Temporal Monitoring of Hydrocarbon Lake Extents on Titan's Ligeia Mare Based on Cassini SAR Data

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Keywords: Titan, Cassini SAR, Ligeia Mare, Hydrocarbon Lakes, Lake Size Variation, T29 Flyby, T108 Flyby, Methane Cycle, Radar Backscatter, Geomorphology, Surface Evolution, Remote Sensing, Planetary Hydrology, Polar Region, Fluvial Channels.

Abstract

Titan is Saturn's largest moon, which is uniquely positioned in planetary science due to its methane-based hydrological cycle and Earth-like surface processes. The temporal study of lake size variations along the western shoreline of the Ligeia Mare is conducted using Cassini SAR observations from the T29 (2007) and T108 (2015) flybys. The boundaries of the selected lakes were manually delineated using high-resolution BIDR-processed SAR imagery to quantify areal changes. The lakes included Logtak, Sevan, Vanern, and Ohrid Lacus. These lakes were chosen for their distinct visibility and distribution within the study area. A SAR mosaic was generated to compare the spatial extents of the lakes during the two-time frames. The results clearly suggest a loss in surface areas for certain lakes over the 8-year time interval and thus may suggest evaporation, infiltration, or subsurface exchange processes. Such variability in lake size provides a strong argument for an active climate system on Titan along with surface-atmosphere interactions. The study stands in favor of radar data as the effective parameter in monitoring geomorphologic changes on Titan, especially over regions obscured by the dense atmosphere, and adds to the study of Titan's methane cycle and surface evolution.

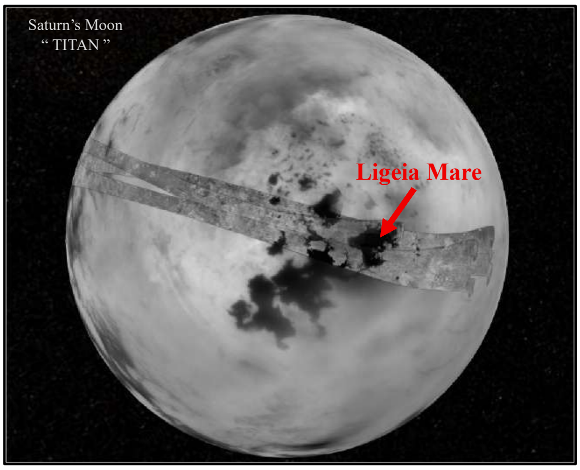
1. Introduction

Titan, Saturn's largest moon, stands out in the solar system due to its dense nitrogen atmosphere, hydrocarbon lakes and likely subsurface ocean (Tobie et al., 2014). Slightly oblate and possibly formed closer to Saturn, Titan shows signs of active surface transport faster than internal adjustment (Andrew et al., 2009). Ligeia Mare, its second-largest sea (~126,000 km²), lies in the north polar region and consists mainly of liquid methane, as confirmed by Cassini's radiometry and altimetry (Le Gall et al., 2016).

The west shoreline of Ligeia Mare shows evidence of dynamic hydrological activity including drowned valleys and rising liquid levels (Hayes, 2016). Using Cassini SAR data from the flybys T29 (2007) and T108 (2015), this study analyzes lake size variation of four small lakes—Logtak Lacus, Sevan Lacus, Vanern Lacus and Ohrid Lacus —located along this margin. The aim of this study is to provide a complete understanding of Titan's surface liquid dynamics, specifically focusing on how its hydrocarbon seas and lakes change in size and affect its climate and hydrological evolution.

2. Study Area

Figure 1 shows a globe representation of Titan with the location of Ligeia Mare which is overlaid by bright SAR swaths from Cassini T25, T28, and T29 flybys and focused



Source: Image generated via NASA Titan Trek Portal using Cassini SAR data (NASA/JPL-Caltech)

Figure 1: Global view of Titan with SAR coverage of Ligeia Mare's western shore from T25, T28, and T29 flybys.

on the north polar region. The study focuses on the western shoreline of Ligeia Mare, located at approximately 80°N, 250°W (Wasiak et al., 2013). This place holds a series of small methane-rich lakes—named Logtak Lacus, Sevan Lacus, Vanern Lacus, and Ohrid Lacus (Barnes et al., 2011). Using the raw Cassini SAR data from the flybys T29 (2007) and T108 (2015), lake

