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Key Points:

- First direct evidence of the presence of liquid channels on Titan
- First observation of hundred meter deep canyons on Titan
- Vid Flumina canyons are drowned by the sea, but few isolated observations show the presence of surface liquids standing at higher elevations

Supporting Information:

- Supporting Information S1
- Figure S1
- Figure S2
- Figure S3
- Figure S4

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Liquid-filled canyons on Titan

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Abstract In May 2013 the Cassini RADAR altimeter observed channels in Vid Flumina, a drainage network connected to Titan's second largest hydrocarbon sea, Ligeia Mare. Analysis of these altimeter echoes shows that the channels are located in deep (up to ~570 m), steep-sided, canyons and have strong specular surface reflections that indicate they are currently liquid filled. Elevations of the liquid in these channels are at the same level as Ligeia Mare to within a vertical precision of about 0.7 m, consistent with the interpretation of drowned river valleys. Specular reflections are also observed in lower order tributaries elevated above the level of Ligeia Mare, consistent with drainage feeding into the main channel system.

1. Introduction

Saturn's largest moon, Titan, has an active methane-based hydrologic cycle [Lunine and Atreya, 2008] that drives the formation and evolution of morphologic features and processes with striking similarities to those found on Earth [Hayes, 2016]. Titan's north polar region is partially covered by three large hydrocarbon seas (in order of areal extent: Kraken, Ligeia, and Punga Mare) that have been observed by the Cassini RADAR [Elachi et al., 2004] using its synthetic aperture radar (SAR) mode (Figure 1, left). Prior analysis of radar altimeter mode data acquired in May 2013 (T91 flyby) revealed reflections from both the seabed and sea surface. Mastrogiuseppe et al. [2014b] used the time difference between these reflections to measure depths up to 160 m along the altimetry track. The relative returned power between the surface and subsurface reflections was used to estimate the liquid loss tangent, the low value of which implies a methane-dominated composition [Mastrogiuseppe et al., 2016]. As formerly predicted by Lorenz [1993], Ori et al. [1998], and others, Titan also has networks of fluvial valleys and channels that extend for hundreds of kilometers across the surface at all latitudes [Lorenz et al., 2008; Burr et al., 2013]. The most prominent examples are in the north polar region, where 90% of the surficial liquids are located. Herein, we report an analysis of altimetry echoes acquired from Vid Flumina (Figure 1, right), a network of channels that drain into Ligeia Mare.

Even though SAR images reveal the presence of sinuous radar-dark features interpreted as fluvial valleys [e.g., Burr et al., 2013], they do not directly prove the physical extent and/or presence of liquid filling them. Such features display a variety of forms and characteristics quite similar to our terrestrial examples [Burr et al., 2013], and due to their low microwave backscatter, it has been assumed that they are liquid filled like the seas, yet no direct measurement has ever been made to demonstrate such a claim.

Herein, we use Cassini Ku band ($\lambda = 2.17$ cm) radar altimeter nadir observations to directly detect the presence of liquid in Titan's north polar channels and characterize their width and geomorphologic context. Altimeter returns from the Vid Flumina channels are highly specular, and the measured steep increases in backscatter with respect to the surroundings require surfaces roughness on the millimeter scale over the ~250 m diameter of the Fresnel zone (see below). Similar to Wye et al. [2009], Zebker et al. [2014], and Mastrogiuseppe et al. [2014b], we interpret these smoothness constraints as requiring liquid surfaces. This represents the first direct detection of liquid-filled channels on Titan. Furthermore, channels exhibit canyon-like morphology, with the liquid surface elevations of the higher-order tributaries of the Vid Flumina network (herein we will refer to the Strahler stream order [Strahler, 1957]) occurring at the same elevation as Ligeia Mare. We also find lower order tributaries with liquid surface elevations above the level of Ligeia Mare, consistent with elevated tributary networks feeding into the main channel system.

