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Some aspects of accuracy of radar/satellite fixes of tropical cyclone over Bay of Bengal

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सार — 10 चक्रवात संसूचन रडारों की स्थापना और उपग्रह प्रेक्षणों की उपलब्धता के फलस्वरूप चक्रवातों के मार्ग का पता लगाने के दौरान उपग्रह और दो या अधिक रडारों द्वारा चक्रवातों के फिक्सज (Fixes) की उपलब्धता एक सामान्य बात हो गई है। प्रायः किसी सीमा तक ये फिक्सज एक दूसरे से भिन्न होते हैं। इस शोधपत्र में तटीय रडारों और उपग्रह द्वारा सूचित किए गए बंगाल की खाड़ी में चार चक्रवातों के मार्गों का अध्ययन प्रस्तुत किया गया है। यह देखा गया है कि प्रायः रडार फिक्स की तुलना में उपग्रह फिक्स तट के निकट रहा है। रडार फिक्सों में, रडार का फिक्स तूफान के निकटतम तन्त्र का उत्तम फिक्स माना जा सकता है।

ABSTRACT. Consequent to installation of 10 cyclone detection radars and availability of INSAT observations, availability of fixes* of cyclones by two or more radars and satellite has become a common feature during tracking of cyclones. Generally these fixes differ from each other to some extent. The paper presents a study of tracks of four cyclones in Bay of Bengal as determined by coastal radars and satellite. It is seen that satellite fix is generally closer to coast as compared to radar fix. Amongst radar fixes, the fix of radar closest to the storm may be considered as best fix of the system.

Key words — Radar fixes, Radar network.

1. Introduction

With the installation of 10 cyclone detection radars in the Indian Network (6 on the east coast and 4 on the west coast), tracking of a tropical cyclone in the Bay of Bengal by two or three radars simultaneously has become a common feature. In addition, cyclones are tracked by satellites (INSAT & NOAA) as well as by synoptic methods. A cyclone forecaster thus receives fixes of the storm from several sources, all of which may show some variation from each other. He is plagued by uncertainty of fixes and is unable to decide upon the best fix of the cyclone for deciding the future course of the storm and subsequent warning to the concerned coastal areas. Satellite fixes differ to some extent from radar fixes (when the system is within radar range). Sometimes these differences can be explained by inherent error in the centre estimation process. In any case, since radar and satellite look at the system from completely different angles, some differences in the fixes may be expected. But the difference in fixes given by two or more radars need explanation. The synoptic method, may have large errors in fixes when storm is far out in sea due to non-availability of wind/pressure data over ocean. However, close to coast, if wind and pressure data from coastal stations are available, then the analysis yields a fairly accurate fix.

Conover (1962) made a study of fixes reported by several land based radars and aircraft radar of hurricane *Donna*. He found that maximum difference in fixes given by radars located close to each other (at Miami) approached 24 km. He attributed these differences to combined effect of several types of errors like observed radar range and azimuth errors and error in charting the azimuth and range.

It appears worthwhile to study the fixes reported by various methods in several storms and examine the extent of variability and whether these could be explained by inherent errors in the method. This would be of immense help to a cyclone forecaster leading to a better appreciation of fixes of storm from different sources.

2. Data

In the present study, the following four cases have been taken where the fixes by radars in addition to normal satellite and synoptic fixes were available :

(1) Sriharikota cyclone	11-14 Nov 1984,
(2) Balasore cyclone	24-26 May 1989,
(3) Kavali cyclone	6-9 Nov 1989, and
(4) Machilipatnam cyclone	6-9 May 1990.

The plot of fixes reported by radar and satellite as reported operationally is shown in Figs. 1-4. Only those fixes have been chosen in which confidence of fix as reported by station was good. Tables 1-4 show vector deviation in position as given by the radars and satellite. Deviation in fixes is taken from radar fix of the radar closest to storm (most of the time) as reference,

*Position of the centre of storm.