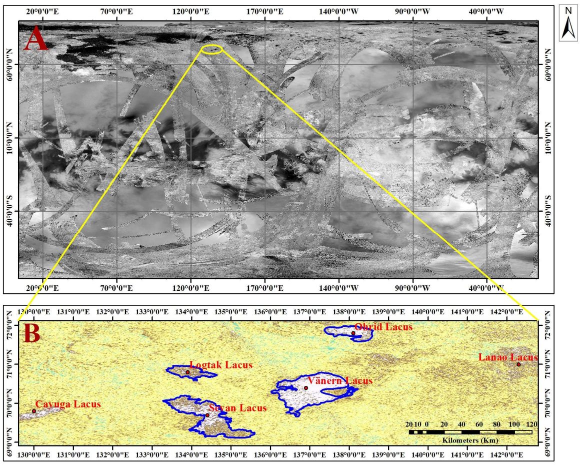


Figure 2. Study Area Map of Ligeia Mare and Nearby Lakes on Titan.

borders were manually digitized to compare size change with time. Radar backscatter patterns and surface features show active river processes and hydrocarbon activity in this polar basin. These characteristics make the area important for studying Titan's water cycle and landscape changes, giving clues about how liquid methane moves, causes erosion, and how the climate might change over time or with the seasons.

3. Datasets And Their Sources

The following datasets were utilized for lake size variation analysis and study area mapping on Titan:

DATA TYPE	SOURCE	RESOLUTION	PURPOSE
Cassini SAR T29 (26-Apr-2007)	NASA Trek Portal/ NASA Planetary Data System (PDS)	175.56 m/pixel	Lake size analysis (2007 observation)
Cassini SAR T108 (Jan-2015)	NASA Trek Portal/ NASA Planetary Data System (PDS)	175.56 m/pixel	Lake size analysis (2015 observation)
Titan SAR HiSAR Mosaic (T104)	NASA Trek Portal	351.11 m/pixel	Background basemap and contextual mapping of study area
Titan ISS Global Albedo Mosaic (June 2018)	NASA Trek Portal	~2.8 km (latitude) or 16 pixel/degree	Study area delineation and surface context visualization

Table 1. Summary of Datasets Used for Lake Size Variation

Multi-temporal and source datasets of the Cassini mission are employed in this study to understand Titan's lake size variations and surface characteristics. Cassini SAR imaging of flybys T29 (2007) and T108 (2015) taken from NASA Trek and the NASA PDS was used at 175.56 m/pixel resolution for change analysis of lake extent. For regional contextualization and basemap creation, Titan SAR HiSAR Mosaic (T104) at 351.11 m/pixel provided high-contrast surface details. Further, Titan ISS Global Albedo Mosaic (June 2018), with about 2.8 km resolution, was used in study delineation and to help surface interpretation.

Synthetic Aperture Radar (SAR) datasets related to T29 and T108 were used for lake boundary extraction, to be compared on the basis of radar backscatter variations. These SAR observations provided consistent coverage of the selected study area during two different mission periods, allowing for a precise evaluation of temporal surface changes. Lake extents were digitized manually for both years, forming the basis for temporal analyses in size variabilities.

The HiSAR Mosaic was used as a base map showing various geomorphic features, while the ISS Albedo Mosaic was used for interpreting surficial features and exact delineation of the study area. These datasets, taken together, help in assessing the dynamics of hydrocarbon lakes in the western polar region of Titan.

4. Methodology

This research methodology focuses on hydrocarbon lake dynamics and shoreline morphology of Ligeia Mare using multi-temporal Cassini SAR data. The workflow included three major phases: Data acquisition, Data pre-processing, and Data analysis.

SAR datasets from flybys T29, and T108 were obtained from NASA Trek and NASA PDS then mosaicked, denoised, and processed to delineate and analyze lake variation. Georeferencing was carried out using the HiSAR global mosaic as a spatial reference to align the datasets from different flybys. The mosaicked scenes were denoised to reduce speckle noise, improving both visual clarity and analytical precision. The processed data were then used for detailed analysis, including manual digitization of lakes. Lake extents from T29 and T108 were compared to assess temporal size changes and surface hydrocarbon dynamics.

The overall workflow adopted in this study is illustrated in Figure 3.

