

Seakeeping on Ligeia Mare: Dynamic Response of a Floating Capsule to Waves on the Hydrocarbon Seas of Saturn's Moon Titan

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ABSTRACT

Titan has seas of liquid methane and ethane, which are exciting targets for future in situ scientific exploration. A proposed Discovery-class mission, the Titan Mare Explorer (TiME), would have sent a capsule to splash down in Ligeia Mare, a 400-km-wide methane-ethane sea near Titan's north pole in 2023. This article reports an evaluation of the dynamical characteristics of the capsule, designed in part for the aerodynamic and aerothermodynamic demands of its hypersonic delivery from space, on the Titan sea surface. This first quantitative evaluation of extraterrestrial seakeeping required development of environmental models of the sea fluid properties, the wind, and waves, as well as adaptation of commercial simulation tools to Titan conditions. The vehicle response is not in fact monotonic with wave height in a fully developed sea: the capsule size and Titan gravity conspire to generate the largest dynamic response at intermediate wave heights, where the wave period is close to those of the natural modes of the vehicle. A bottom interaction model was introduced to show that the capsule could beach safely on encountering a variety of shoreline types.

INTRODUCTION

In our solar system, only Earth and Saturn's moon Titan presently have extensive deposits of surface liquids.^{1–3} As on Earth, the opportunity to make a voyage on unknown seas presents exciting possibilities for scientific discovery,⁴ spanning such disciplines as geology, oceanography, meteorology, and, just possibly, biology. Wind and tidal currents; thermal and compositional stratification and mixing; suspension of sediments; air-sea exchange of heat, moisture, and momentum; and the generation of wind waves are just a few examples of the familiar and important processes that can be studied under conditions instructively different (see Box 1) from those in our own oceans. Furthermore, the possibility⁵ that a nonpolar solvent such as the methane and ethane in Titan's seas might host chemical systems capable of

information storage and replication remains an important new dimension in origins of life research and astrobiology. The Titan Mare Explorer (TiME) mission⁶ was formulated to address these questions by making *in situ* measurements on a capsule floating in one of Titan's seas, Ligeia Mare (Fig. 1).

The TiME Mission

Very soon after the discovery of Titan's lakes and seas,⁷ TiME was proposed in response to a 2007 NASA call for mission ideas that would be enabled by an efficient new radioisotope power source, the ASRG (Advanced Stirling Radioisotope Generator), under development by NASA. The concept was developed further and pro-

posed by a Lockheed Martin/Johns Hopkins University Applied Physics Laboratory (APL) team to the 2010 NASA Discovery solicitation, and it was one of three (of 27 proposals) selected for a \$3 million Phase A study to generate detailed plans for possible flight implementation. The consideration of a stand-alone mission to Titan, under the very tight cost cap of the Discovery program (\$425 million) was unprecedented and demanded

innovative design as well as a disciplined scientific focus. Key to the concept's success was operational simplicity and the use of direct-to-Earth (DTE) communication.

After launch in 2016, TiME would enter into Titan's atmosphere in July 2023, directly from its interplanetary trajectory. After parachute descent, much like that of the Huygens probe (which landed in Titan's equatorial desert in January 2005, operating for a few hours before its bat-

