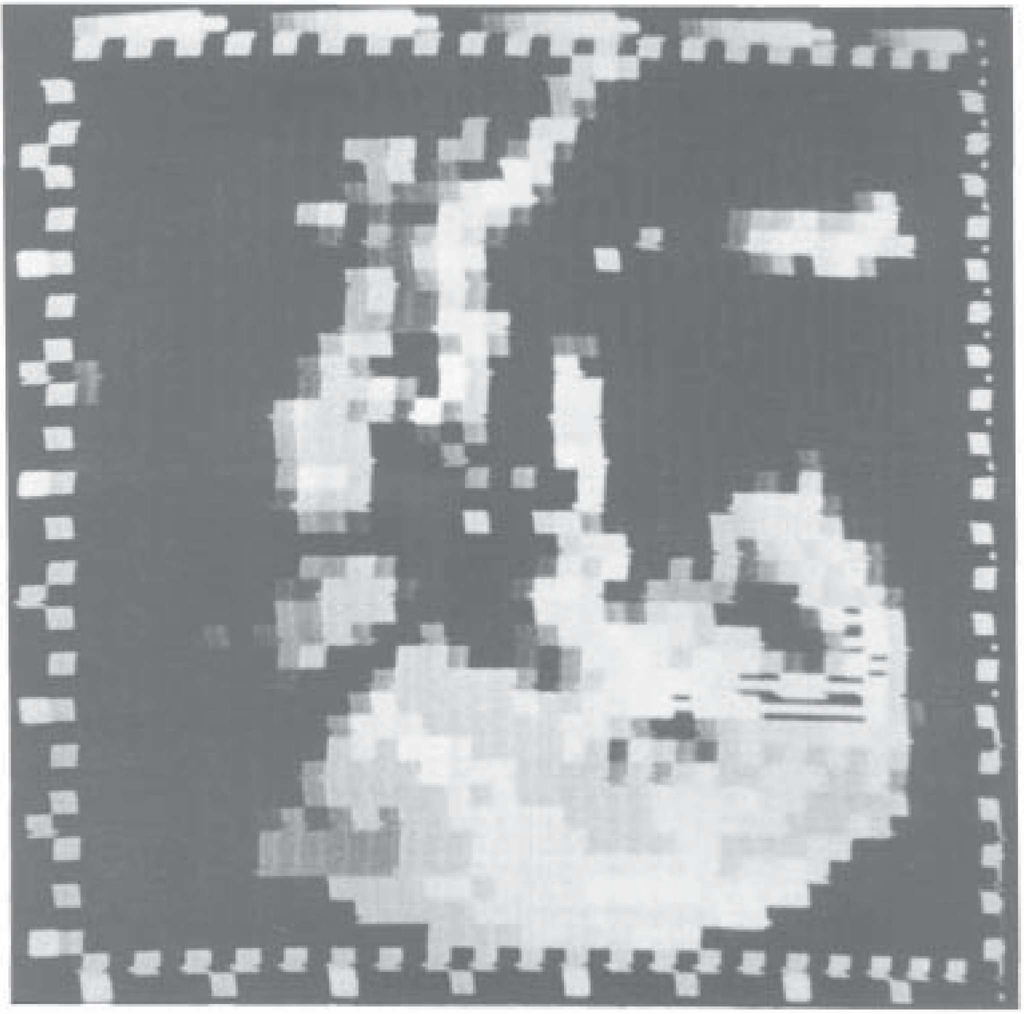


Fig. 30.

STATUS: AREA WEIGHTED RAINFALL AVERAGING
STATUS: QUANTISATION AND DISPLAY

JAN
LP
AK = 0.01 BETA = 1.20 B = 32.00 PT = 5.24 HEAD LOSS = 7.20
ELEVATION RECORDED = 0.79
(-105.00, 22.50) (-90.00, 112.77) (-70.00, 137.05) (-25.00, 244.75)

DATE : 18 OCT.82 TIME: 09.15.09 Operator:VR Meteorologist:SR

~~STATUS: INTEGRATED RAINFALL FOR SELECTED CELLS~~

STATUS: INTEGRATED RAINFALL FOR SELECTED CELLS

INTEGRATED RAINFALL 15 MINUTES FOLLOWS

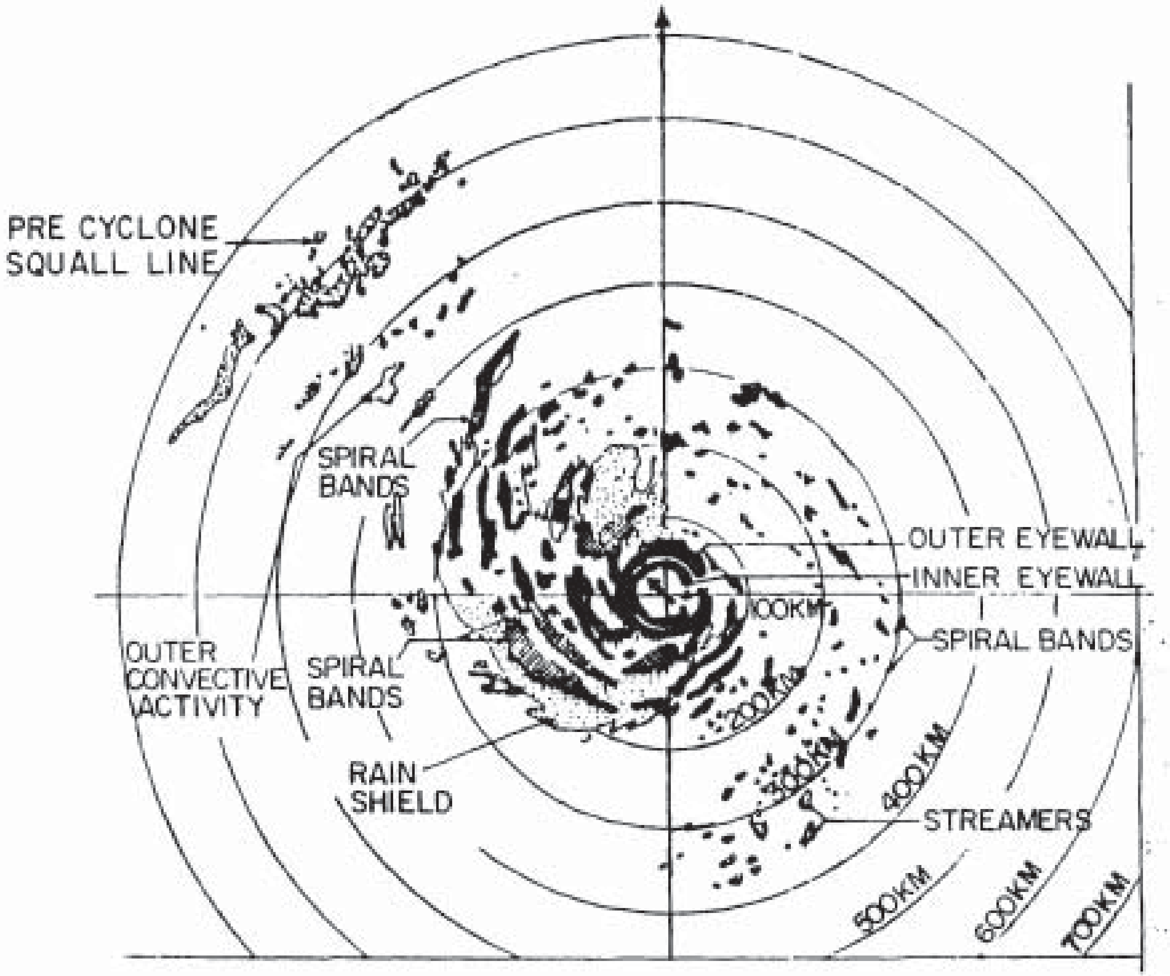
1.9(5,13)	2.4(5,14)	2.7(6,13)	2.2(6,14)	3.7(6,15)
2.3(9,15)	4.9(9,16)	2.1(10,14)	1.9(10,15)	3.1(10,14)
0.8(12,17)	1.2(12,18)	0.9(13,16)	0.2(13,17)	0.5(13,10)
1.0(15,19)	0.1(16,18)	0.0(16,17)	0.0(18, 4)	0.0(18, 5)
0.0(19, 6)	0.0(19, 7)	0.7(19, 8)	0.5(19, 9)	1.8(19,10)
0.0(20, 6)	0.0(10, 7)	1.1(20, 8)	1.5(20, 9)	2.5(20,10)
1.2(20,16)	0.0(21,)	0.0(21, 5)	0.0(21, 6)	0.1(21, 7)
0.2(21,13)	0.3(21,10)	1.0(21,15)	0.0(21,16)	0.0(21,17)
2.3(22, 9)	3.7(22,10)	4.0(22,11)	0.8(22,13)	0.1(22,14)
0.0(23,16)	0.0(23,17)	0.0(24,18)	0.2(24,19)	5.7(24,20)
0.0(26,19)	2.0(26,20)	0.0(27,18)	0.0(27,19)	1.0(27,20)
0.0(29,20)	0.0(30,10)	0.0(30,19)	0.0(31,18)	0.0(31,19)