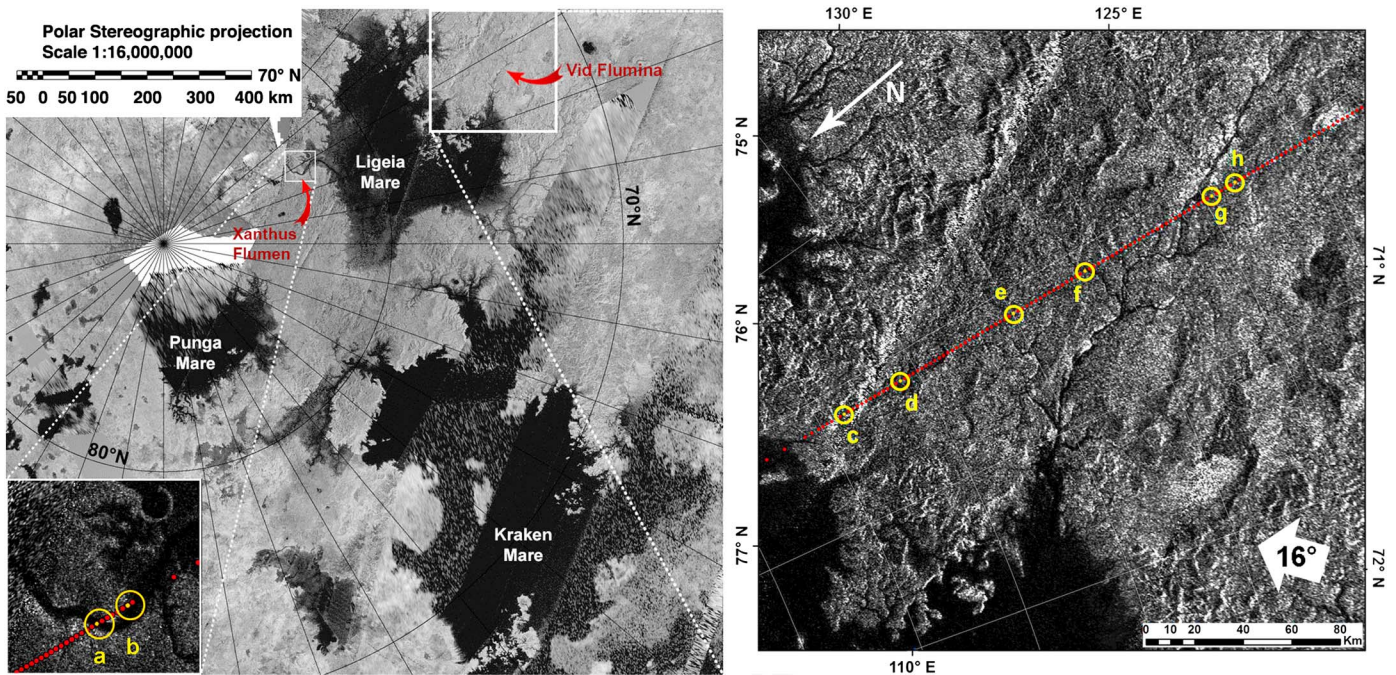


Figure 1. The northern polar area of Titan and Vid Flumina drainage basin. (left) On top of the image, the Ligeia Mare; in the lower right the North Kraken Mare; the two seas are connected each other by a labyrinth of channels. On the left, near the North pole, the Punga Mare. Red arrows indicate the position of the two flumina significant for this work. At the end of its mission (15 September 2017) the Cassini RADAR in its imaging mode (SAR+ HiSAR) will have covered a total area of 67% of the surface of Titan [Hayes, 2016]. Map credits: R. L. Kirk. (right) Highlighted in yellow are the half-power altimetric footprints within the Vid Flumina drainage basin and the Xanthus Flumen course for which specular reflections occurred. At 1400 km of spacecraft altitude, the Cassini antenna 0.35° central beam produces footprints of about 8.5 km in diameter (diameter of yellow circles). It is easy to note that we do not have a specular reflection at each intersection of the altimetric track with the channels. This is mainly due to the very limited area covered by the Fresnel zone (~250 m) and to the 0.6 s of the Burst Repetition Interval of the radar. The result is that in some cases the Fresnel zone just missed the strong reflection from the liquid coming from nadiral direction.

2. Radar Observations of Channels

Vid Flumina is classified as a dendritic network whose links span for total length of 412 km [Burr et al., 2013]. Its drainage basin has been imaged several times by SAR (notably on flybys T28, T86, and T92), where it appears as a branching, sinuous, radar-dark feature that terminates at the shoreline of Ligeia Mare. The very low backscatter may be indicative of the presence of a smooth surface, absorptive materials, or a shadowing effect. This SAR-dark appearance contrasts with many of Titan’s equatorial channels, which instead appear radar bright [Lorenz et al., 2008; Le Gall et al., 2010]. In such cases, the brightness of the channels could indicate dry river beds with coarse gravel and/or strongly retroreflective cobbles [Le Gall et al., 2010]. The May 2013 T91 altimeter track, which crossed a number of Vid Flumina’s channels, provides an opportunity to understand this scattering difference by combining SAR images with closest-approach altimetry observations.

