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Utilizing Image Processing on Satellite Data for Accurate Tropical Cyclone Tracking

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Abstract:

Coastal regions face significant threats from tropical cyclones, necessitating precise prediction and vigilant monitoring. Weather satellites, operating in polar and geostationary orbits, play a pivotal role in unraveling these meteorological complexities. Geostationary satellites, exemplified by Kalpana-1, offer a unique advantage in temporal resolution, delivering frequent updates, while their polar counterparts excel in spatial resolution. This study harnesses the capabilities of Kalpana-1, a geosynchronous satellite equipped with the Very High-Resolution Radiometer (VHRR) sensor, to advance our understanding of tropical cyclones. Access to data from Kalpana-1 and METSAT geostationary satellites, facilitated by the Meteorological and Oceanographic Satellite Data Archival Centre (MOSDAC), forms the cornerstone of this research. Kalpana-1, India's pioneering meteorological geostationary satellite, furnishes VHRR sensor data at 30-minute intervals. Its spectral repertoire encompasses visible, thermal infrared, and water vapor channels, each indispensable for cyclone analysis. While the visible bands capture daylight images, the thermal infrared channels ensure uninterrupted day-and-night observation, a critical asset for gauging cloud characteristics. Cloud top brightness temperatures serve as the linchpin for identifying low, medium, and high-level clouds. Image processing techniques take center stage in facilitating cloud identification and cyclone tracking.

Keywords: Kalpana-1, Geostationary Satellites, Weather Satellites, MOSDAC.

Introduction:

Tropical cyclones pose serious hazards to people all over the world, and satellite observations are essential for comprehending, forecasting, and tracking their motions [1,17]. These spacecraft can be divided into two groups: polar and geostationary satellites. Polar orbiting satellites provide high spatial resolution measurements as they pass over the poles at altitudes between 600 and 850 km (NOAA, 2018). High temporal resolution is the fundamental benefit of geostationary satellites, which orbit at a height of around 36,000 km above the surface of the Earth [18].

These satellites' acquired data include a lot of knowledge about numerous atmospheric characteristics. The capabilities of the onboard sensors, the geographic resolution of observations, orbital parameters, including orbital height, inclination, and swath width, all have a significant impact on how successful satellite observations are for monitoring and prediction [19]. The Very High-Resolution Radiometer (VHRR) sensor aboard Kalpana-1, a geosynchronous satellite, operates in three spectral bands: visible, infrared, and water vapour [18]. Resolutions for these bands are 2 km, 8 km, and 8 km, respectively.

In this part, we set out on a mission to reconstruct the path of the powerful tropical storm Hudhud, which formed in the North Indian Ocean's Bay of Bengal region. On Kalpana satellite data in the Indian area, we use cuttingedge digital image processing techniques. To be more precise, we compare the cyclone tracks we extract from the infrared and water vapour bands to the best track estimations offered by the Indian Meteorological Department (IMD) [9, 15, 17].

Monitoring and forecasting of tropical cyclones (TC) rely heavily on satellite measurements. The properties of the sensors, observational resolutions, and satellite orbital parameters, such as swath width, orbital height, and inclination, all have a role in how successful these efforts are. Utilising the microwave, visible, and infrared electromagnetic spectrum, meteorological satellite observations provide data on a variety of atmospheric characteristics [19]. The use of visible and infrared satellite measurements for meteorological purposes was crucial in the early phases of TC research.

The majority of geostationary satellites use infrared and visible sensors to deliver routine observations every 30 minutes. Geostationary satellites excel in temporal resolution but have poorer spectral and spatial resolutions [16,20]. To track and predict the severity of cyclones, it is essential to measure the temperature of the cyclone's eye and the surrounding cloud cover using infrared satellite imagery.

Cloud top temperatures, cloud thickness, cloud categorization, cloud height, and cloud motion vector winds may all be seen in visible and infrared satellite photos. Geostationary satellites with visible and infrared sensors continually gather vital meteorological information and play a key role in keeping track of powerful tropical cyclones. Microwave frequencies are used to get around the visible and infrared bands' restrictions. Microwaves are useful because they can pass through clouds, making it possible to measure atmospheric parameters even when the sky is hazy [19].

The prediction of tropical cyclonic storm paths, intensities, and predictions are improved because to the seamless integration of satellite information into global and mesoscale models. Tropical cyclogenesis may be accurately projected using infrared satellite imagery, giving operational forecasters and emergency management vital time to plan and make preparations.

The Indian Meteorological Department (IMD) is the main organisation in charge of keeping track on and forecasting the weather in India. 24/7 weather data, including surface and upper air observations, is provided through a network of weather observatories. The INSAT series of geostationary satellites, created to suit the operational requirements of meteorology and weather services, is evidence of India's dedication to meteorology and weather forecasting. [3,5].