4.6(7,14)	6.3(7,15)	5.3(8,14)	2.6(8,15)	3.3(9,14)
2.1(11,15)	2.4(11,16)	1.8(11,17)	2.6(12,15)	1.5(12,14)
0.4(14,17)	0.4(14,18)	1.4(14,19)	0.3(15,17)	0.1(15,18)
0.0(18, 6)	0.0(18, 7)	0.0(18, 8)	0.0(19, 4)	0.0(19, 5)
2.2(19,11)	0.6(19,12)	0.1(19,13)	0.0(20, 4)	0.0(20, 9)
2.4(20,11)	1.1(20,12)	0.0(20,13)	0.0(20,14)	0.6(20,15)
1.2(21, 8)	2.1(21, 9)	3.0(21,10)	2.8(21,11)	1.9(21,12)
0.0(22,14)	0.0(22, 5)	0.0(22, 4)	0.0(22, 7)	1.0(22, 8)
0.0(22,15)	0.4(22,16)	0.0(22,17)	0.3(23,14)	1.0(21,15)
4.1(24,31)	0.0(25,16)	0.4(25,17)	5.2(25,20)	0.0(24,10)
0.0(28,18)	0.3(28,19)	0.4(26,20)	0.0(29,18)	0.0(29,19)
0.2(32,18)	0.0(32,19)			

TOTAL RAIN (CUMULATIVE) FOR THE TARGET AREA = ~~[illegible]~~ 15.8

FIG.31

STRUCTURE OF A TROPICAL CYCLONE AS SEEN BY RADAR



ARROW AT STORM CENTRE SHOWS DIRECTION OF MOTION OF STORM

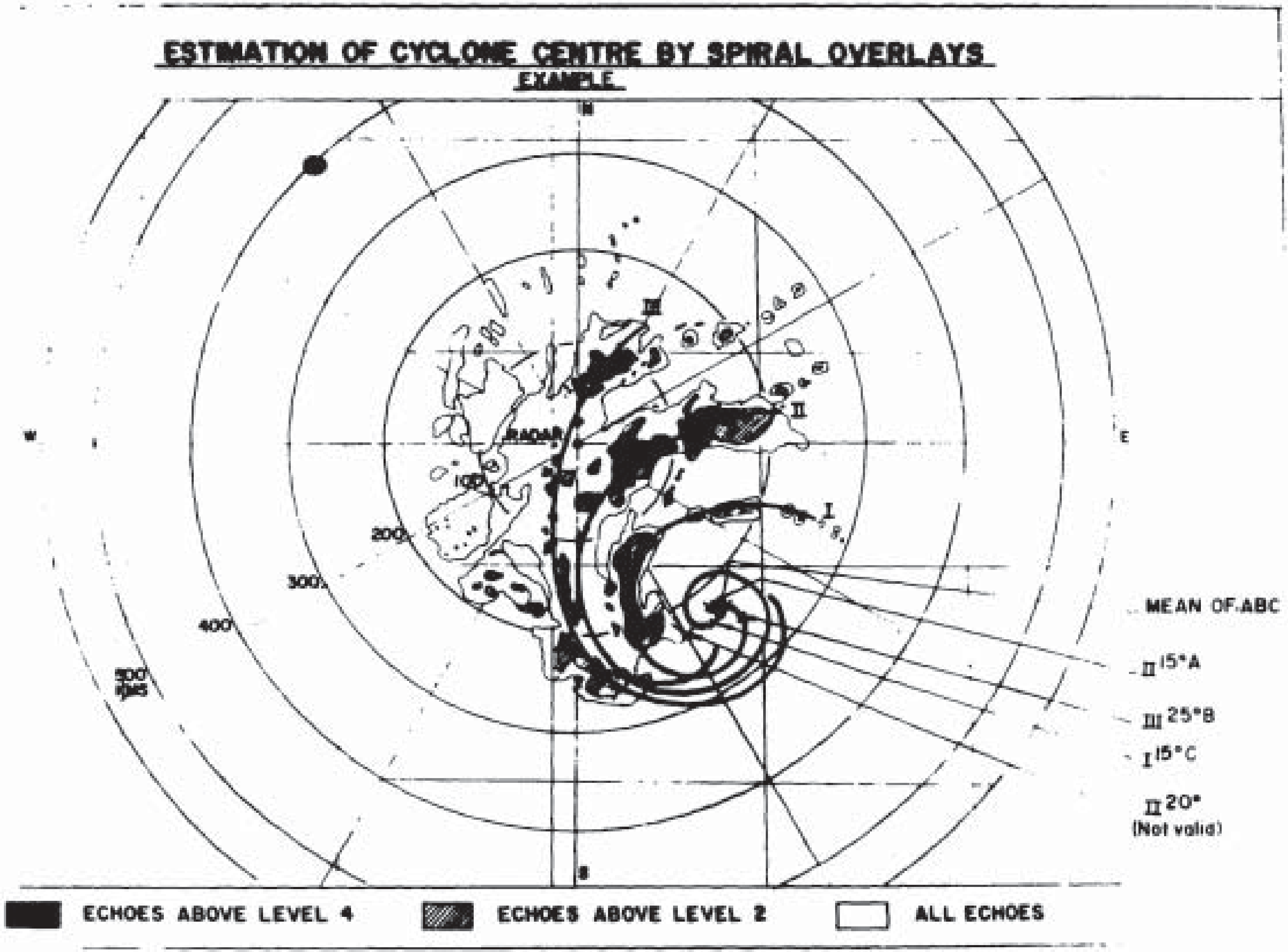

ESTIMATION OF CYCLONE CENTRE BY SPIRAL OVERLAYS
EXAMPLE
N
W
E
S
RADAR
100
200
300
400
500 KMS
MEAN OF ABC
II 15°A
III 25°B
I 15°C
II 20°
(Not valid)
ECHOES ABOVE LEVEL 4
ECHOES ABOVE LEVEL 2
ALL ECHOES

Fig. 33.