The morphological similarities of Titan’s dark patches shown in SAR images with terrestrial lakes, their location in topographic depressions, and the presence of branching valley networks along the seas shorelines have been used to suggest that these features are liquid filled [Stofan et al., 2007; Hayes et al., 2008; Wye et al., 2009]. Furthermore, the exceptionally strong reflection from altimetry returns with subradar point that falls onto these radar-dark patches requires exceptional flatness of $< 2.7 \text{ mm}$ ($= \lambda/8$, according to the Rayleigh Criterion) root-mean-square (RMS) height and is a strong indication of the liquid nature of these features. In fact, reflections are specular when received from a smooth plane reflector and comply with the Fresnel reflection laws. In these cases, the backscattered signal, composed by both coherent and incoherent power, is mainly dominated by the coherent component and the resulting fraction of total incident power specularly reflected is equal to $e^{-2(2\pi\sigma_n/\lambda)^2}$ [Skolnik, 2008]. It is also interesting to note that Cassini has observed liquid-filled channels previously—strong near-nadir radar echoes observed during Cassini’s flyby of Earth were determined [Lorenz et al., 2001] to be due to the dammed Paranaiba River in Brazil.

When a specular reflection occurs, the transmitted signal is reflected by the Fresnel zone, an area that is located at nadir when observing a liquid surface and whose diameter is always smaller than a few hundred meters at the operative altitudes of the Cassini radar altimeter. See also *Grima et al.* [2012], who exploited these concepts for determining surface roughness on Mars. In 2014, *Zebker et al.* [2014] provided estimates regarding the surface flatness of Ligeia Mare, indicating RMS height values of roughness σ_h ranging from 0.5 to 1.5 mm over the Fresnel zone. Contributions coming from scatterers composing these extremely flat surfaces add coherently and yield the raw signal to assume unexpected strong amplitudes that occasionally caused the Cassini RADAR receiver saturation [*Wye et al.*, 2009].

In order to show the liquid nature of the Vid Flumina channels, we compare the backscattering values (σ_0) obtained by the Cassini radar altimeter for the T91 flyby with those pertaining to all solid surfaces of Titan. The exploited data set consists of all altimetric observations from Ta to T98, covering roughly 10 years of the Cassini mission and excluding all observations of Ontario Lacus (T49), Ligeia Mare (T91), small lakes of T92/T95, and putative tropical lakes of T98. As a result, Vid Flumina channels are characterized by σ_0 values (~ 30 dB) that no solid surface of Titan, observed to date by the altimeter, has been capable to produce (see the supporting information for more details, in particular, Figure S2).

3. Measurements and Results

We selected eight bursts along the T91 altimetric track, two north of Ligeia Mare and six to the south (Figure 1), that are marked from “a” to “h.” Mean surface height estimations useful for outlining the topographic profile are obtained by tracking the centroid of the observed power distribution, as described by the first moment of the altimetry echo with respect to time [*Zebker et al.*, 2009]. The resulting profile is characterized by significant decreases of hundreds of meters (Figure 2, middle), to which correspond strong enhancements in the level of received power (Figure 2, top).

Among these eight observations, the -3 dB antenna footprints relative to features “e,” “f,” and “g” are perhaps the most interesting because they illuminate areas crossed by two tributary branches of Vid Flumina (e and f) and by its main trunk (g). The elevation profile of the regions comprising these specular reflections shows the presence of deep and tight valleys that range in depth from 220 to 330 m with respect to the surrounding terrain and less than a kilometer in lateral extent (see below). The associated specular reflections, as we have seen, suggest that the bottom of these canyon-like features are very smooth with respect to the Cassini RADAR incident wavelength, a typical characteristic of altimeter returns from Titan’s liquid bodies. Considering the high values of backscatter recorded on the channels (above any solid surface of Titan), we determine the elevation of the floor of these channels with respect to the surface of Ligeia Mare in order to infer the process that led to the formation of such features and, at the same time, investigate possible hydraulic connections between Vid Flumina channels and the sea that SAR images clearly would suggest (e, f, and g).