A Very High Resolution Radiometer (VHRR) payload working in two spectral bands—visible [0.55-0.75 m] and thermal infrared [10.5-12.5 m]—was carried by the INSAT 1 series of satellites, which were launched in the 1980s. These satellites offer hourly meteorological images that reveal cloud systems, their motions, and possible severe weather occurrences in India (ISRO, 2020). Where observational data are limited, INSAT/VHRR pictures are essential for detecting cloud systems overseas and are essential for cyclone tracking, strength assessment, and storm surge forecasts. In order to improve the forecasting of cyclone strength and trajectory, meso-scale models and satellite data are being integrated in current research projects throughout the globe [2,3,4].

Fig 1. View of INSAT

Comprehensive ground and volumetric data are required for atmospheric investigations, however the current monitoring network frequently falls short in these areas. Important weather information is provided by devices including Automatic Weather Stations (AWS), Doppler Weather Radars, Boundary Layer Lidar, and GPS Sondes. These information are fed into weather models, which provide forecasts for the next 24 to 72 hours. As a result, meteorological data paired with satellite observations are an important source for cyclone monitoring and forecasting [5,6]. These models depend on reliable, frequently updated weather data. In order to follow cyclones, detect cloud systems over seas, gauge their severity, and forecast storm surges, INSAT/VHRR photos are frequently used [6].

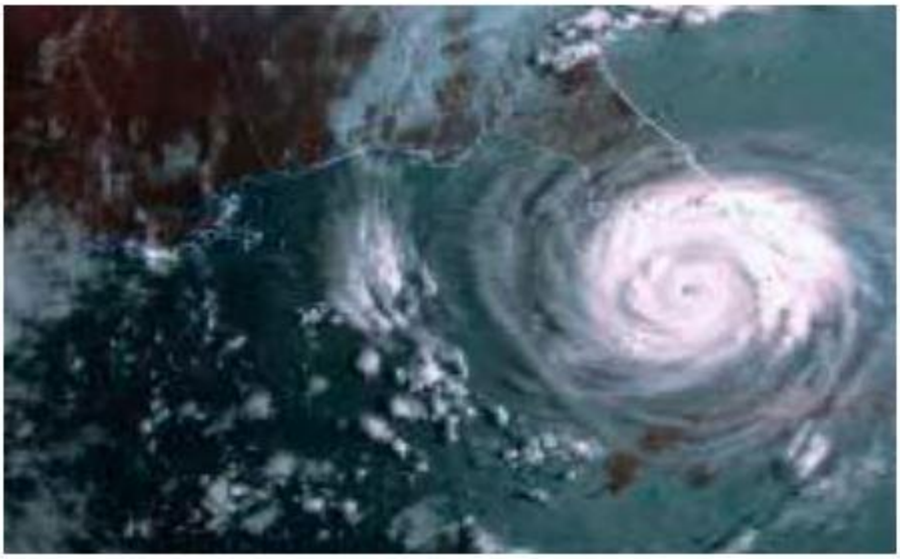

Fig 2. Showing the Tropical Cyclone using INSAT Dataset

Space observations began in 1982 with the deployment of the INSAT satellite, which gave early peeks into the dynamic cloud formations over India. A number of satellites have been operating since the launch of INSAT 1A in 1982, and IMD has compiled a long-term dataset that includes cloud cover, emitted long-wave radiation

(OLR), rainfall, and more. Products from INSAT are positioned to be crucial in local and regional climate change studies. Currently, the VHRR payload aboard INSAT satellites, which works in two spectral bands: visible [0.55-0.75 m] and thermal infrared [10.5-12.5 m], provides global and regional observations. Cloud Motion Vectors (CMVs), Quantitative Precipitation Estimates (QPEs), Vertical Temperature Profiles (VTPRs), and Sea Surface Temperatures (SST) are a few examples of quantitative products created from INSAT data that provide critical numerical insights [7]. Based on the idea that the time delay in the arrival of signals from GPS satellites corresponds with the moisture content and temperature profile of the atmosphere, data from GPS satellites are used to infer atmospheric conditions. Refractivity based Lifted measure (RLI), a novel stability measure proposed, is intended to produce outcomes similar to the lifted index conventionally generated using radiosonde profiles of temperature, pressure, and humidity. Notably, enhanced tropical storm track predictions are shown using Kalpana-1 multispectral Atmospheric Motion Vectors (AMVs). When integrating AMVs from the water vapour channel of the Kalpana-1 satellite into models as opposed to those from the infrared channel, more improvements are seen [8,9]. The main goal of this study is to extract the path of the powerful tropical storm Hudhud in the Bay of Bengal region using digital image processing techniques using Kalpana satellite data. The project specifically attempts to:

- Extract cyclone tracks from the water vapour and infrared bands of the Kalpana satellite data.
- Compare the derived tracks to the most accurate track predictions offered by the data from the Indian Meteorological Department (IMD).
- Compare the infrared band's cyclone tracking ability to that of the water vapour band.