SPIRAL BANDS IN A DEVELOPING CYCLONE

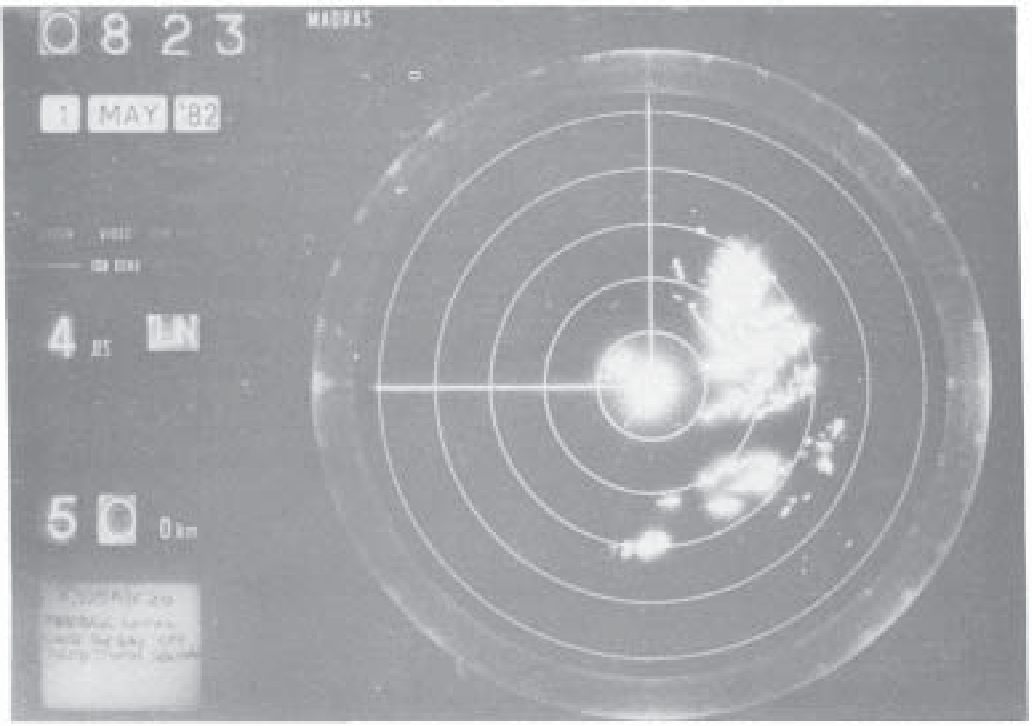


Fig.34.

CYCLONE OVER LAND SHOWING EYE

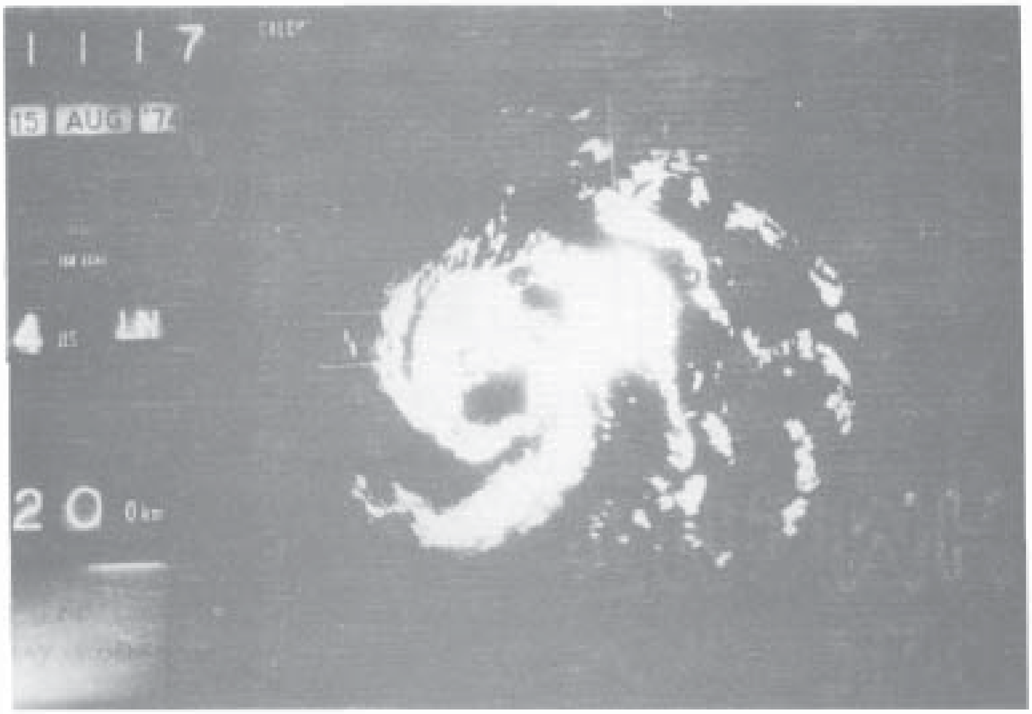


Fig.35.

CYCLONE SHOWING EYEWALL AS AN EXTENSION OF SPIRAL BAND

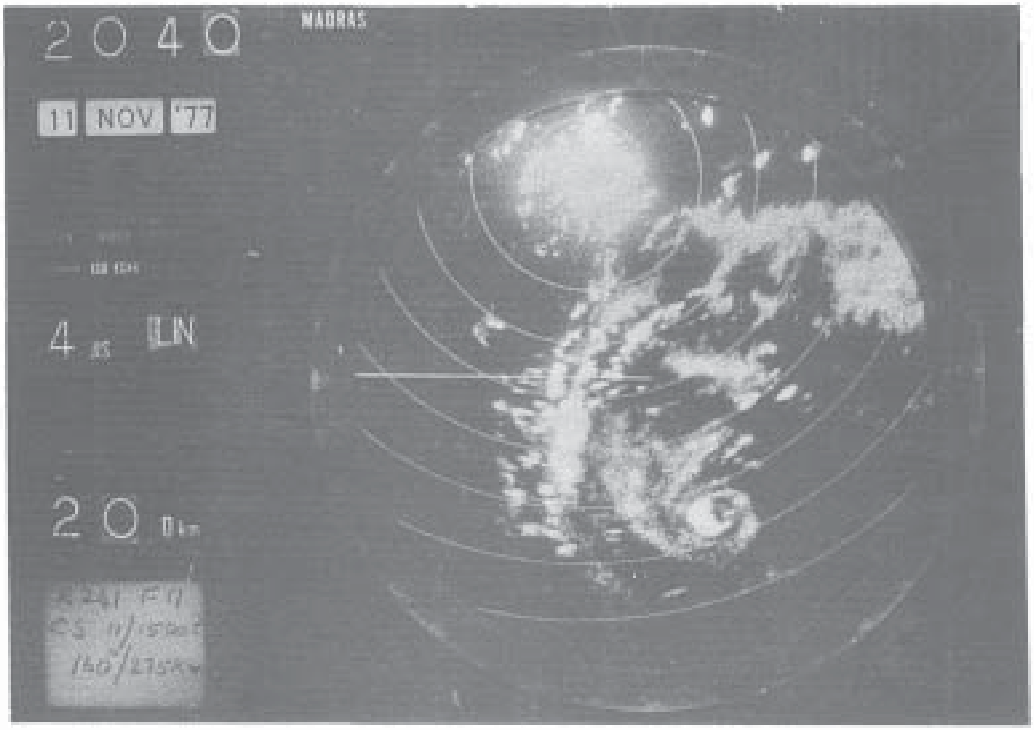


Fig.36.