First, we examine specific shape of the received altimetric waveforms (Figure 3, right columns). Targeted radar signal simulations (an example of which is also represented in Figure 3) have explicitly shown that saturated echoes from canyon floors, including specular reflections, are expressed as three-peaked waveforms. With reference to the arrival time, the first reflection is attributed to the canyon rim and surrounding topography. The second and most powerful peak of the triplet is perfectly symmetrical in shape at -6 dB and is identifiable as the reflection returning from the flat liquid surface at the bottom of the canyon. We interpreted the third peak as a postcursor echo or “ghost echo,” which is an effect that has been observed in terrestrial data by *Wingham and Rapley* [1987] using the Seasat altimeter. This artifact is the result of instrument saturation and has been studied by *Mastrogiuseppe et al.* [2016] using data acquired over Ontario Lacus (T49) and Ligeia Mare (T91) along with radar data simulations. Simulations have been able to reproduce saturation effects, including also distortions introduced by the Cassini RADAR’s 8 bit analog to digital converter and the 4 bit block adaptive quantizer. In both *Wingham and Rapley* [1987] and *Mastrogiuseppe et al.* [2016], finally, it is shown that the range measurement of well-defined precursors and postcursors is unaffected. Regarding the Vid Flumina waveforms, the first and third peaks are precisely symmetric in time with respect to the echo received from the liquid channel. As such, our interpretation of the data from both the SAR images and individual altimetric waveforms is a scenario where there are two main reflectors, one associated with the smooth liquid surface at the canyon bottom and another that corresponds to the elevated, surrounding terrain adjacent to the canyon (Figure 3, left column).