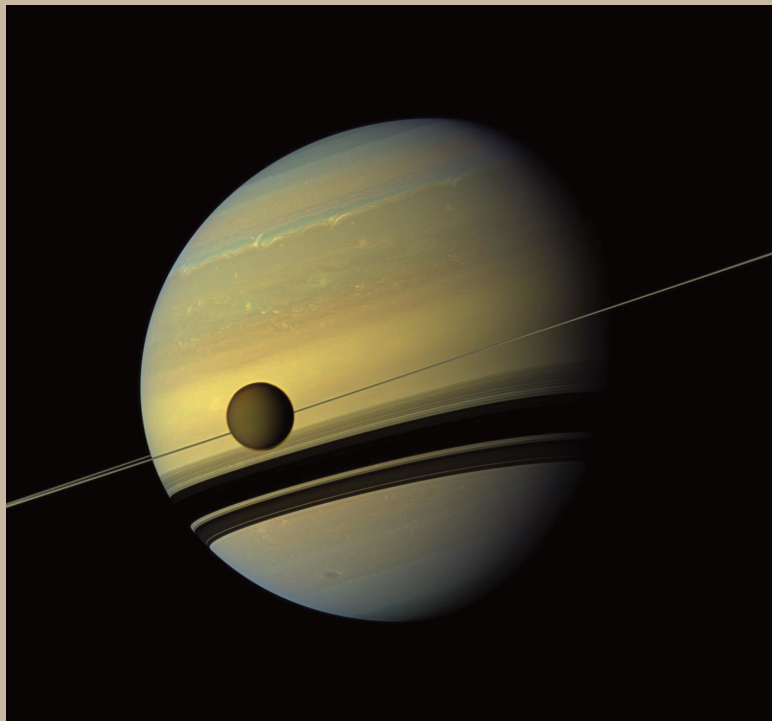
BOX 1. THE TITAN ENVIRONMENT

Titan is a unique satellite in the solar system¹⁻³ in that it has a dense atmosphere, mostly of molecular nitrogen, with a surface pressure of 1.5 bar. This atmosphere endows Titan (at 5150 km diameter, larger than the planet Mercury) with many of the processes and phenomena more familiar on terrestrial planets than on the icy moons of the outer solar system. At Saturn's distance from the sun (10 AU), the surface temperature on Titan is 94 K, a result of the competing greenhouse effects (due principally to methane and nitrogen) and an anti-greenhouse effect due to sunlight absorption by the organic haze, which renders Titan's atmosphere an obscuring orange-brown. Methane, which is present at about 1.7% in the stratosphere, rising to ~5% near the surface, is a condensable greenhouse gas, just like water vapor on Earth. Similarly, methane forms clouds, hail, and rain: the latter phenomenon carves river valleys on Titan's surface. The weak sunlight that drives Titan's hydrological cycle results in rain being a rare occurrence (on average only a few centimeters per year, concentrated in high-latitude summer); a given location on Titan may see rain only every few centuries, but as a massive downpour depositing tens of centimeters or even meters of rain in a few hours. In some respects, Titan is to Earth's hydrological cycle what Venus is to its greenhouse effect—a terrestrial phenomenon taken to a dramatic extreme.

Titan orbits Saturn synchronously (with a period of 15.94 Earth days), such that Titan always presents the same face to Saturn, which hangs almost motionless in Titan's sky. In fact, from Ligeia Mare, Saturn is permanently below the horizon, although it might give a faint glow at night due to scattering by Titan's haze. Titan's gravity is 1.35 ms^{-2} , about the same as the Earth's moon.

Titan and Saturn are tilted at 26.5° to the ecliptic, so they experience quite profound (and long—a Saturn year is 29.5 Earth years) seasons. TiME was proposed to exploit northern summer, which allows direct—and for a limited period, continuous—illumination and Earth view from Ligeia.

Titan's slow rotation and seasons give an atmospheric circulation that dries out equatorial regions (which are covered with vast fields of sand dunes) and allows liquid methane and ethane to accumulate around the poles. Most of the hundreds of lakes, and three seas, are found in the northern hemisphere. This dramatic asymmetry is thought to be the result of the astronomical configuration of Titan's seasons in the current epoch, which has the result that the northern summer is less intense but longer in duration than that in the south. This results in a longer “rainy season” in the north, such that methane and ethane accumulate there. This seasonal configuration lasts several tens of thousands of years, much like the Croll–Milankovitch cycles that play a part in Earth's ice ages and the Martian polar layered terrain.



Titan in relation to its parent planet, seen in a color mosaic of Cassini images acquired on May 6, 2012, at a distance of 778,000 km from Titan. This is 3 years after northern spring equinox, as evidenced by the ring shadow on Saturn, and a variation of Titan's color with latitude is evident, attesting to seasonal changes.