CYCLONE OF FIG.36 SIX HOURS LATER SHOWING A SMALL EYE DISTINCT FROM SPIRAL BANDS

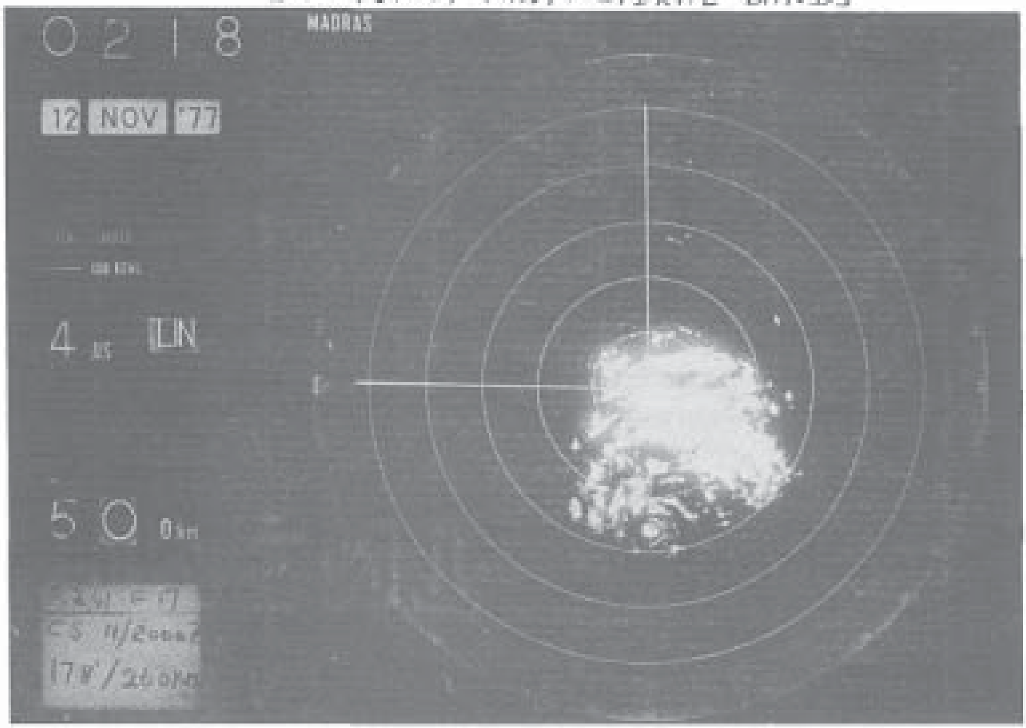


Fig.37.

CYCLONE SHOWING DOUBLE WALLED EYE

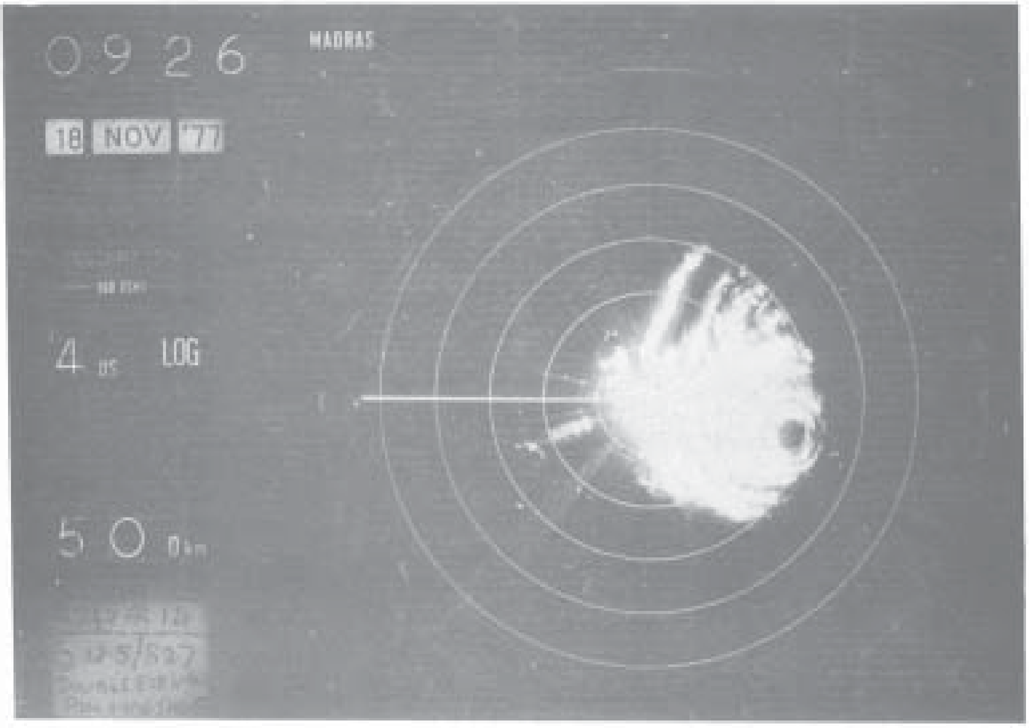


Fig.38.

CYCLONE OF 13 NOV.,1984

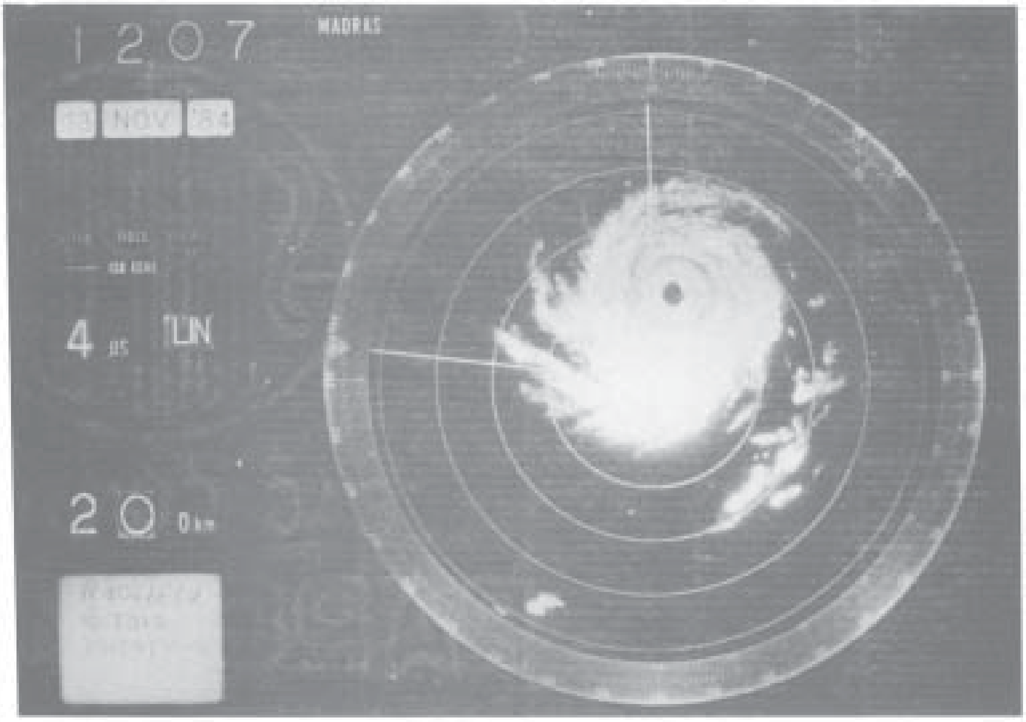


Fig.39.

CYCLONE OF FIG.39 ISO ECHO THRESHOLD LEVEL 42 dBZ

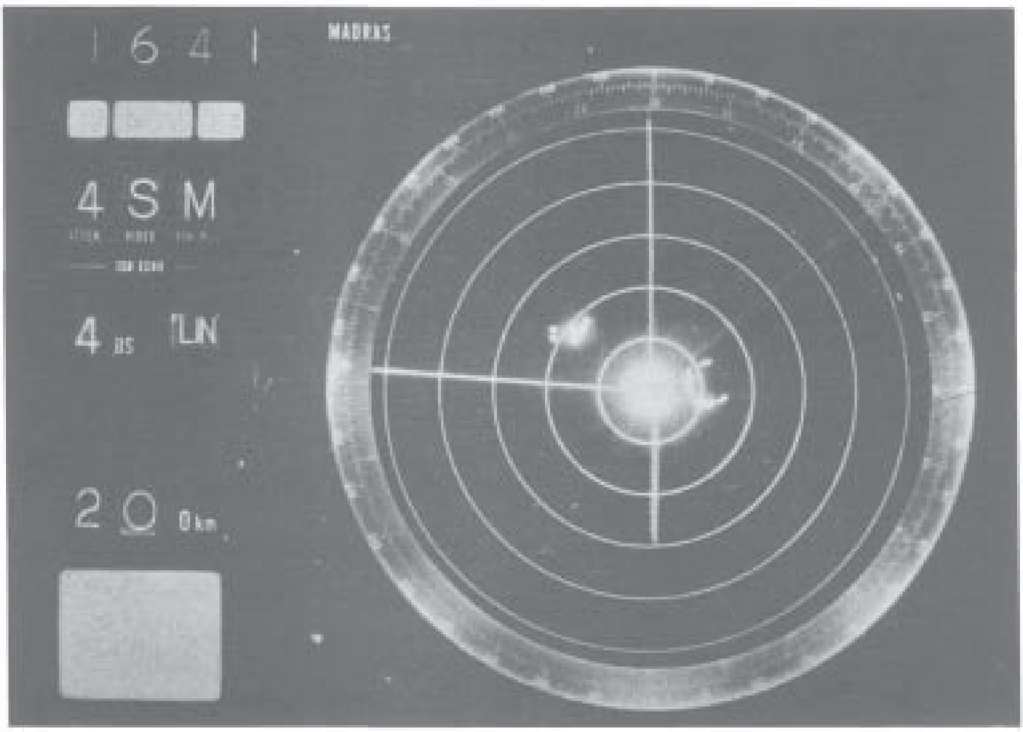


Fig.40.