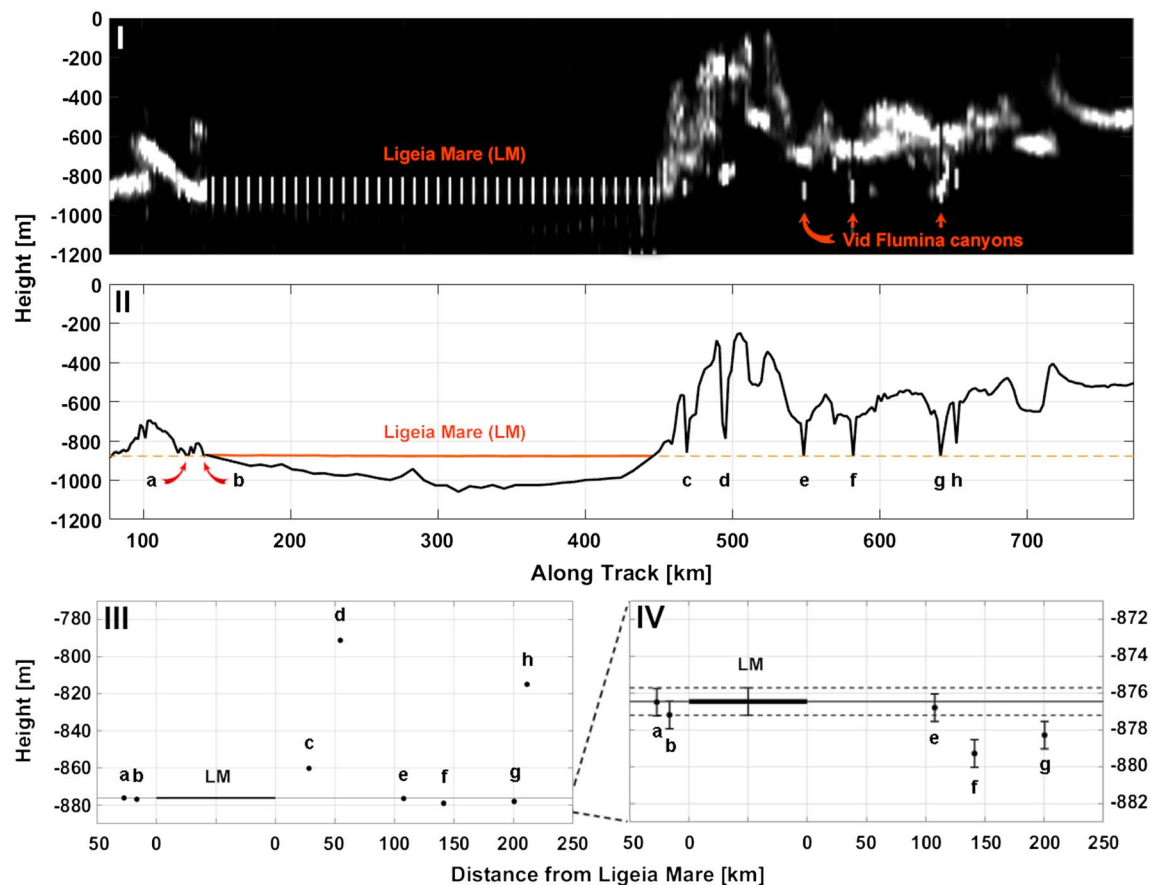


Figure 2. Radargram and results. (top, I) Each column of the radargram represents an incoherently averaged echo received during the T91 flyby from the region hosting Ligeia Mare and channels. Pixel intensity indicates the received backscatter as function of time. The surface of Ligeia Mare is dotted because of the peculiar design of the T91 flyby, which consisted in an alternated acquisition of echoes from a nadir and a slight off-nadir antenna pointing geometry. Arrows indicate specular reflections from the main trunk (feature g) of Vid Flumina and from two of its tributary branches (features e and f). (middle, II) Titan's heights given by the Cassini Processing of Altimetric Data (CPAD) are reported as relative to a 2575 km sphere, centered at Titan's center of mass [Alberti *et al.*, 2007]. Observations featuring specular reflections from the liquid are indicated with progressive letters from north to south; the position of Ligeia Mare can be recognized by the extremely flat region extending from about 140 to 440 km along track; Vid Flumina hydrographic basin interests an area ranging from about 440 to 680 km along track. The altimetry profile shown here is useful to give an idea of the geomorphologic shape of the area and highlines the relative flatness of the surface, whose greatest elevation difference between higher and lower points is about 630 m. This profile has been produced by means of a centroid tracker, which is a leading edge estimator based on the Offset Centre of Gravity algorithm. In particular, we used the I moment tracker, which sets the altimetric echo two-way travel time by computing the centroid of the observed power distribution, as described by the first moment of the echo with respect to time. For all the echoes relative to channels, the centroid has been computed only on that portion of the signal reflected from the liquid. (bottom left, III) Channel level and relative distance from the sea along the T91 altimetric track. Measurements have been provided with an error bar indicating a 2σ precision of ~ 0.7 m (see the supporting information for further details). The mean Ligeia Mare level is at -876.5 m. This panel shows a coarse detail altimetry of the levels of the liquids filling the channels. (bottom right, IV) This panel shows a more detailed altimetry spanning in a reduced range of heights around the sea level. Note that the features that stand about at the same level of the sea, in this more detailed figure, are placed in a range of heights from 0 to 2.8 m below the mean sea level (see the supporting information for further details).

Because of the uncertainty in spacecraft orbit tracking, the absolute elevations determined in different Cassini flybys may have relative errors of about 100–200 m [Zebker *et al.*, 2009]. However, for the purposes of this study we exclusively consider the T91 flyby; uncertainties along a single track are much smaller. We find that to within a ~ 0.7 m precision (2σ , see the supporting information), all the echoes received from Vid Flumina's main trunk and tributary branches (in particular e, f, and g) are found to be at the same level as the sea surface, even though they are located in a wide range of horizontal distances from Ligeia Mare (Figure 2, bottom row). For all the echoes relative to channels, the centroid has been computed only on that portion of the signal reflected from the liquid. Since the scattering is almost fully coherent, the obtained waveform resembles the radar impulse response and we are able to apply a time window, which selects that interval included between the -10 dB points with respect to the peak.