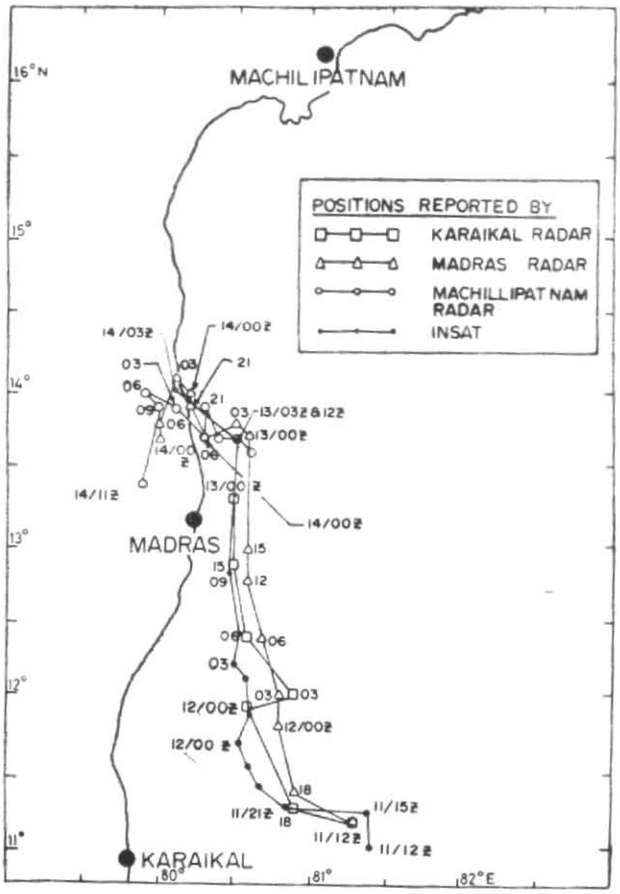

Fig. 1. Tracks of Sriharikota cyclone (11-14 Nov 1984) as determined by radars and INSAT

Deviation of fixes to the left of reference track is taken as negative and to the right as positive. Mean and root mean square deviation of the fixes by radar or satellite are also indicated at the bottom of each table.

It is seen from the available observation of these particular cyclones in the Bay of Bengal that maximum difference in the fixes of radar is ± 45 km. In the case of satellite and radar fixes, the maximum difference is 110 km. The difference in fixes between radar and satellite is quite large in the case of Balasore cyclone (Table 2) as compared to other three cases. It must be noted that these fixes were reported operationally and, therefore, include errors due to human element in addition to inaccuracies inherent in the method of fixing itself. It is also seen that the track of fixes of radar closest to the storm is generally farthest from the coast for northerly moving storms in the Bay of Bengal.

3. Discussion

3.1. *Difference between the radar and satellite fixes*

Since the radar (S-band) has a nominal range of 400 km, comparison between the satellite and radar fixes is possible only when the system comes within radar range. In the case of a northward moving system, due to the orientation of the Indian coast usually only one radar is able to give fix with good accuracy. A few observations of fixes with fair to good accuracy from two coastal radars, when the system is located within range of two radars are also sometimes available (Tables 1-4). An interesting feature in the case of north or northwestward moving systems was that generally the satellite track was to the left of reference radar track, *i.e.*, the satellite fix was closer to the coast. In the case of a westward moving system (Kavali cyclone) the satellite track is generally to the north of reference radar track (Fig. 3). Here also, except for one fix (08/12 UTC), each satellite fix was to the west of radar fix showing the satellite fix to be closer to the coast.

TABLE 1

Deviation (in km) of reported fixes of Sriharikota cyclone taking fix of radar closest to storm as reference (Nov 1984)

Date/Time (UTC)	Deviation (in km) of			T-No.
	Karaikal	Machili-patnam	Satellite	
11/12	0		—15	3.0
12/03	+10		—30	5.0
12/06	—10		—15	5.0
12/09	—15		—25	5.0
12/12	—15		—5	5.0
12/15	—15		—10	5.0
12/19	—15	—15	0	5.0
13/00	—45	—10	—10	5.0
13/03		—10	—5	5.5
13/06		+10	0	5.5
13/09		+10		5.5
13/12		+10		6.0
13/15		+10		5.0
13/21		+10		5.0
Mean error	—11.23	1.87	—11.5	
Root mean square deviation	14.7	10.5	9.43	

Deviation to the left and right of the reference track are considered negative and positive respectively.