CYCLONE OF FIG.39 ISO ECHO THRESHOLD LEVEL 37 dBZ

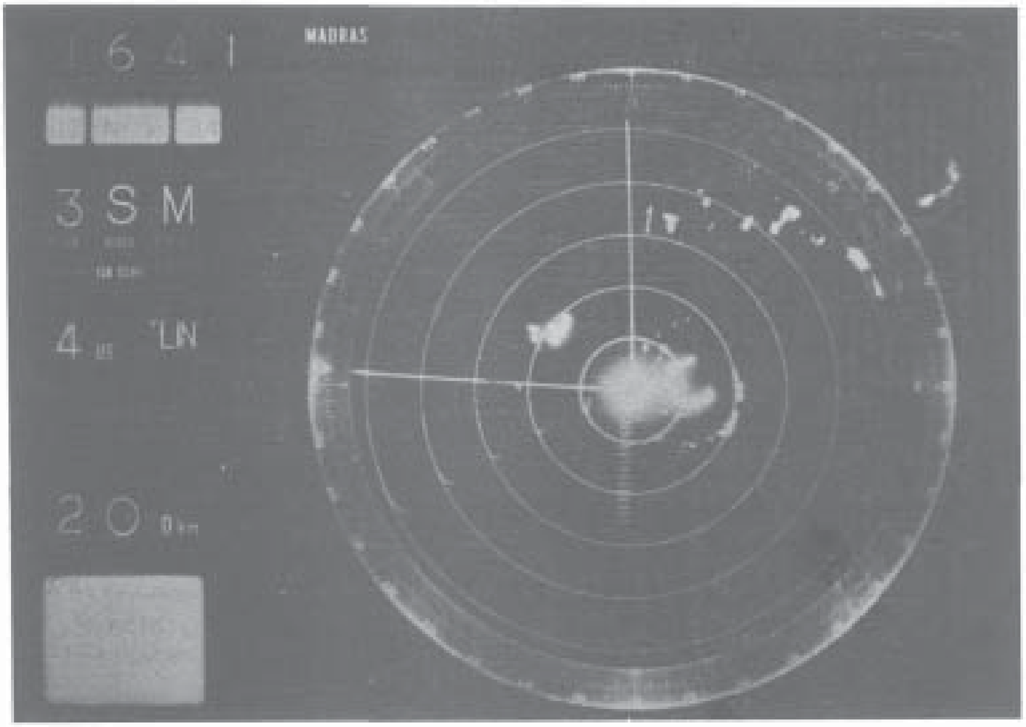


Fig.41.

CYCLONE OF FIG.39 ISO ECHO THRESHOLD LEVEL 32 dBZ

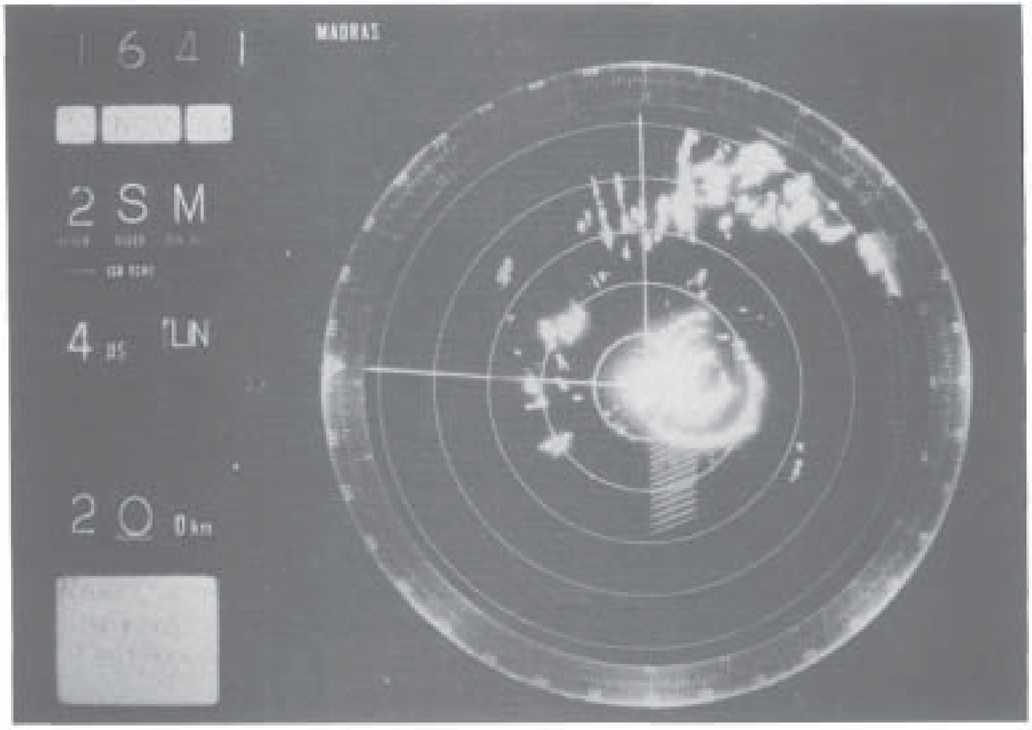


Fig.42.

CYCLONE - EYEWALL SEEN AS A COMMA MORE THAN 400 km AWAY

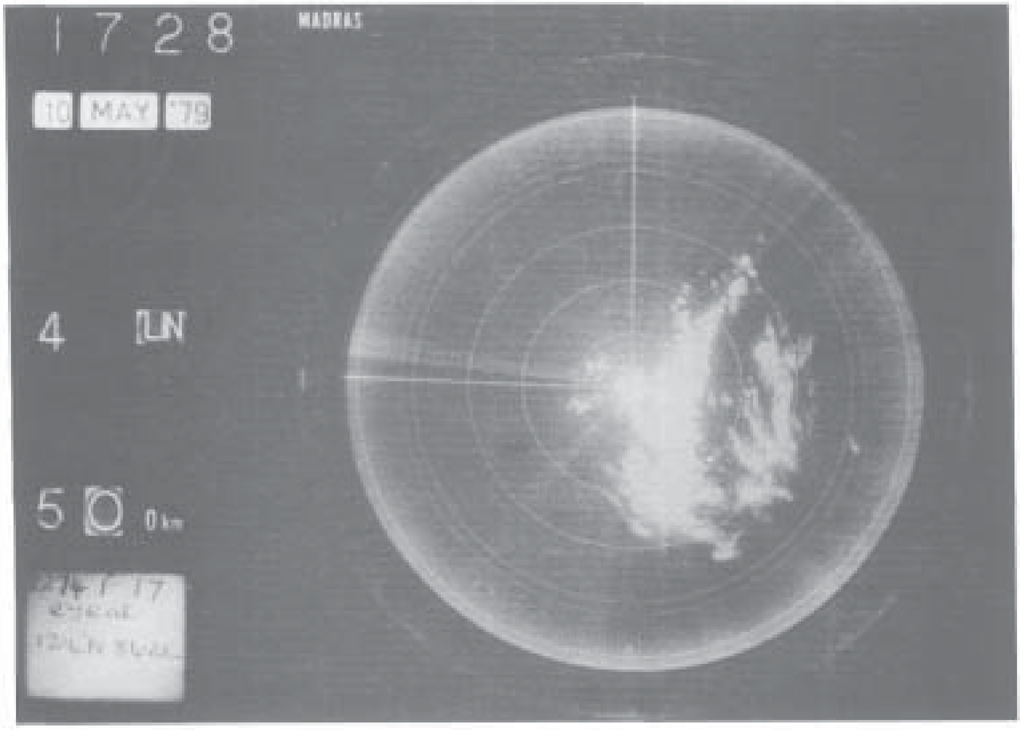


Fig.43.