The study article is divided into sections. Section 1 offers an introduction, background information, the two main groups of satellites, and emphasises the significance of satellite data features. Section 2 describes the research methodology, which included using digital image processing methods on Kalpana satellite data. It discusses the extraction and comparison processes for cyclone tracks. Section 3 presents and discusses the research's findings and their significance for forecasting and monitoring tropical cyclones. It also includes a comparison of cyclone tracks derived from the infrared and water vapour bands. Finally, the study report summarises the main findings and their relevance to cyclone monitoring and forecasting.

1. Proposed Approach

Image processing methods are employed to predict the path of the Hudhud cyclone using data from the geostationary satellites Kalpana-1 and METSAT, which are available through the MOSDAC (Meteorological and Oceanographic Satellite Data Archival Centre) data centre. MOSDAC acts as a storage facility for satellite data that is overseen by ISRO and the Indian government. The first meteorological geostationary satellite launched by India, Kalpana-1, is equipped with a Very High Resolution Radiometer and a data relay transponder. In particular, the Kalpana-1 satellite releases photos every 30 minutes.

- For picture capturing, Kalpana-1 provides several unique spectral bands:
- • The visible band only captures photograph during the day and does not provide any images at night. Denser clouds reflect more energy and appear darker in this band [7].
- The thermal infrared band measures temperature variations and provides reliable vision day and night. The ability to measure cloud top brightness temperatures using infrared photos, which are accessible 24 hours a day, is crucial for identifying low, medium, and high-level clouds [21]. Cloud top temperatures may be translated into cloud top heights by examining the temperature profile.

- Cloud top brightness temperature values for high clouds are lower than those for low clouds. In the Thermal Infrared band, cold cloud tops of lofty clouds seem brighter. The Water Vapour (WV) channel further monitors atmospheric water vapour concentrations, with clouds containing a lot of water looking bright [10–12].

A database contains satellite photos that were downloaded from the MOSDAC site [22]. To help in visual analysis, images from the Infrared (IR) and Water Vapour (WV) channels of the Kalpana satellite are given in pseudocolor format, making it easier to quickly identify convective zones and cloud movement. Areas with high intensity values in these photos often denote dense cloud cover in the IR channel and higher water vapour concentration in the WV channel. The identification of thunderstorm clouds is done by combining IR and WV pictures.

Based on these intensity levels, a process for forecasting the cyclone trajectory entails recognising particular cloud types. For instance, the presence of high clouds like cirrus and cirrostratus is suggested by high intensity values in the IR picture and low intensity values in the WV image, but the presence of middle-level clouds like altocumulus and altostratus is suggested by the opposite combination. A tropical cyclone's maximum wind radius is mostly determined by the cyclone eye's radius and, to a lesser extent, by the separation between the eye and the top of the produced cumulonimbus cloud [23,25].