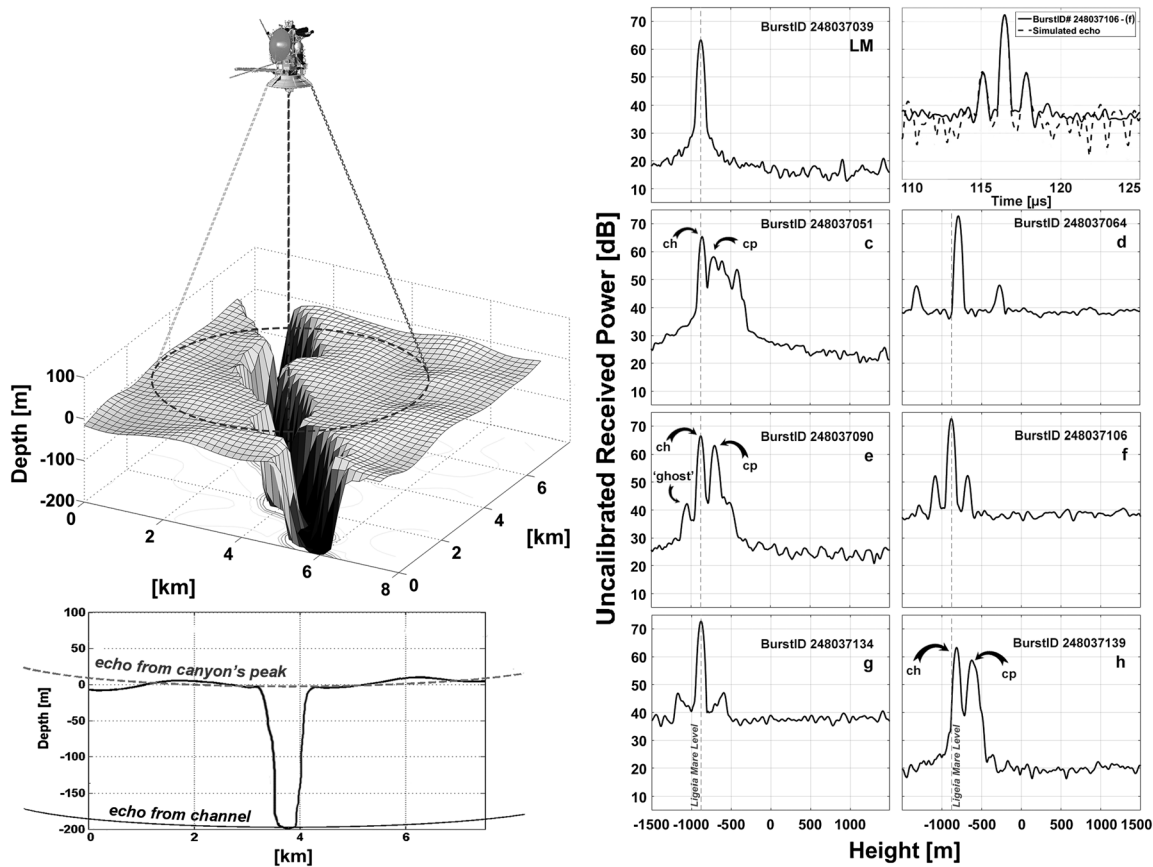


Figure 3. Acquisition scenario and echoes received from Vid Flumina canyons. (left column) Simplified scheme of Cassini radar altimeter observing a canyon. The nadir looking antenna receives first the echo from the overlying surface, and then it receives the strong reflection from the smooth liquid surface of the channel at the bottom of the canyon. (right columns) Cassini altimetric time series acquired during flyby T91 over the Vid Flumina canyons. Blackman taper function and incoherent averaging were used to process the received echoes. The echo indicated as “LM” (Figure 3, top left) is one of those acquired on Ligeia Mare, and it is used here as a reference to indicate the sea level (see the dotted gray line). Received echoes (from c to h) are characterized by a first echo from the canyon’s peak (or “cp”), a second one from the liquid channel (or “ch”) and a third (named “ghost”). The “ghost signal” is an artifact due to saturation occurring in the Cassini RADAR receiver. This postcursor is located in a time-symmetric position respect to the echo associated to the reflection from the peak of the canyon. In the case of echo c the isolation of the specific peak relative to the canyon edge has been possible thanks to a range-Doppler analysis. In Figure 3 (top right) a comparison between the echo received from the canyon located at feature f and a simulated echo. The simulator makes use of a SAR image of the area comprising the canyon of interest for generating the most likely scenario, which is therefore represented by means of the facet method [Casoli and Seu, 1996] as a Brownian surface of dimensions larger than the -3 dB footprint scale. Hagfors model is adopted in order to retrieve scattering from each facet relative to surroundings and walls of the canyon [Hagfors, 1964]. Finally, we modeled the flat liquid surface of channel as a single scatterer located at nadir characterized by radar cross section described by Picardi et al. [1992]. In order to obtain the simulated echo shown in figure, we set depth of the canyon according to the depth measured for feature f (243 m) and a RMS height of macroscale surface roughness of 18 m for the area surrounding the canyon. As a result it is possible to appreciate the simulation ability to reproduce signal postcursors due to the strong saturation of channels altimetric observations.

The measurement of the time interval between the first two echoes is a direct measure of the depth of the canyons. In particular, we measure the time delay from the leading edge of the first echo (-6 dB from the peak) to the peak of the second echo associated to the liquid. In this way, we obtain an estimate of the mean level of the area illuminated by the altimetric footprint. The precision of the depth measurements of these canyons is mainly dependent on the signal-to-noise ratio (SNR) of the signal reflected from the surface at the cliff’s edge and on the large-scale vertical roughness of this surface itself. Thus, it can be inferred to be in the same order of the radar range resolution (35 m, see the supporting information). See Table 1 for the reported measurements of all canyon depths.