(*Ref.* : Madras radar)

Before comparing the fixes given by satellite and radar, it would be worthwhile to first consider the accuracy of position estimates by satellite method. In the satellite estimates, the cloud system centre (CSC) position analysis which should correspond to the location of the centre of cyclone circulation may have the following sources of error (Sheets and Grieman 1975) :

(a) Gridding error,

(b) Cloud system centre (CSC) location error,

(c) Real difference between the correct CSC location and that of the cyclone centre.

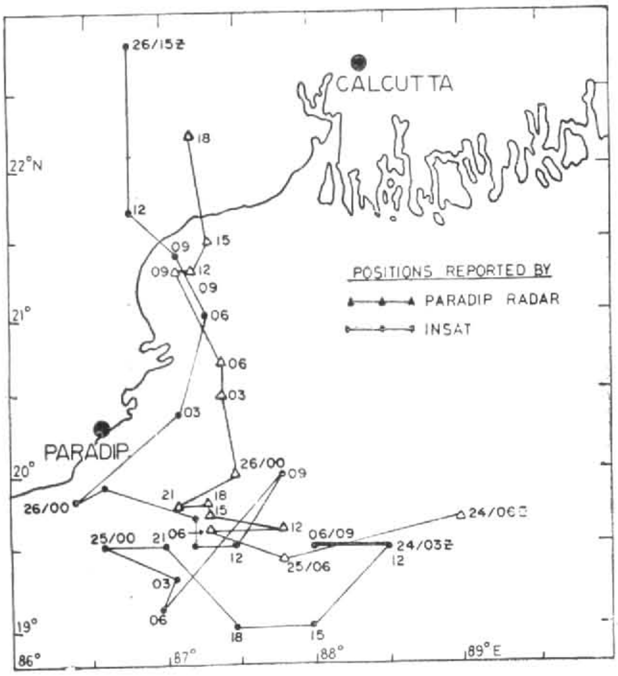

Fig. 2. Tracks of Balasore cyclone (24-26 May 1989) as determined by radars and INSAT

The resolution of INSAT is 2.75 km in the visible channel and 11 km in the infrared channel. The conversion of the line and element number of a point in the satellite picture to the latitude and longitude of the point is known as earth location or navigation. In the INSAT data processing system, navigation is accomplished with an accuracy of ±1 pixel (picture element). Hence gridding error can be ±2.75 km in a visible picture and ±11 km in infrared picture.

Night time IR pictures have slightly larger error due to indistinct land marks. Regarding (b) and (c), the magnitude of errors from both these sources tend to vary inversely with the storm intensity. In an intense cyclone, the CSC, the pressure centre and the centre of circulation, all tend to be well defined and coincident and any discrepancies are usually small. The error due to (b) will be negligible in cases where the centre of circulation is clearly visible in the picture. In three of the four cases studied, this has been the case. In the fourth case (Fig. 2) due to asymmetry in the storm and absence of visible centre of circulation, the fixing of CSC introduced larger error as seen in Table 2. However, this kind of problem does not occur in all cases. This extreme case has been deliberately chosen to show that large differences can always be attributed to errors in analysis of estimation of centre either by radar or satellite.

Regarding (c), in an intense system the displacement of centre of the system in vertical is little. However, the eye tends to be larger at the upper levels and small changes in centre position have been noted in some tropical storms (Jorgensen 1984).

One reason for difference in fixes by radar and satellite could be due to mechanism of centre estimation by the two methods. Radar detects the precipitation whereas the satellite detects clouds through sensing of infrared emission or visible light reflection. The echo return

TABLE 2

Deviation (in km) of reported fixes of Balasore cyclone (May 1989)

Date/Time (UTC)	Deviation of satellite (km)	T No.
25/03	—65	3.0
25/06	—55	3.0
25/12	—35	3.0
25/15	—15	3.0
25/18	—15	3.0
26/00	—110	3.0
26/03	—35	3.0
26/06	+35	4.0
26/09	—10	4.0
26/12	—45	3.0
Mean error	—35	
Root mean square deviation	36.5	

(*Ref.* : Paradip radar)

from non-precipitating clouds at the upper levels where the drop size may be a few tense of microns cannot be detected by radar. Therefore, it appears likely that centre located by radar and satellite may show some difference depending upon the structure of the eye wall region. This will vary from storm to storm. But the reason for satellite fix to be generally closer to coast as compared to radar fix is not known.