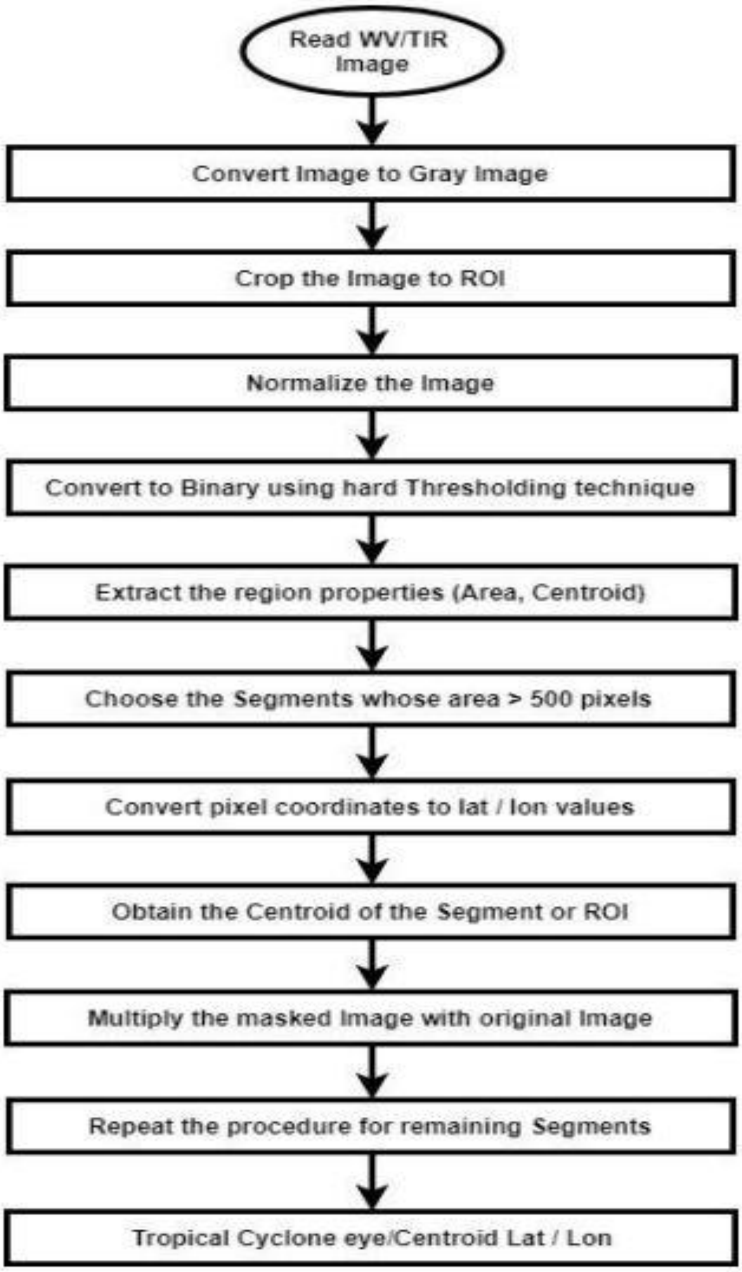

Fig 3. Cyclone Tracking Prediction Flowchart using Image Processing Method

High intensity values in both the IR and WV pictures indicate vertically extended deep clouds like cumulonimbus or thunderstorm clouds. Fig. 3 is a visual representation of the whole cyclone track prediction system. RGB pseudo-color pictures are converted into grayscale using Equation 1 to change the pixel intensity values, which makes it easier to analyse the images. Equation 2 illustrates how normalisation alters the range of pixel intensities and is helpful for enhancing contrast and dynamic range.

$$Y = 0.288\,R + 0.478\,G + 0.121\,B \qquad 1$$

$$Normalized\ Data = \frac{pixel\_value - \min\_value}{\max\_value - \min\_value} \qquad 2$$

Equation 3 explains how the normalised grayscale picture is further transformed into a binary image by thresholding procedures in order to detect cloud areas. The threshold value (T) is applied to the input Kalpana-1 image (f(a,b)) to produce the binary image (h(a,b)).

$$\begin{aligned} h\ a,b &= 1 \qquad if\ f\ a,b > T \\ &= 0 \qquad if\ f\ a,b \leq T \end{aligned} \qquad 3$$

There are two types of thresholding: global and local. Global thresholding applies a single threshold to the whole picture. On the other hand, local thresholding employs several thresholds for separate picture blocks, making it appropriate when the foreground and background of images call for different thresholds. When pictures are evenly lit, global thresholding is preferred [13,24]. The area threshold for extracting the cyclone zone from an image is 500 pixels. The centroid pixel values are then translated into latitude and longitude coordinates. The Kalpana satellite produces a total of 48 photos each day with a 30-minute temporal resolution. To determine the tropical cyclone's course using Kalpana satellite pictures, this technique is repeated.

2.1. Predicting the Tropical Cyclone Tracks

Geostationary satellite images from the Kalpana satellite were processed using image processing algorithms to predict the tropical storm Hudhud's track positions. The specific details concerning the cyclone that was analysed in this inquiry are shown in Table 1.

Table 1: Details of Tropical Cyclone Track Prediction Using Kalpana Satellite Data

S. No	**Name of the Cyclone**	**Start Date**	**End Date**
1	HUDHUD	08/10/2014 0000 UTC	13/10/2014 1200 UTC

2.2. Predicting the Hudhud Cyclone Tracks

Fig 4 and 5 show, respectively, the pictures illustrating the IR and WV bands taken from Kalpana satellite data.