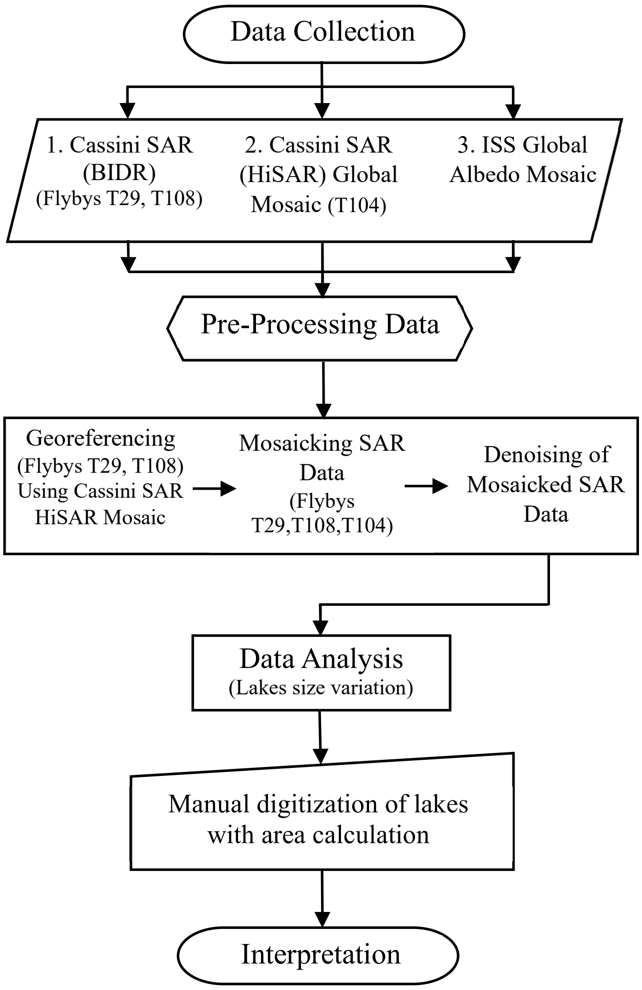


Figure 3. Methodological flowchart of the study.

BIDR's calibrated data are essential for Titan scientific studies as they provide instrument and environmental corrections to SAR backscatter measurements. These corrections are necessary to compare features from different areas and flybys observed under varying geometries. The data are projected using an oblique cylindrical coordinate system aligned with the spacecraft's ground track to minimize distortion and enhance scientific value. BIDRs help in assessing surface texture, identifying geomorphic features like dunes or channels, and evaluating temporal changes.

For this study, BIDR-processed Cassini SAR data from flybys T29 and T108 were specifically selected to analyze the hydrocarbon lake dynamics and shoreline morphology of Ligeia Mare's western margin on Titan.

These datasets provide normalized radar backscatter cross-section values (σ_0), which quantify the radar energy returned per unit surface area and are instrumental in distinguishing surface types. The σ_0 values were calculated from received radar power using the radar equation and then normalized for variations in range, antenna gain, and incidence angle. The radar backscatter cross-section is expressed as: (Stiles, 2005)

$$\sigma_0 = \frac{64 P_r \pi^3 L r^4}{P_t G_r G_{ar} G_{at} A \lambda^2}$$

Here,

P_r is the received power for the pixel,

r is the range of pixel,

P_t is the transmit power,

G_r is the receiver gain,

G_{ar} is the antenna gain of the pixel at receive time,

G_{at} is the antenna gains of the pixel at transmit time,

L is the system loss,

A is the projected pixel area, and

λ is the radar wavelength signal.

5. Lakes Size Variation Analysis

The figure below illustrates the spatial extent of four hydrocarbon lakes—Logtak Lacus, Sevan Lacus, Vanern Lacus, and Ohrid Lacus.

These are identified from Cassini SAR data acquired during the T29 flyby in year 2007. In below figure 4 the top panel provides a regional view of the SAR swath coverage and bottom panel present a detailed map of