The maximum root mean square deviation of difference in fixes of satellite and radar was 37 km. In case where CSC is visible, maximum root mean square deviation was slightly lower at 29.3 km.

3.2. *Difference in radar centres*

Raghavan *et al.* (1980), have discussed the various sources of error which are likely to be present in fixing the centre of a cyclone by radar. They have found that various factors such as wave propagation condition, the beam width errors of radar, appreciable height of the radar beam and the personal errors of the observations involved in real time radar reports contribute to errors in radar fixes. From a study of cyclone of sub-hurricane intensity, Raghavan *et al.* (1985) found the difference in fixes reported by three radars (Madras, Karaikal and Machilipatnam) varied from 15 to 52 km.

In the present case, all the cyclones (except Balasore) were of hurricane intensity and eye geometry was steady almost throughout the period (in the period of study). The accuracy reported was also good in most of the fixes (within 10 km). The differences in fixes vary from zero to 45 km which though slightly better is still considerable. The maximum root mean square deviation was 26.3 km.

The larger difference in fixes have been found to be in those cases when the system is on the edge of effective range of one radar. For instance, in case of Sriharikota cyclone, the system at 13/00 UTC was about 300 km

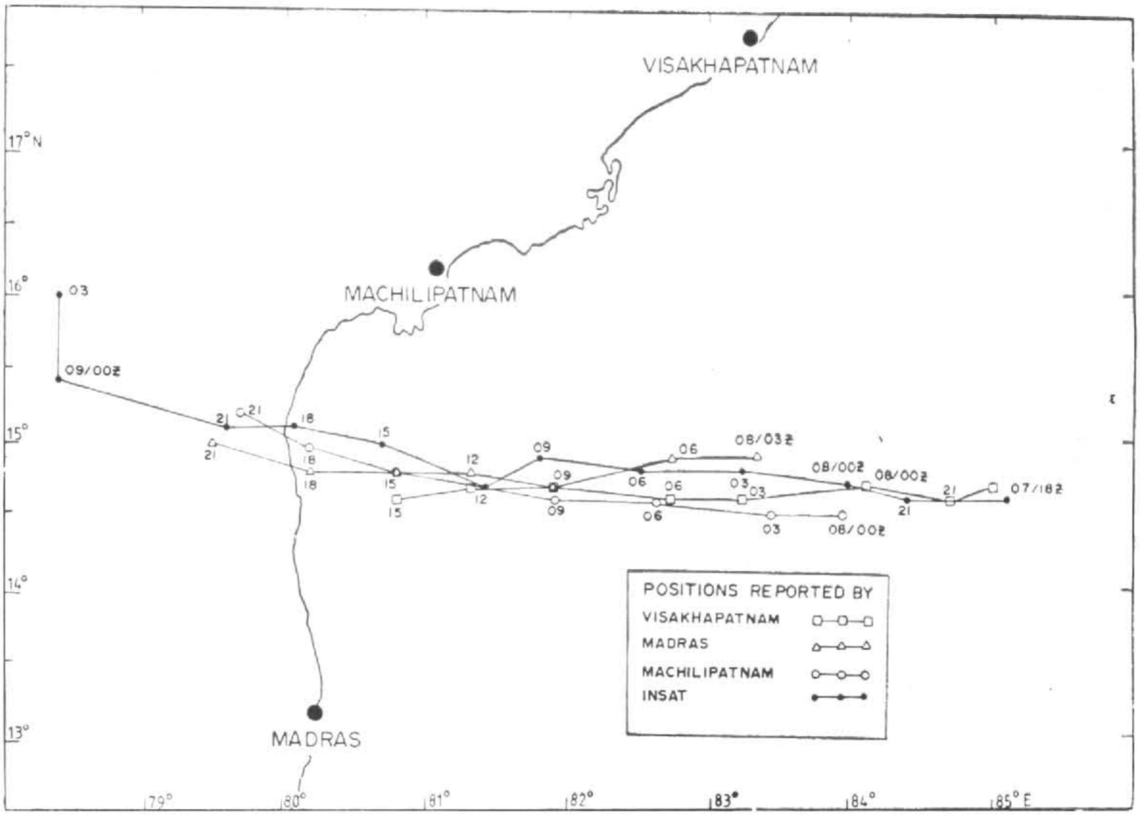

Fig. 3. Tracks of Kavali cyclone (6-9 Nov 1989) as determined by radars and INSAT

TABLE 3

Deviation (in km) of reported fixes of Kavali cyclone taking fix of radar closest to storm as reference (Nov 1989)

Date/Time (UTC)	Deviation (in km) of			T-No.
	Madras	Visakha-patnam	Satellite	
08/03	+45	+25	+35	6.0
08/06	+35	+10	+22	6.0
08/09	+10	+10	+10	6.5
08/12	+15	—10	0	6.5
08/15	0	—20	+15	6.5
08/18	—20	—	+15	6.5
08/21	—35	—	—15	5.5
Mean error	7.1	2.1	11.7	
Root mean square deviation	26.3	13.6	14.8	

(*Ref.* : Machilipatnam radar)

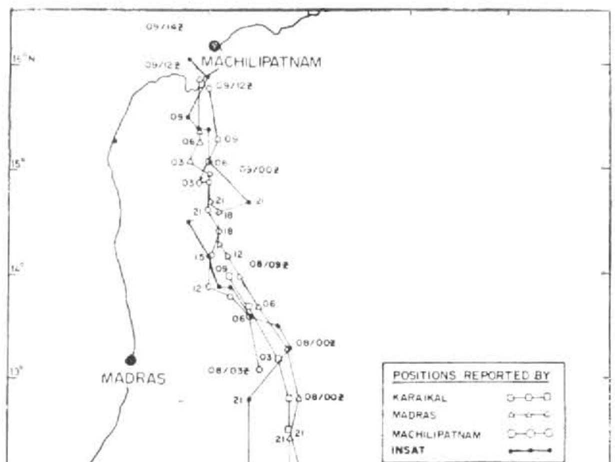

Fig. 4. Tracks of Machilipatnam cyclone (6-9 May 1990) as determined by radars and INSAT

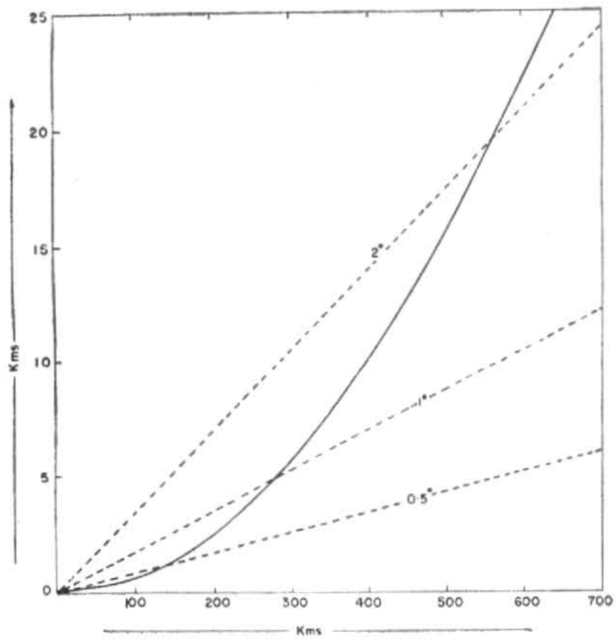

Fig. 5. Solid curve shows minimum height above sea level at which a radar target could be detected due to curvature of earth. Dashed lines show vertical extent of radar beam of several angular widths (for antenna at 0 deg elevation)