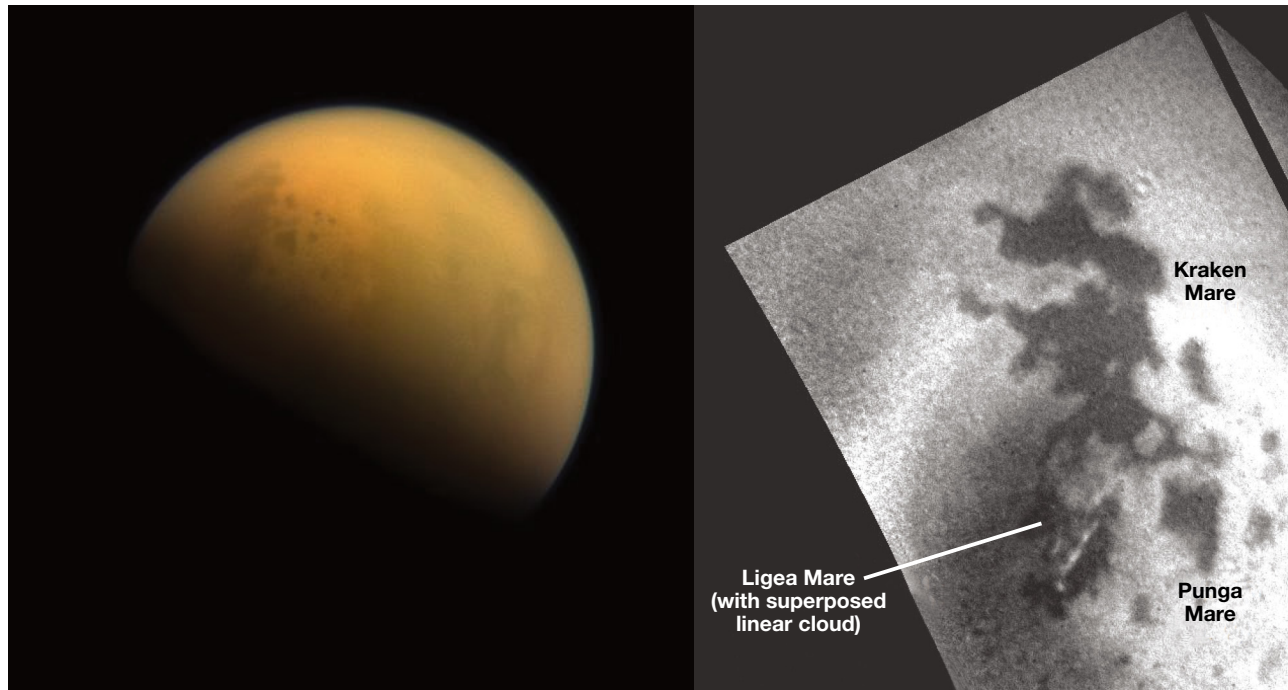


Figure 1. At left is a Cassini image composite of Titan's north polar regions on October 7, 2013, acquired at some 1.3 million km from Titan (Titan is 5150 km across). The image is slightly false-color, with the red colors representing a near-infrared wavelength (938 nm) where the haze is somewhat more transparent than in the visible. At upper left, near the north pole, are several dark patches—these are Titan's seas; Ligeia Mare is just visible close to the terminator. Some more subdued dark areas at right are the equatorial deserts, covered in giant dunes. At right is a 938-nm view, zoomed in on the polar region, with contrast stretched to show the seas better. This view is shown in the same orientation but was acquired at a different epoch, on this occasion showing a streak of clouds across Ligeia. (Credit: NASA/JPL/LPL/SSI.)

teries expired), the capsule would splash down and begin its prime science mission, transmitting its data direct to Earth at intervals. The unified design, embracing spaceflight, hypersonic entry, and atmospheric flight in a single vehicle configuration that then would operate on the sea surface as a drifting buoy (Fig. 2), posed interesting new challenges.