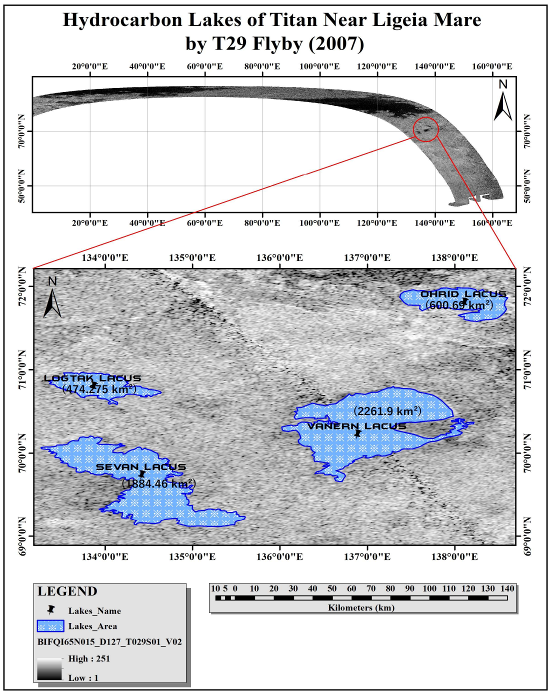


Figure 4. Hydrocarbon Lake Size Variation on Titan from T29 (2007) Flyby

individual lakes, each shown in blue with corresponding surface area values (in km²) marked in black. The lakes exhibit low radar backscatter, appearing as dark regions consistent with liquid-filled basins, whereas surrounding terrains show higher backscatter values, which indicate rougher or solid surfaces. These tonal contrasts assist in distinguishing liquid bodies from surrounding geology and offer insights into Titan's polar geomorphology and surface material composition.

The surface areas and geographic coordinates of the selected lakes from the Cassini SAR T29 flyby (2007) are presented in the table below:

S.No.	Lake Name	Total Area	Latitude (°N)	Longitude (°E)
1.	Logtak Lacus	474.275	70.81	133.86
2.	Sevan Lacus	1884.46	69.74	134.41
3.	Vanern Lacus	2261.9	70.22	136.87
4.	Ohrid Lacus	600.69	71.80	138.09

Table 2. Total Calculated Areas and Coordinates of Selected Lakes from Cassini SAR T29 (2007) Flyby

Above table presents the total calculated areas and geographic coordinates of the selected lakes—Logtak, Sevan, Vanern, and Ohrid Lacus—derived from the Cassini SAR T29 flyby (2007). Among these, Vanern Lacus exhibits the largest surface area of approximately 2261.9 km², followed by Sevan Lacus with 1884.46 km², indicating their dominance within the studied region along Titan's western shoreline of Ligeia Mare.

Logtak Lacus and Ohrid Lacus, with their respective areas of 474.28 km² and 600.69 km², are located at slightly higher latitudes than the other lakes and their formation is therefore likely to have occurred in depressions that were elevated or smoothed off by their topography. The tight grouping of the bearish (latitude and longitude) between 69°N and 72°N means that the four lakes are all in the northern polar area of Titan. This distribution can be seen as a starting point for monitoring any changes and movements of hydrocarbons in the future flybys.

In below Figure 5, two images from the T108 flyby (2015) Cassini SAR swath are shown. The top panel gives a regional view, highlighting the main hydrocarbon lakes near Ligeia Mare. The bottom panel zooms in on the study area, where lakes Logtak, Sevan, Vanern, and Ohrid Lacus are clearly marked in green, with their naming in black and surface areas labelled in blue (km²). These mapped features help compare changes over time and show backscatter differences similar to the T29 data, improving our understanding of Titan's surface water cycle.

The green shading marks confirmed liquid-filled basins, while the higher backscatter around them suggests solid or rough terrain. You can clearly see differences in lake sizes, allowing for comparison across flybys. These images are important for spotting landform patterns and tracking Titan's methane-based water processes over time.

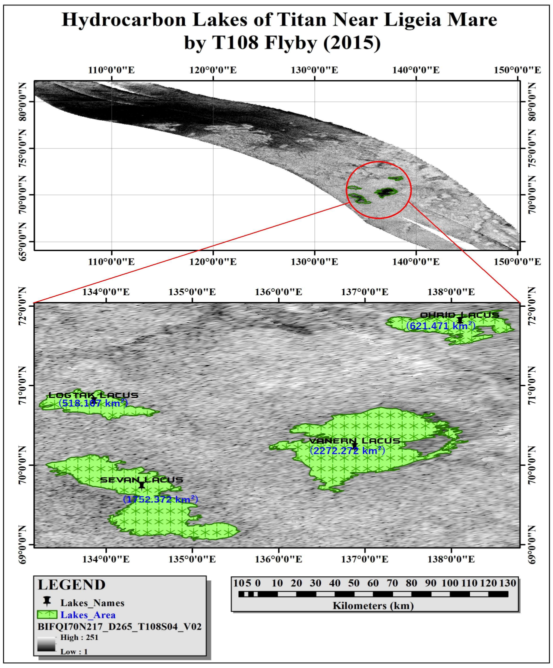


Figure 5. Hydrocarbon Lake Size Variation on Titan from T108 (2015) Flyby

Below table present the surface area with coordinates of the lakes from T108 (2015) flyby:

S.No.	Lake Name	Total Area	Latitude (°N)	Longitude (°E)
1.	Logtak Lacus	518.107	70.81	133.86
2.	Sevan Lacus	1752.372	69.74	134.41
3.	Vanern Lacus	2272.272	70.22	136.87
4.	Ohrid Lacus	621.471	71.80	138.09

Table 3. Total Calculated Areas and Coordinates of Lakes from T108 (2015) Flyby

This table displays the total measured areas as well as the geographic locations of the four chosen lakes which are situated on Titan's western coast. Among these lakes, Vanern Lacus is the largest with a surface area of about 2272.27 km² and is followed by Sevan Lacus with 1752.37

km², which shows their prevalence within the monitored hydrocarbon system.

Logtak and Ohrid Lacus, whose areas of 518.11 km² and 621.47 km² are much smaller than the others', are positioned at slightly higher latitudes, which implies that possibly topographic or climatic factors are at work in the development and preservation of these lakes. The latitude and longitude figures corroborate the proximity of these lakes to one another in the extremely northern polar region where stable methane-ethane reservoirs occur more frequently. This geographical positioning corresponds to earlier Cassini findings, thus underlining the fact that Titan's most significant lacustrine features are gathered around the north pole.

6. Conclusion

Based on the temporal analysis of the variations in lake size along the western shore of Ligeia Mare on Titan, the study revealed an active hydrocarbon lake behaviour occurring between the T29 (2007) and T108 (2015) Cassini SAR flybys. Changes involving the four lakes of interest, Logtak Lacus, Sevan Lacus, Vanern Lacus, and Ohrid Lacus, were analyzed for their surface areas.

Lake Name	Total Area of Flyby T29	Total Area of Flyby T108	Change in Area (km^2)	Trend
Logtak Lacus	474.275	518.107	+43.832	Expanded
Sevan Lacus	1884.46	1752.372	−132.088	Shrunk
Vanern Lacus	2261.9	2272.272	+10.372	Expanded
Ohrid Lacus	600.69	621.471	+20.781	Expanded

Table 4. Change in Titan Lake Areas Between Flybys T29 (2007) and T108 (2015)

As seen in Table 4, the area of Logtak Lacus has been remarkably increased by about +43.83 km², and this is probably due to the methane accumulation on the surface that was going on between the flybys of 2007 (T29) and 2015 (T108). Furthermore, Vanern Lacus and Ohrid Lacus also show an increase in their surface area: by +10.37 km² and +20.78 km² respectively, are the positive numbers. In opposition to this, Sevan Lacus reveals a very strong decrease of −132.09 km², which can be interpreted as a possible liquid volume decline or even fragmentation during the same period.

All the lake-size changes mentioned above suggest that Titan's hydrocarbon systems are still very active and dynamic in the region of the western shore of Ligeia Mare, and it is even possible that these are governed by seasonal or episodic processes of methane precipitation, evaporation or subsurface exchanges. It is possible that the regions showing positive changes are the ones where either the inflow of methane or the amount of precipitation has increased, whereas the negative trend observed in Sevan Lacus may be due to water being drained, evaporated, or being absorbed by the subsurface material which is porous.

In conclusion, the changes in the sizes of the lakes have been a major proof of the operation of Titan's methane-based hydrological cycle in the freeze-thaw conditions akin to those on the Earth's water cycle, thus giving us an insight into the interaction of Titan's surface and climate and its long-term environmental evolution.

Abbreviations

SAR	Synthetic Aperture Radar
HiSAR	High-Resolution Synthetic Aperture Radar
ISS	Imaging Science Subsystem
BIDR	Basic Image Data Record
NASA/JPL	National Aeronautics and Space Administration /Jet Propulsion Laboratory
PDS	Planetary Data System

Acknowledgment

The authors of this paper sincerely acknowledge the availability of Cassini SAR datasets through the NASA Trek and NASA PDS Portals which were instrumental in the data acquisition, processing, and analysis conducted in this study. The authors also extend their gratitude to the Indian Institute of Remote Sensing (ISRO) and Doon University, Dehradun, for providing the academic and technical support necessary to complete this research work. Additionally, the authors acknowledge the constructive assistance of artificial intelligence (AI)-based tools which were utilized to enhance the clarity, structure, and language refinement of the manuscript.

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