CYCLONE WITH DOUBLE WALLED EYE

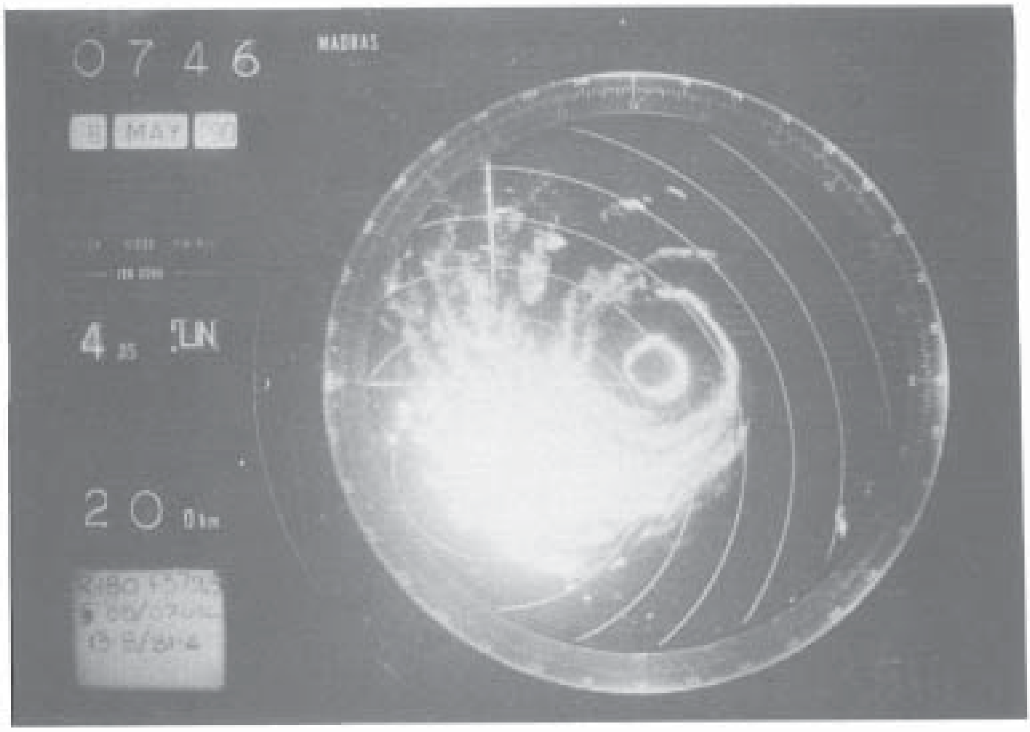


Fig.44.

RHI OF FIG.44 SHOWING DOUBLE EYE WALL

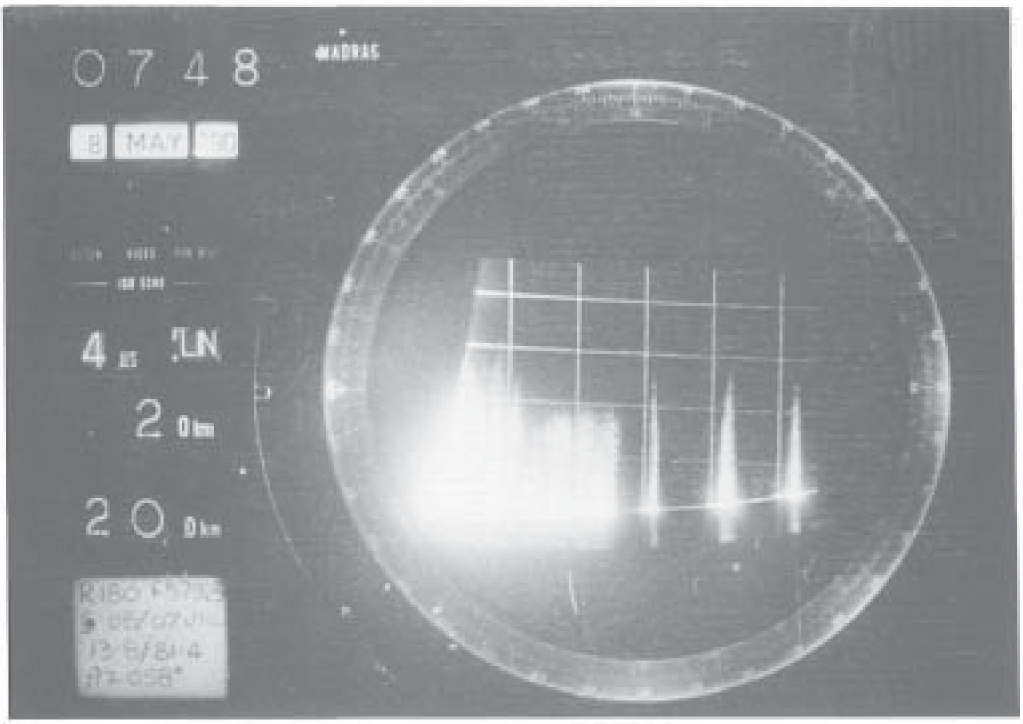


Fig.45.

MODEL OF SURFACE STRUCTURE OF CYCLONE OF NOVEMBER 1984.