TiME's science objectives (Box 2) would be met through measurements of the organic composition of Titan's sea Ligeia Mare (Fig. 3) using a mass spectrometer, characterization of the air-sea interactions with an imaging system, and a package⁸ to record meteorology and physical properties sensing of the liquid (including acoustic depth sounding⁹).

The nominal target of the TiME mission is Ligeia Mare, the second largest of Titan's seas. This was chosen because at the time

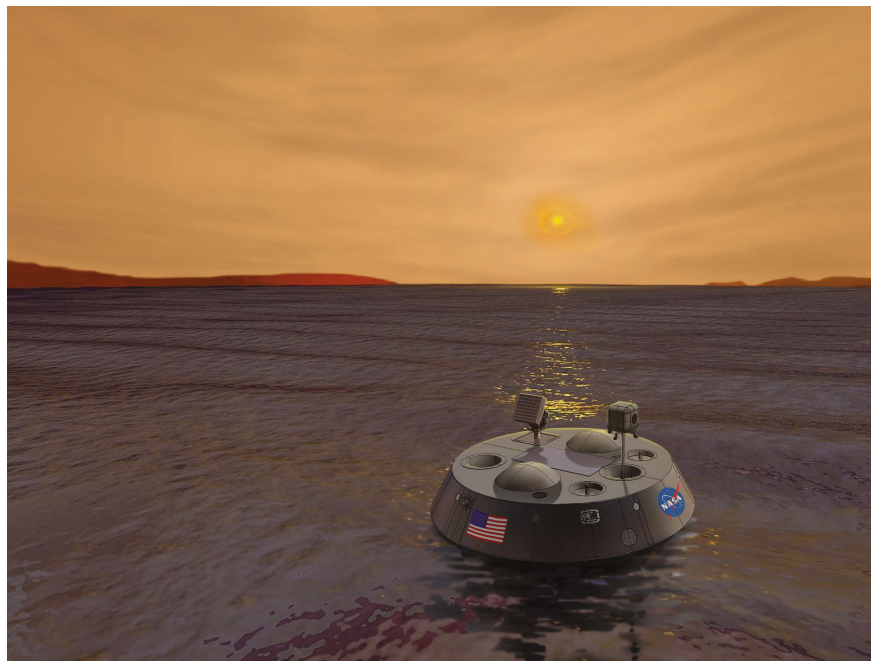


Figure 2. Artist's impression of the TiME capsule floating on a hydrocarbon sea on Titan. Note that seen from Ligeia Mare in Titan's arctic, the Sun and Earth never climb higher than about 30° above the horizon.

(~2008) it was the best mapped (Fig. 3a), allowing the confident definition of a large, safe splashdown area with no risk of encountering shallows or islands. Radar-dark areas were estimated to be more than 10 m deep.

Although there were no fundamental lifetime limitations to the capsule at Titan, because it would use a radioisotope power system, a nominal mission duration of 6 Titan days (Tsols; 1 Tsol = 15.945 Earth days) was defined because this would amply satisfy the science objectives and would allow a significant data return. A consequence of the presence of wind-driven¹⁰ and tidal¹¹ currents in the sea, as well as wind-driven motion^{12,13} of the capsule relative to the sea (i.e., sailing; see Fig. 3b) was that the capsule had a reasonable probability of encountering the shoreline sometime after 3 Tsols. (Although the capsule is nominally a passively drifting buoy, the popular media referred to TiME as “sailing” on Titan, which correctly evokes the romance of wind-

driven maritime exploration. It would in fact be possible to formally earn this term by deliberately slewing the communications antenna to manipulate the wind drag area of the capsule.) All key scientific objectives would be obtained by this point, with three day–night cycles being adequate to characterize the diurnal meteorological cycle. On the other hand, encountering the shoreline would be tremendously exciting and would offer the possibility of short-range imaging of beach processes and coastal geomorphology.