away from Karaikal and 60 km away from Madras. The diffierence in fixes was found to be —45 km. Fig. 5 is the curve showing the minimum height to which the precipitation cells would have to extend at various ranges to be detected by radar. It can be seen that a storm would have to extend 10,000 metres in order to be detected from a station near sea level at a range of 400 km. Therefore in this case, the radar sees only the uppermost portion of the system. Added to this is the effect of finite beam width. For 2° beam (for all the coastal radars) at 0° elevation the radar energy is covering a layer of about 3500 m at 200 km and 7,000 m at 400 km. It is obvious that the return signal displayed on the radar results from the integrated effect of hydrometeors through rather deep layers. At long ranges, a large portion of the lower part of the system is offering no contribution because of the curvature of the earth. Also, though the relevant specification of three radars are broadly comparable, the effective detection capability of one radar will differ from another due to range attenuation depending on the distance of the radar from the storm.

In an intense storm the radar reflectivity profile of the eyewall core decreases rapidly above 0°C (Jorgensen *et al.* 1985). From a study of two storms off Florida coast, they found that the radar reflectivity profile of the eyewall core was approximately constant at 42 dBz below 5.5 km and fell to 10 dBz at 11 km. The net result of these factors would be that a radar at longer range will not display the eye of the same size and shape as many features would not be detected. The exact extent of inaccuracy in fix is difficult to quantify as it would depend upon the structure of eyewall (generally-asymmetric) and may vary from storm to storm.

TABLE 4

Deviation (in km) of reported fixes of Machilipatnam cyclone taking fix of radar closest to storm as reference (May 1990)

Date/Time (UTC)	Deviation (in km) of			T-No.
	Karaikal	Machili-patnam	Satellite	
06/21	—20		—25	5.0
07/00	+25		+50	5.5
07/03	—10		+35	5.5
07/06	—10		—15	6.0
07/09	0		—50	6.0
07/12	—15		—30	6.0
07/15	—10		—15	6.0
07/18	+10		—40	6.0
07/21	—10		—50	6.5
08/00	—10		—40	6.5
08/03	—15		0	6.5
08/06	—10		—10	6.5
08/09	—10	—20	—10	6.5
08/12		—35	—30	6.5
08/15		—15	—15	6.0
08/18		—20	—30	6.0
08/21		—10	+40	5.5
09/00		—10	+10	5.0
09/03		—20	+20	5.0
09/06		+25	+25	5.0
Mean error	—6.5	—13.12	—9.0	
Root mean square deviation	11.4	16.2	29.35	

(*Ref.* : Madras radar)

The propagation effect is also likely to contribute to difference in fixes as sub-refraction or super refraction may occur in certain preferred directions due to presence of system over sea. However, this is not likely to be large. The fixing of geometric centre from eye geometry may introduce an error of about 0.1° (10 km).

Another important aspect which is generally not realised is that centres reported operationally by different radars may not refer to the same time of observation. When hourly fixes are to be reported, movement of system, rapid changes in eyewall characteristics, oscillatory tendency of system etc may introduce a significant error in position of centre seen on scope when a difference of ten to fifteen minutes occur between observations by two radars. Workers who are aware of rush of work during cyclone tracking would appreciate that this may occur sometimes. However, this problem may not be there at sites where facility of data recording is available. Data of the exact hour could be recorded and recalled for measurement of centre. At Karaikal and Calcutta such systems known as WDDS (Weather Data Display System) are now in operation.

Raghavan *et al.* (1985), on the basis of study of one storm wherein a reassessed track of one radar was compared with track of other two radars concluded that the centre given by the radar nearest to the system would be farthest from the coast. In the present case the same trend is generally seen in two northward moving systems. But in case of westward moving system the fixes do not exhibit this trend.

4. Conclusions

The study shows :

(*i*) Centres of storm reported by satellite observations may show differences of the order of 37 km or more when compared with radar centres. This will be less in a very intense system. The satellite centre is generally closer to coast when compared with radar centre.

(*ii*) When several radar centres of the system are available, the centre reported by radar closest to the system should be taken as best fix as this would have least error.

(*iii*) In case of northward moving systems, centre reported by radar closest to storm is generally farthest from coast in comparison with centres of radars farther from the system. In the case of westward moving system no such trend was noticed.

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