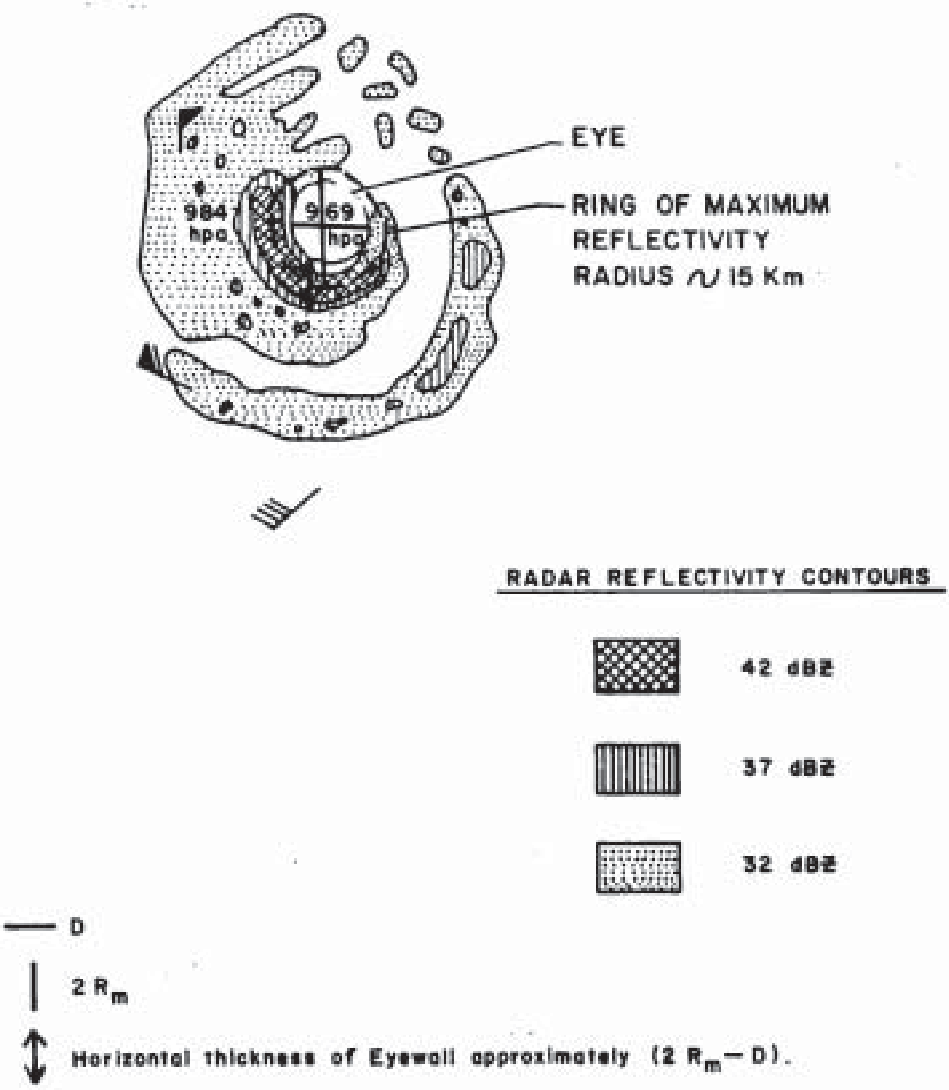
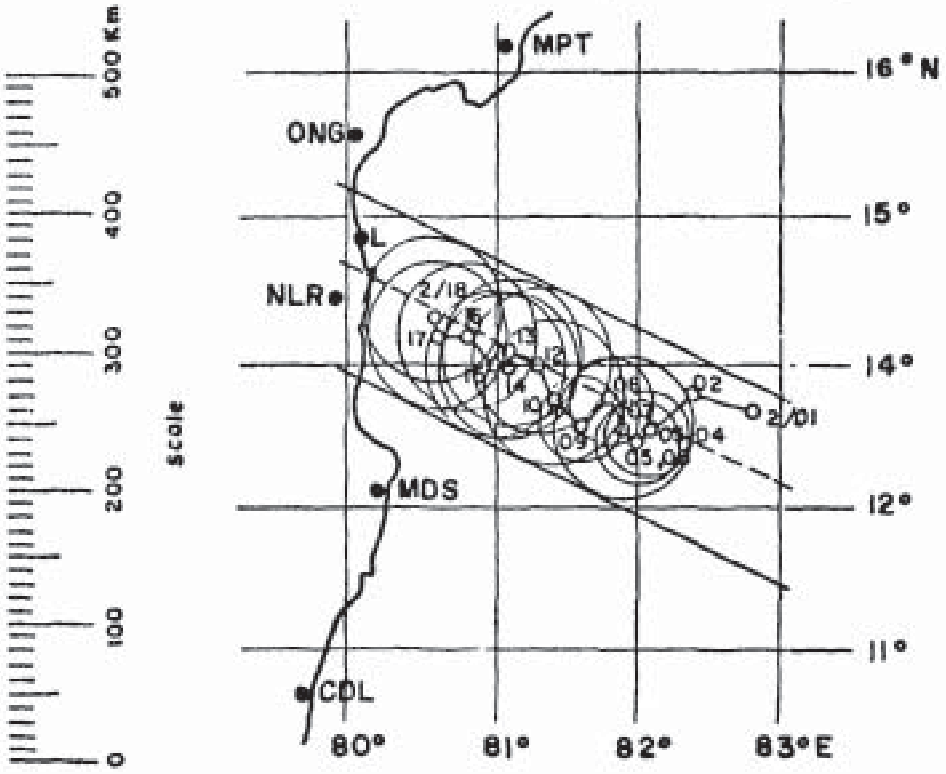


Fig. 46

EXAMPLE OF TRACK EXTRAPOLATION
BAY OF BENGAL CYCLONE OF 2-3 NOVEMBER 1987
EXTRAPOLATION MADE AT 18 Hrs. UTC OF 2nd NOVEMBER



RADAR FIXES

LIMIT OF ACCURACY OF RADAR FIXES

ENVELOPE OF TRACK

CENTRE LINE OF FORECAST TRACK

CONFIDENCE OF FIX :

WITHIN 50KM FROM 13 TO 18 UTC

FORECAST TIME OF LANDFALL

2300 HRS UTC OF 2nd

L ACTUAL LANDFALL 2200 HRS. UTC OF 2nd.

FIG. 47.

TRACK OF CYCLONE 15–19 NOVEMBER, 1977.

(TIME IN U.T.C.)