The composition of Titan’s seas is predominantly^{14,15} methane and ethane, the two principal components of liquefied natural gas on Earth. At Titan conditions, methane and ethane are both liquids, although the latter is much less volatile. The relative amounts of these two compounds are not presently known, and determining the mixing ratios is a major science goal. In fact the composition may be different¹⁶ for the two

BOX 2. TIME SCIENCE OBJECTIVES AND PAYLOAD

TiME science objectives,⁶ responsive to goals from the 2003 Solar System Decadal Survey, are as follows: (i) measure the sea chemistry to determine the seas’ role as a source and sink of methane and its chemical products; (ii) measure the sea depth to help constrain organic inventory; (iii) constrain marine processes including sea circulation and the nature of the sea surface; (iv) determine sea surface meteorology; and (v) constrain prebiotic chemistry in the sea. To achieve these objectives, the mission was intended to last 96 days (6 Titan days). The payload comprises three principal instruments: a Mass spectrometer with a specially designed cryogenic inlet, a camera suite, and a meteorology and physical properties package.

The mass spectrometer, to be provided by Goddard Space Flight Center, would acquire samples of sea liquid and volatilize them for study in a quadrupole mass analyzer. It may be noted that although it is not trivial, acquiring Titan materials for analysis is far simpler for a liquid surface than a solid surface. The ability to ingest liquid at ambient temperature and seal it for subsequent heating required an innovative thermal design. Extensive design and testing of the inlet system was performed in Phase A, and successful sampling of cryogenic liquids was performed. In addition, the function of valve seats over multiple operations and with particulate-laden liquids was demonstrated. The mass range and sensitivity of the instrument would substantially exceed that of the Huygens mass spectrometer, which operated on the surface of Titan in 2005, and would accurately characterize the organic composition of the sea as well as isotopic ratios and noble gases.

The camera system from Malin Space Science Systems comprises two camera heads and a single electronics unit. A descent camera would image the atmosphere and surface during parachute descent, while a surface camera would be deployed on a small mast after splashdown. In addition to searching for shoreline features and observing clouds and

atmospheric scattering, the surface camera would study the sea surface and near surface. Nighttime observations would be conducted with separately commandable above- and below-waterline illumination.

The meteorology and physical properties package to be developed at APL combines above- and below-the-waterline measurements with simple sensors managed by a common electronics box. Air temperature, pressure, wind speed and direction, and methane humidity would be recorded simultaneously with vehicle dynamics, liquid temperature, turbidity, and gross composition (via dielectric constant measurements). These contemporaneous measurements would allow exploration of the air–sea exchange processes on Titan, such as the wind speed associated with different wave heights or the evaporative cooling of the sea surface. The turbidity and methane humidity measurements were implemented with novel fiber-coupled instrumentation, allowing the optoelectronic components to be retained inside the comfortably warm capsule interior. One other measurement system was a down-looking echo sounder able to measure the depth of the sea as well as potentially detect layering or suspended sediments. Phase A development activities for the meteorology and physical properties package included the demonstration of sonar transducer performance in cryogenic liquids.

In addition to the three instruments, scientific data would be obtained from engineering systems. The inertial measurement unit would measure the entry deceleration history and thus permit the recovery of the polar atmospheric density profile from ~1000 km down to the mid-stratosphere. The inertial measurement unit would also be a sensitive means of detecting waves on the sea surface.

Similarly, the radio link would permit propagation studies and measurement of capsule motion. Specifically, ranging and Doppler information would be used to determine on the ground the location of the capsule and, thus, its drift in response to winds and ocean currents.