Using T28 flyby SAR images, and following the method described in detail in the supporting information, we have been able to measure the width of the two sections of Vid Flumina comprising features f (a first-order tributary) and g (main trunk). In these two sections, respectively centered around footprints f and g, the width that we measure for both ranges roughly from 0 to 1 km, with a mean value of 0.7 km. The abrupt changes in

Table 1. Saturation Has Been Evaluated by Taking Into Account the Number of Clipped Amplitude Samples of the Returning Chirped Signal Respect to Its Whole Length^a

Feature	Flyby	Burst ID	Latitude (deg)	Longitude (deg)	Altitude (km)	Off Nadir (deg)	Saturation (%)	SNR (dB)	σ_0 (dB)	Sea Distance (km)	Canyon Depth (m)	Liquid Level (m)
a	T91	248036839	83,32	117,18	1793.01	0.0259	61	35,12	27,94	27	-	-876,5
b	T91	248036845	83,08	117,30	1780.55	0.0239	59	35,38	27,50	16	-	-877,2
c	T91	248037051	75,76	240,98	1458.22	0.0349	0	43,11	19,13	28	171	-860,4
d	T91	248037064	75,17	240,92	1437.09	0.0338	60	35,23	28,89	55	572	-791,0
e	T91	248037090	73,99	240,80	1395.97	0.0431	0	40,83	22,29	108	221	-876,8
f	T91	248037106	73,24	240,74	1371.44	0.0353	56	35,34	30,05	141	243	-879,3
g	T91	248037134	71,92	240,63	1330.03	0.0426	54	36,11	29,47	201	330	-878,3
h	T91	248037139	71,68	240,62	1322.80	0.0421	0	44,70	22,22	211	263	-814,8
Ligeia Mare	T91	248036949/ 37039	80	248	1546	0.0316	0	48,81	39,67	-	-	-876,5

^aThe SNR has been recorded at the peak of the reflection from the liquid, relatively to the noise level. The distance from the sea is intended along the subsatellite track. Liquid levels are given with a 2σ precision of about 0.7 m. Canyon depths are given by measuring the time delay from the leading edge of the echo reflected from the top of the canyon (-6 dB from the peak) to the peak of the echo associated to the liquid level and, thus, with a precision of the same order of magnitude of the Cassini RADAR range resolution (35 m). For Ligeia Mare averaged values acquired on the southern part of the sea are presented. For the two returns (a and b) associated to the Xanthus Flumen, range-Doppler analysis showed that a canyon scenario for these riverbanks is not applicable.

backscattering (up to 10 dB) between the dark spots pertaining to the channel course and the surrounding terrains testify the great steepness characterizing the Vid Flumina canyons walls. Given the measured canyon's depths respectively of about 240 and 330 m for features f and g, we can infer mean slopes $>40^\circ$ for their walls.

In an attempt to confirm canyon widths obtained by means of the SAR images analysis, we applied the advanced altimetry data processing technique described in detail by *Michaelides et al.* [2016], who used it to enhance along-track resolution for May 2007 (T30) altimetry observations and measure the profile of empty lake basins on Titan. Iso-Doppler regions, extending within the area illuminated by the altimetric pulse, are limited across track by the antenna beam width (~8.5 km) but span along track for only ~1 km. However, due to the narrow nature of these canyon mouths and/or their nonoptimal orientation relative to the ground track direction (indicated with a dotted red line in Figure 1, right), the improved along-track resolution was not enough to confirm the measured widths of Vid Flumina canyons by means of the radar altimeter.

Concerning echoes "c" and "d", these are isolated reflections from regions with no clear fluvial features present or resolved in any of the SAR images (whose resolution in general varies from 350 m to over 1 km). However, the basin-shaped topographic profile, so similar to the other fluvial features here analyzed, and the strong backscattering enhancement recorded with respect to the surrounding terrains (especially in d, where saturation occurred) lead us to conclude that there are fluids and sub-SAR resolution hydrologic features in these locations. Furthermore, from the topographic profile, feature d is incised about 570 m, representing the deepest canyon observed along the T91 altimetry track. For observations c, d, and h the levels of liquid are higher in elevation with respect to the sea. They stand 16.1 m (c), 85.5 m (d), and 61.7 m (h) above it. In particular, the footprint h illuminates an area that is surrounded Vid's main trunk (~10 km away) and a secondary branch of the river (~7.4 km away). Also, in this case SAR images show that the presence of a single liquid body with dimensions of several hundreds of meters is not likely, but the presence of higher-order tributaries occurring several tens of meters above the level of Ligeia Mare could be consistent with drainage feeding into the Vid main channel system.