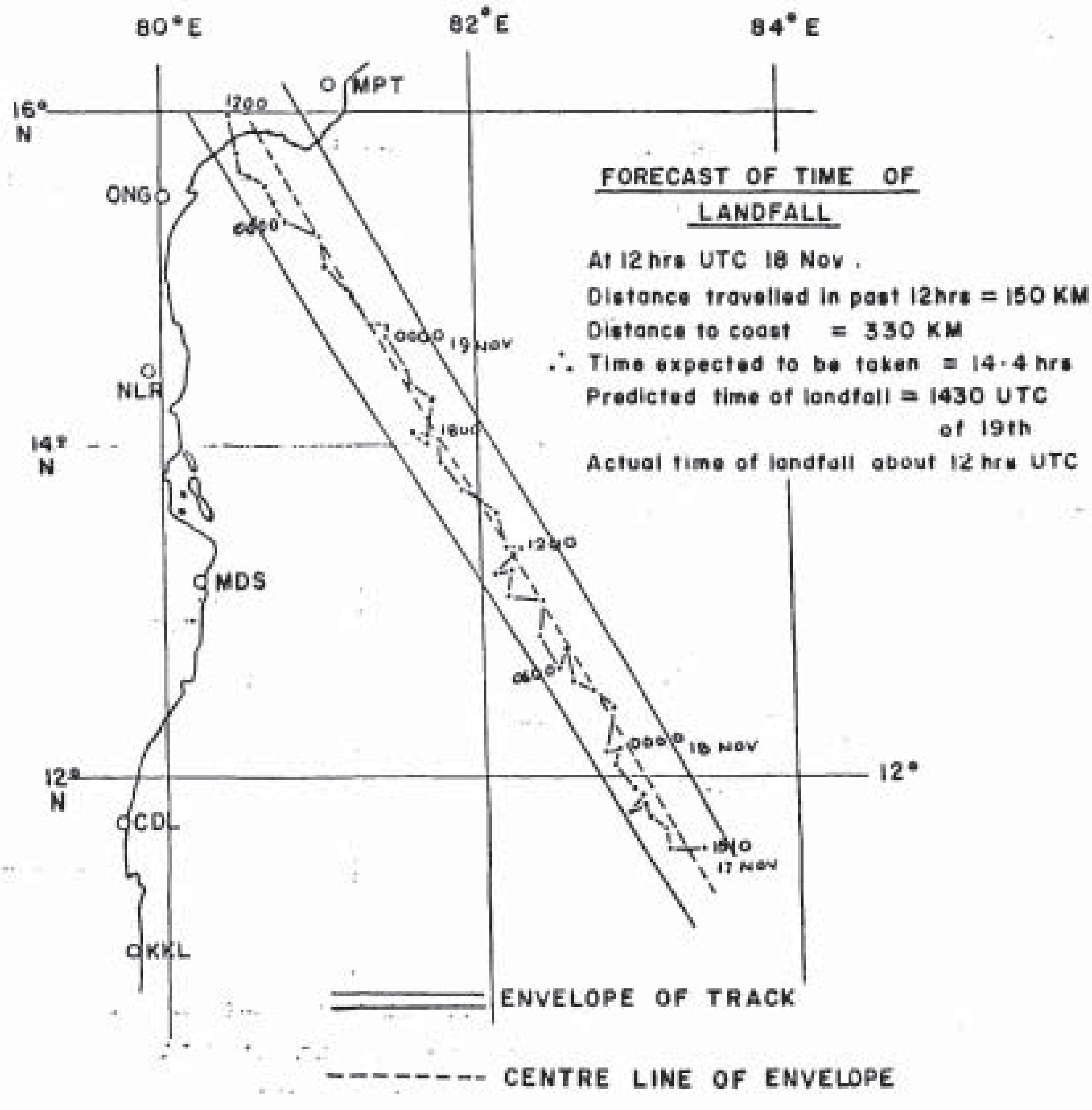
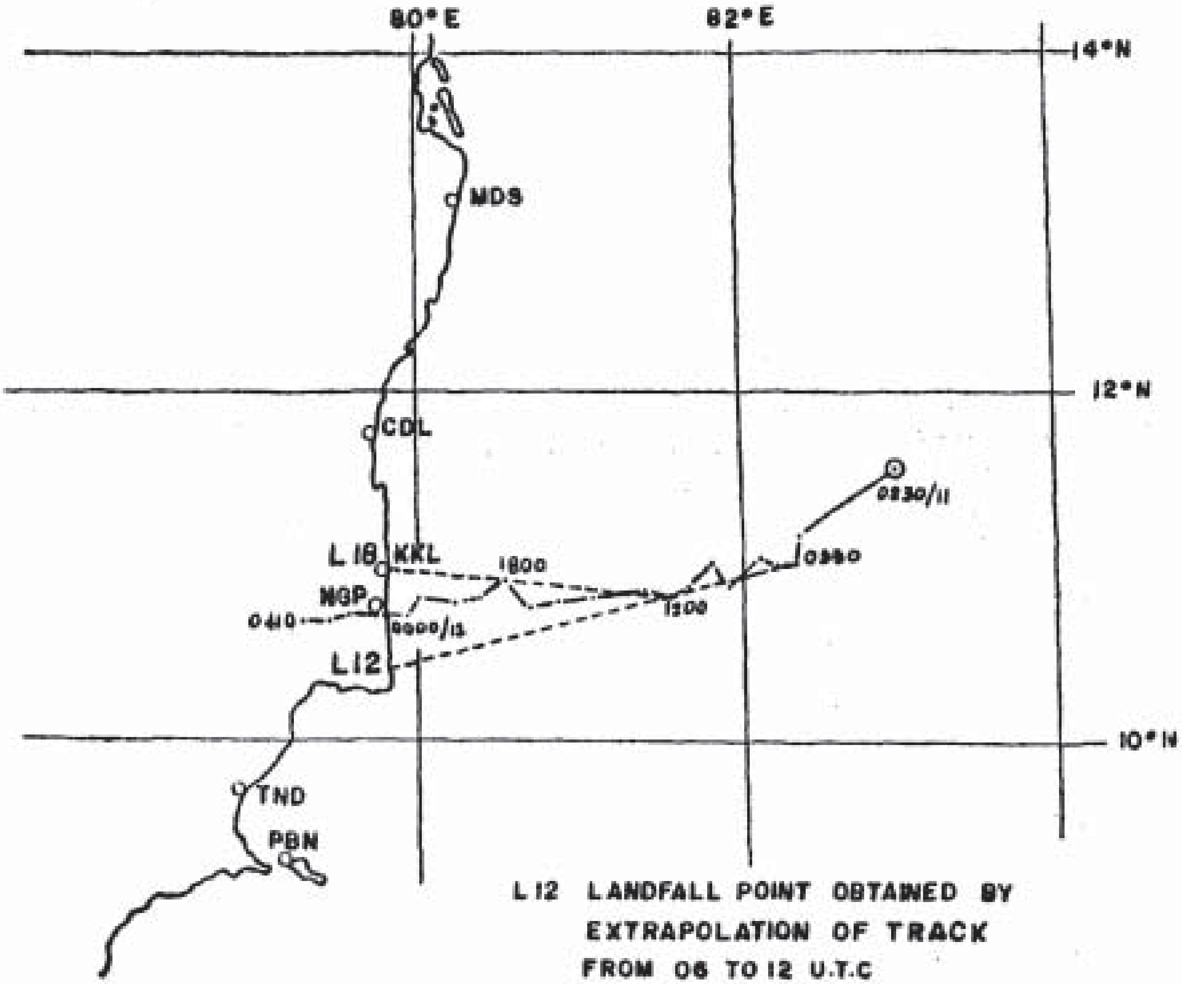


FIG. 48.

TRACK OF
NAGAPATTINAM CYCLONE 11-12 NOVEMBER, 1977



L 12 LANDFALL POINT OBTAINED BY EXTRAPOLATION OF TRACK FROM 06 TO 12 U.T.C

L 18 SIMILAR EXTRAPOLATION 12 TO 18 U.T.C.

FIG. 49.

INSAT - 1B IMAGERY OF CYCLONE OF FIG.44

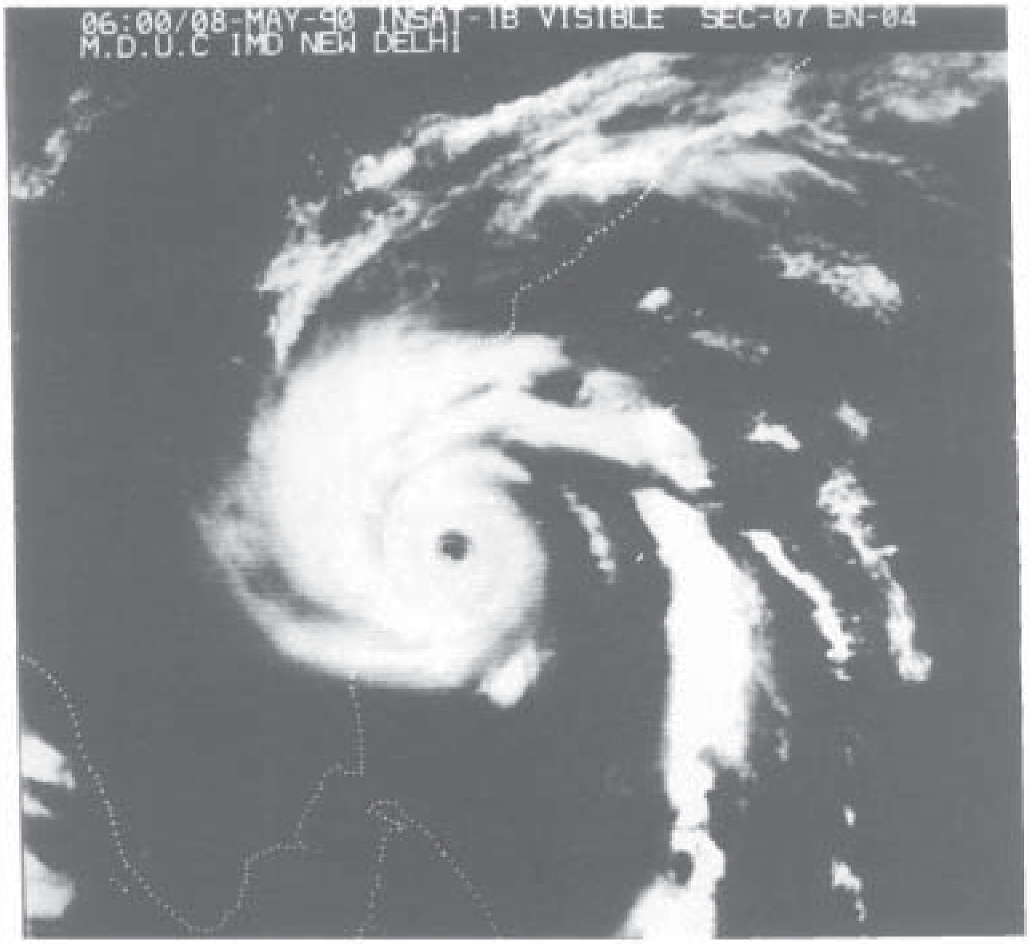


Fig.50.