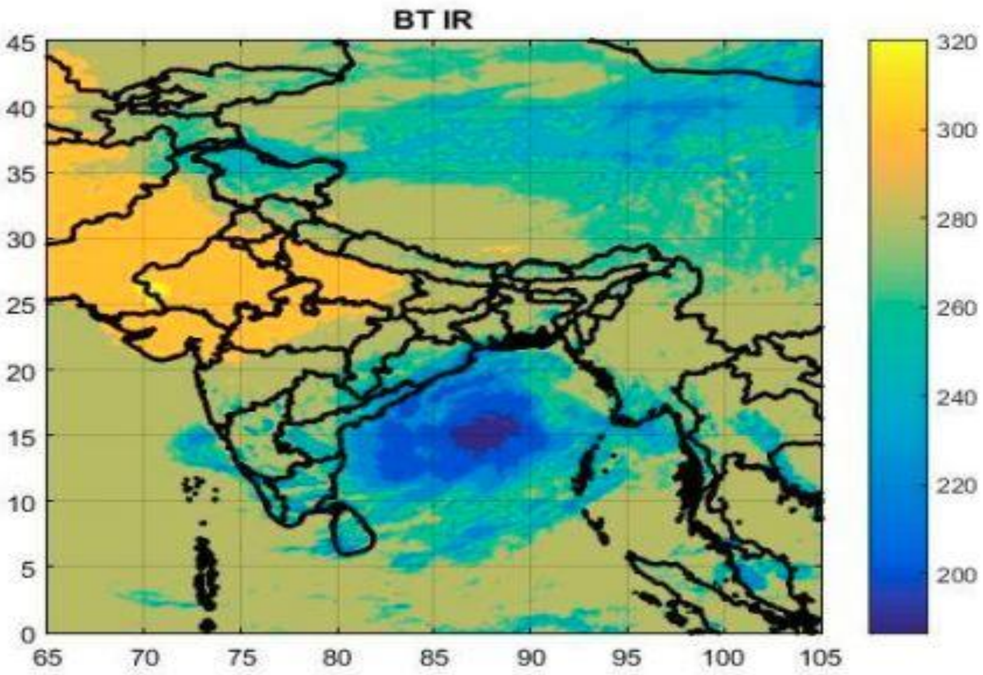

Fig 4 Kalpana IR

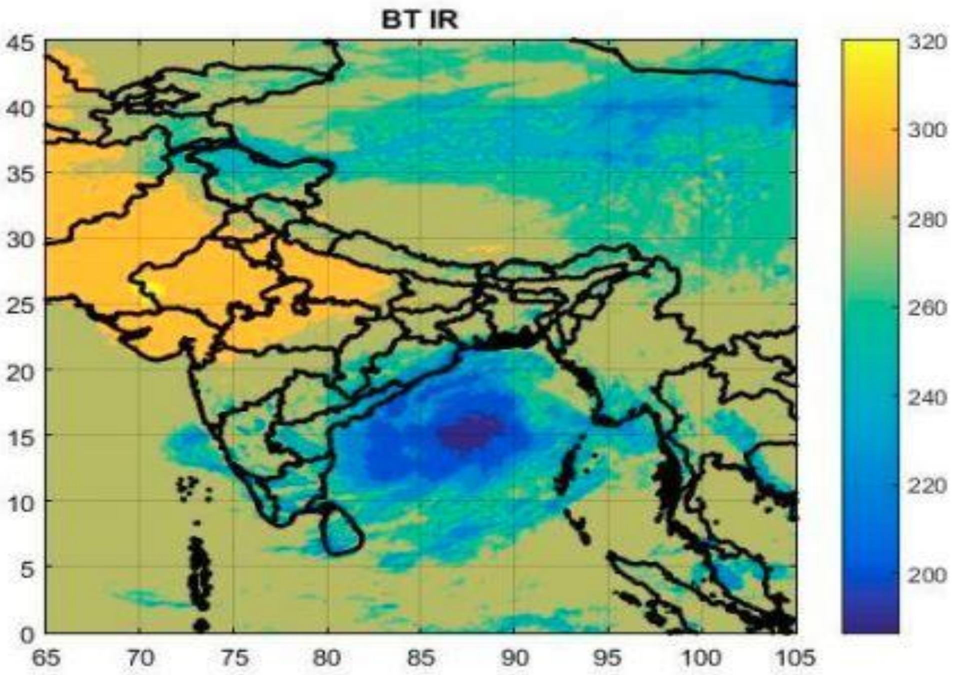

Fig 5 Kalpana WV

Fig. 6 shows the thresholded Kalpana satellite picture next to the map backdrop. The Kalpana satellite picture is then shown in Fig. 7 after the cyclone zone has been extracted.