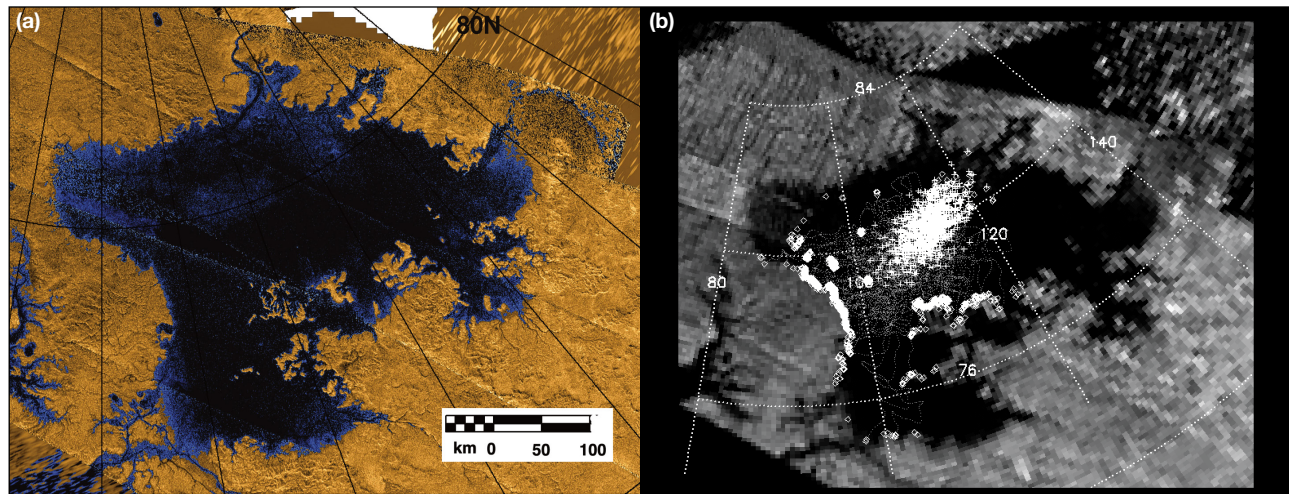


Figure 3. (a) A false-color Cassini radar image mosaic of Ligeia Mare, at around 80° north on Titan. The blue regions show some radar return above the noise floor, suggesting a possible bottom reflection from shallows. The sea is about 400 km across. Note the crenulated coastline and the extensive river networks draining into the sea. (b) A Monte Carlo simulation of the delivery and sailing of the TiME capsule, with 1000 instantiations (crosses) delivered to splashdown in an inclined ellipse near the safe center of the sea, with drift trajectories forced by wind predictions from a global circulation model, resulting in landfall in many cases (diamonds).

main seas Kraken and Ligeia, with the latter more methane rich (like the fresher Black Sea and the saltier Mediterranean) because of stronger methane rainfall at high latitudes. Depending on the mixing ratio in Ligeia (and the amounts of nitrogen and organic compounds dissolved in the sea) the density could vary between 450 and 670 kg/m³ (i.e., by some 30%—about a value half that of water). The viscosity¹⁷ may be a factor of ~5 less than water for pure methane or a factor of a few larger for denser ethane-rich compositions. In fact the vehicle moves at Reynolds numbers too large for viscosity to substantially affect its dynamics; viscosity was an important consideration for liquid sample acquisition and is important in determining the wind threshold for wave generation.

MODELING WAVE-DRIVEN MOTIONS OF TIME

Dynamical Simulation Approach

Beyond the drift of the capsule and the splashdown mechanics of the vehicle at the start of its mission (the subject of a separate and interesting investigation that revealed some surprising behaviors^{18,19}), the short-term dynamics of the vehicle on the sea surface were important for several reasons. First was the need to demonstrate that the capsule would be stable against capsizing in the wave environment. Second, the angular rates encountered would drive the design of vehicle components (such as the gimbal used to maintain Earth-pointing of a medium-gain antenna to transmit the science data to Earth) and payload elements (e.g., the need to avoid image smear drives the optical design and exposure time of the camera system). Finally, measuring the

sea state via vehicle dynamics measurements—essentially the capsule acts as a wave buoy—was a science goal, and the transfer function to relate the output of accelerometers and/or angular rate sensors to the driving wave height was desired.

While scale model tests supplemented by numerical models were principal tools in evaluating the splashdown mechanics of the vehicle (a critical event, but one that happens only once), understanding wave response in the Phase A study was developed exclusively with numerical models, because a wide range of wave conditions might be encountered over the 3-month mission and statistical evaluation was needed.