Finally, observations "a" and "b" pertain to Xanthus Flumen, flowing into Puget Sinus, an arm of the northern part of Ligeia Mare. They are located where the last meander of the channel goes around an 80 m elevated area (with respect to the sea level) and then opens to the sea (see bottom left panel of Figure 1). Combining SAR images with altimeter echoes and adopting the same method used for determining channels width at features f and g, it is possible to measure width also at these locations. We have a mean width of 2.8 km at feature a and 7.3 km at feature b. A deeper analysis did not reveal the presence of any additional topographic feature, such as raised riverbanks, and the liquid level of both channels was indistinguishable from the elevation of the nearby sea surface.

4. Discussion

This paper reports the detection of liquid-floored canyons in the northern polar area of Titan, with the data set acquired by the Cassini RADAR altimeter during the T91 flyby of Titan. The altimeter footprint illuminated two systems of channels connected to Ligeia Mare: we have two observations of Xanthus Flumen close to its mouth and three of the Vid Flumina in the middle of its course. The level of the liquid filling their main trunk and tributary branches stands at the sea level regardless to their distance from the shoreline (hundreds of kilometers). Three more isolated observations attest to the presence of surface liquids standing at higher elevations (tens of meters) and feeding into Vid's drainage basin. From the shape of the received echoes we determined the difference in height between the level of the liquid filling the channels and the surrounding terrains (hundreds of meters). Finally, by considering the width of the channels as shown by the available SAR images (less than a kilometer), we concluded that these features can be recognized as canyons characterized by steep wall slopes (greater than 40°).

While topographic profiles of the observed fluvial valleys are comparable to glacially eroded fjords on Earth, we rule out any glacial formation mechanisms. This is because the presence of any large-scale ices, such as alpine glaciers, on the surface are thermodynamically improbable on Titan [Lorenz and Lunine, 1996].

The presence of deeply entrenched channels indicates periods of prolonged incision into an erosionally weak material. The degree of erosional incision suggests a protracted period of erosion, although erosion rates and hence duration remain to be constrained. In order to drive the incision vertically into the terrain, liquid elevations of the seas must have been lower in the geologic past to drive the potential for flow and transport of sediment. Alternatively, if sea level remained constant, tectonic uplift of the surrounding terrains would cause the river to incise vertically [e.g., Kirkby, 1980; Willgoose *et al.*, 1991], forming a morphologically similar terrain. If formed primarily by sea level variations, then there must have still been sufficient precipitation and channelized flow throughout the periods of lower base levels in order to drive landscape evolution and canyon formation.

Subsequent base level rise within the north polar regions [e.g., Hayes *et al.*, 2011; Hayes, 2016] would then result in a backwater effect of the main branches of the Vid Flumina drainage network and result in liquid elevations equivalent to those of Ligeia Mare. The surrounding tributaries would not be affected by the backwater, resulting in them having the higher liquid elevations that we observe. If they are hydraulically connected, then this would be direct evidence of active flow in Titan rivers.

While a contribution from tectonic uplift cannot be neglected on Titan, we favor a model where the variation in the surface elevation of liquids has driven the formation of the canyons. This is supported by previous observations of drowned river valleys at channel termini in the north [Stofan *et al.*, 2007; Hayes *et al.*, 2011; Hayes, 2016]. Likely, however, both tectonics and sea level variations contribute to the formation of the topographic features that we observe, though to what degree remains unconstrained.

The case of variable sea elevations driving canyon formation, followed by a resurgent, or rising, sea level has numerous counterparts on Earth. Examples include Lake Powell, a reservoir on the Colorado River that was created by the Glen Canyon Dam (see Figure S4 in the supporting information); the Georges River in New South Wales, Australia; and the Nile River gorge, which formed as the Mediterranean Sea dried up during the late Miocene [Ryan, 2009]. Rising liquid levels in the geologically recent past led to the flooding of these valleys, with morphologies similar to those observed at Vid Flumina.

Our study reports the first direct detection and characterization of liquid-filled canyons on Titan. Understanding the processes that led to the formation of such hydrological features will be crucial in understanding the evolution and the present state of Titan's geomorphology. Regardless, any model of polar landscape evolution on Titan needs to explain the generation of such greatly incised, hundred meter deep canyons that drain into the Mare. Future work will extend our methodologies to all the other channels observed by the Cassini radar altimeter on Titan. Furthermore, modeling the altimeter waveforms [Alberti *et al.*, 2009; Mastrogiuseppe *et al.*, 2014a] can make use of a random-walk Monte Carlo approach able to retrieve the best fit model parameters describing geometrical properties of Titan's canyons [Mastrogiuseppe *et al.*, 2016].

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