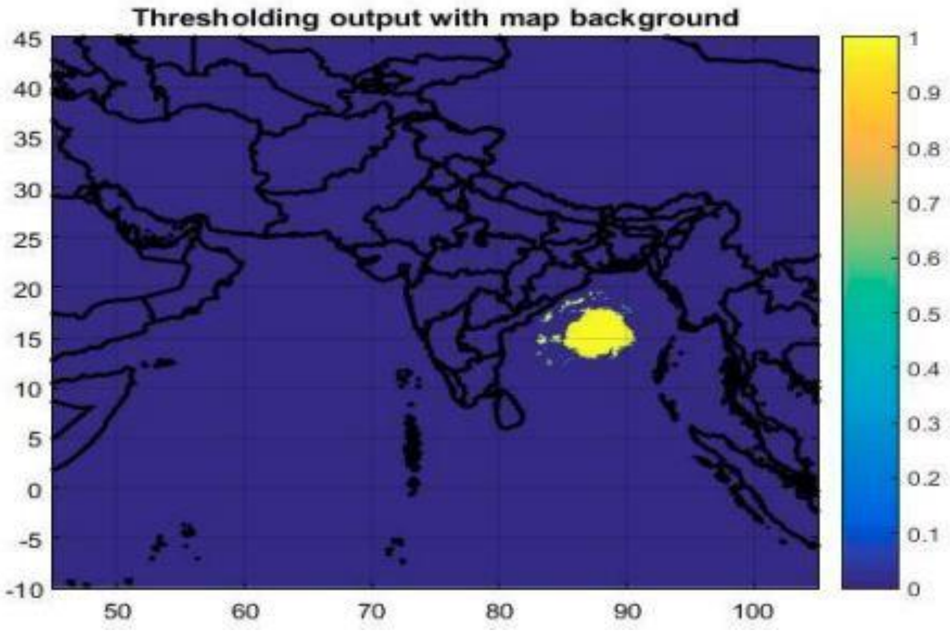

Fig 6 Kalpana satellite Image

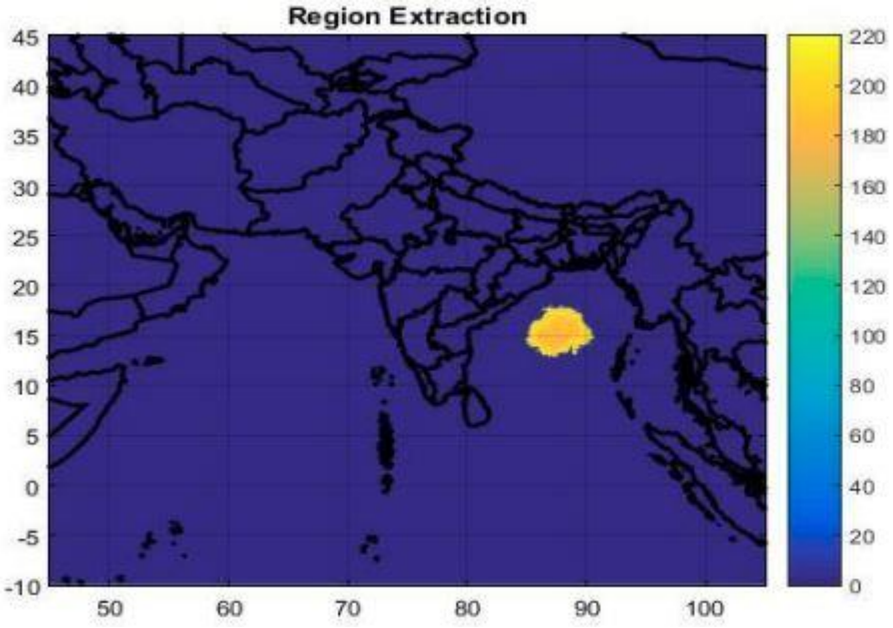

Fig 7 Extracting the Convection Region by Kalpana satellite Image

3. Results

There are representing the experimental result and model execution of our proposed approach.