The TiME capsule and Ligeia Mare surface were modeled in OrcaFlex.²⁰ OrcaFlex is a leading software package for the dynamic analysis of offshore marine systems and is commonly used for towed systems, buoy systems, moorings, and risers. OrcaFlex allows for full 3-D modeling in the time domain using a finite-element model to solve the equations of motion^{21,22} in 6 degrees of freedom (surge, sway, heave, roll, pitch, and yaw.)

Because the TiME capsule hull was axisymmetric (in part for stability during hypersonic entry), the hull model was constructed in OrcaFlex by using a series of stacked cylinders (Fig. 4). The cylinders are a convenient means to discretize the capsule and calculate the submerged volume. The resulting intersection of the water surface with the cylinders making up the capsule determines the heave response and righting moments. The TiME capsule model was constructed from 73 cylinders with diameters ranging from 0.8 m to 2.9 m to capture the hull shape.

A range of masses, and thus center-of-gravity positions and moments of inertia, was considered (the

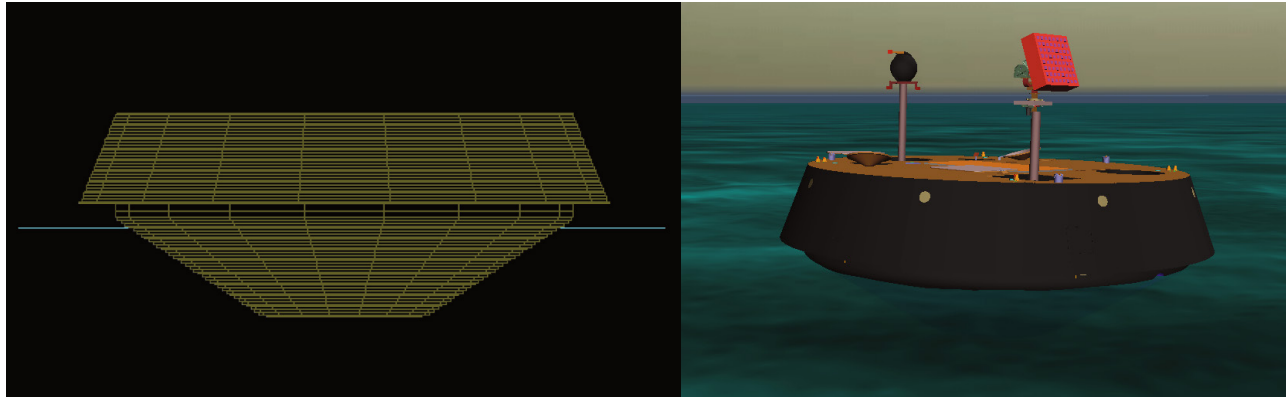


Figure 4. Elevation view of the TiME capsule OrcaFlex model constructed from stacked cylinders. The tool allowed rendering of animated views of the capsule motion with a more elaborate visual model, showing more representative textures and elements (prominent here are a spherical camera pod and a box-shaped medium-gain antenna, both on masts).

spacecraft configuration evolved during the study). A representative mass value is 700 kg, resulting in a beam at the “waterline” of ~ 2 m for an ethane-rich ocean composition, with the center of gravity close to the waterline.

OrcaFlex calculates hydrodynamic loads using an extended form of Morison’s equation,^{21,22} which expresses the total force as a sum of inertial and viscous forces, taking the added mass of fluid into account. The inertial term contains the Froude–Krylov force (force due to the pressure of the incident wave) and the added mass (distortion of the fluid flow by the presence of the body). For this phase of the TiME project, the hydrodynamic coefficients of the capsule were calibrated against a set of computational fluid dynamics (CFD) simulations

performed by Lockheed Martin. While CFD can directly model the individual partial interactions with the capsule and the air, it is computationally intensive, and long run times were a prohibitive limit to the number of cases that could be evaluated. OrcaFlex, simply solving the equations of motions using force coefficients, is considerably less computationally demanding.