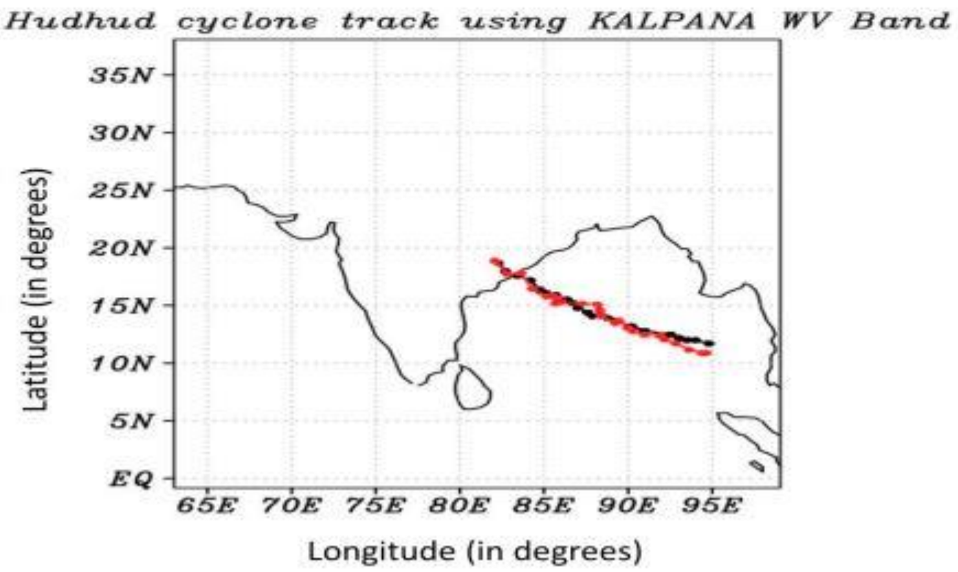

Fig 8 The black line for the IMD course and the red line for the WV Band Track show the prediction of the Hudhud Cyclone course using Kalpana Satellite WV Band imagery.

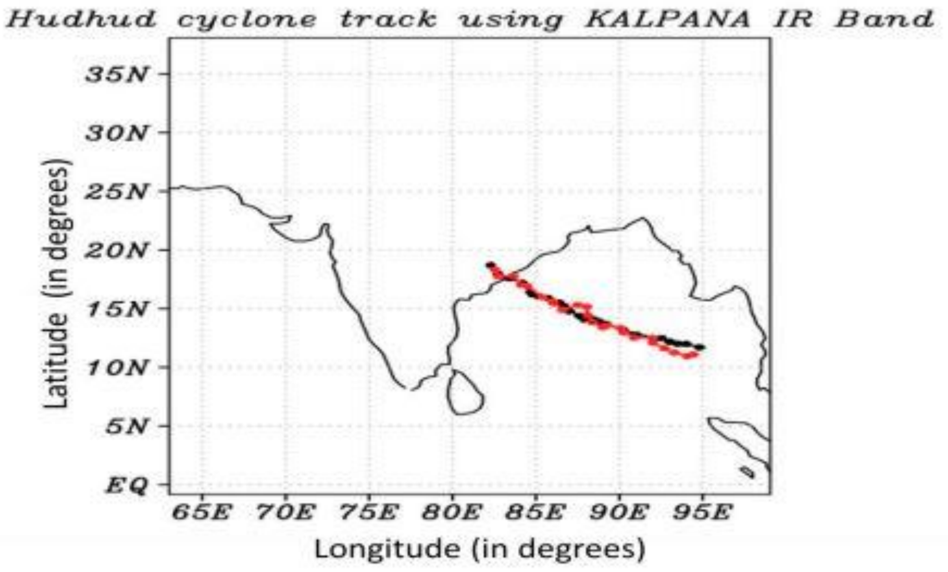

Fig 9 The black line, which represents the IMD course, and the red line, which represents the IR Band Track, indicate the forecast of the Hudhud Cyclone course using Kalpana Satellite IR Band imagery.

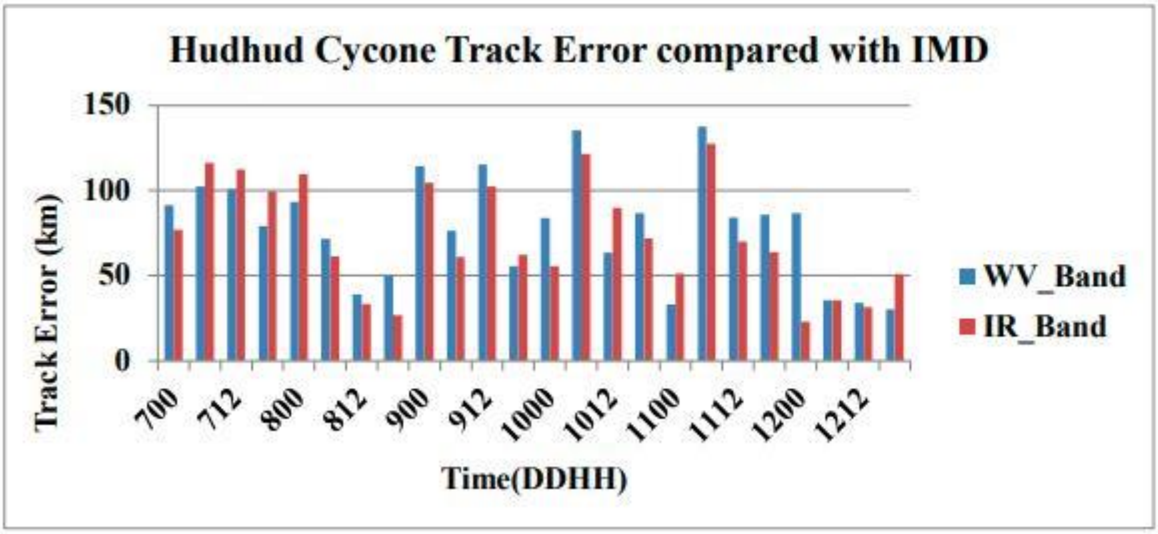

Fig 10 The calculation of the tracking error for the Hudhud Cyclone using Kalpana Satellite images.

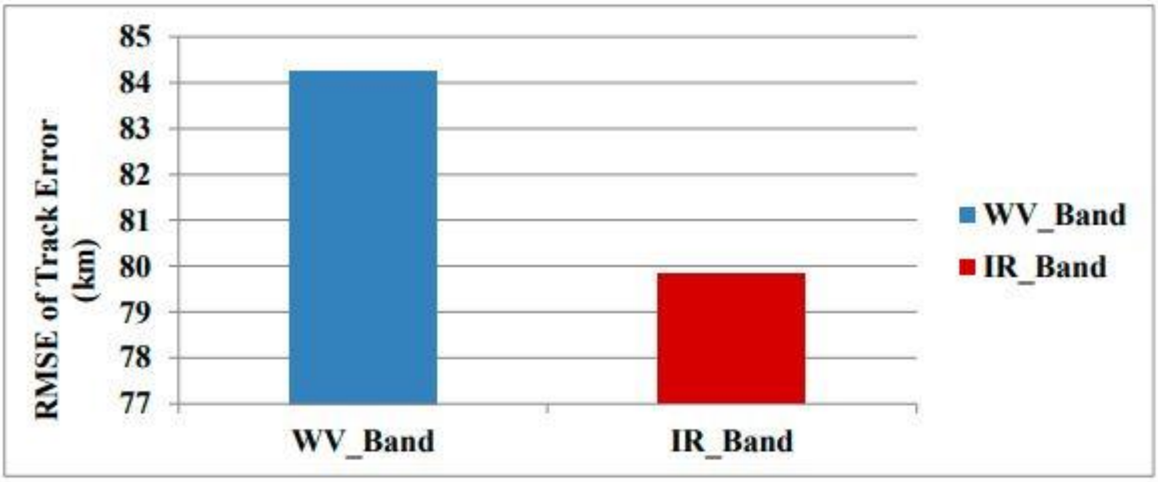

Fig 11 The Hudhud Cyclone's tracking error as measured by the Root Mean Square Error (RMSE) using Kalpana Satellite Images.

Table 2: The Image Processing Method's Track Error's Root Mean Square Error (RMSE)

Serial No.	Kalpana Satellite Data	RMSE (km)
1	WV_Band	84.25
2	IR_Band	79.82

The Kalpana IR_Band, with a length of 79.82 km, has the lowest RMSE when used to track the Hudhud Tropical Cyclone using satellite data. Compared to the WV_Band, this results in an approximately 5% decrease in RMS Error.

Conclusion:

The study emphasises the vital importance of meteorological satellite measurements in tracking, foretelling, and forecasting the motions of tropical cyclones. The quality of these satellite observations, which is determined by several aspects such as sensor features, spatial resolution, orbital parameters, and swath, is crucial for efficient cyclone management and catastrophe preparedness. In this study, we concentrated on using Kalpana-1, the first meteorological geostationary satellite launched by India. The Very High Resolution Radiometer (VHRR) sensor on Kalpana-1 operates in the visible, infrared, and water vapour spectral bands. Despite having various spatial resolutions—2 km for visible, 8 km for water vapour, and 8 km for infrared—each of these bands has significant benefits. The main goal was to use digital image processing techniques on Kalpana satellite data to derive the trajectory of the dangerous Hudhud Tropical Cyclone, which had its birth in the Bay of Bengal region. Our research area included the whole Indian subcontinent, enabling careful comparisons between model-simulated results and pertinent satellite data. Notably, our study was the first to compare cyclone tracks that were retrieved from the infrared and water vapour bands. The best track projections offered by the Indian Meteorological Department (IMD) data were then compared to these results. The outcomes demonstrated the superiority of the cyclone track retrieved from the Kalpana satellite data's infrared band. Additionally, using Kalpana Satellite data, we performed a Root Mean Square Error (RMSE) study for the Hudhud Tropical Cyclone track prediction. The astonishing result showed that the IR_Band had the lowest RMSE, at just 79.82 kilometres. The development of real-time cyclone tracking systems that continually update forecasts based on the most recent satellite data can greatly enhance disaster response and aid in the efficient allocation of resources by the government. Our capacity to successfully monitor and anticipate cyclone behaviour may be improved by collaborative efforts among meteorologists, remote sensing specialists, data scientists, and disaster management authorities.

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