The added mass and damping coefficients of the capsule were tuned to match the results of heave and roll motions simulated in CFD. The heave and roll simulations perturb the capsule vertically and rotationally, respectively, and allow the capsule to reach steady state. The Froude–Krylov force approximation is applicable when waves are longer than the body’s characteristic

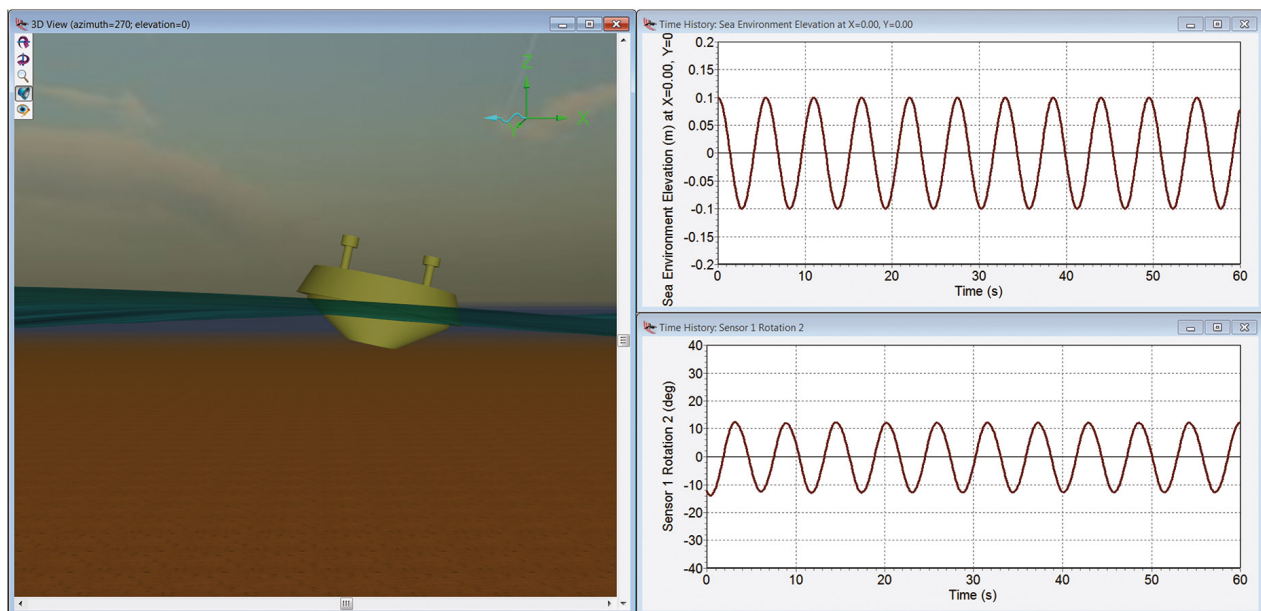


Figure 5. OrcaFlex display of the instantaneous free surface of the liquid and the capsule position. The upper right plot shows the sea surface history at a fixed point, with a 5.5-s wave period and a wave height of 0.2 m—characteristic of the strongest winds likely to be encountered (1 m/s).

dimension. However, on Titan some wavelengths of interest (see Fig. 11) were on the same order of or smaller than the TiME capsule's diameter, introducing diffraction effects not automatically modeled in OrcaFlex. To represent buoy motions in the diffraction regime, the damping coefficients were calibrated against a CFD simulation with regular waves of a wave height of 5 cm, a period of 2.15 s, and a wavelength of 1 m. A simple monochromatic sinusoid wave train, and the vehicle response, is shown in Fig. 5.

Wind/Wave Environment Specification

The formulation of the wave environment specification was a major task in the Phase A study (as, indeed, was the definition of the wind environment,²³ which not only drove the waves but also determined the splashdown footprint and the drift across the sea¹³). Measurements by the Huygens probe in Titan's atmosphere, as well as Cassini cloud-tracking and thermal infrared observations, in conjunction with results from four different global circulation models, were used to develop predictions of the wind environment tailored to the location and season (late northern summer) of the TiME mission. Of relevance here is the overall near-surface wind speed probability distribution (specific to the late summer season of the TiME mission in 2023—near midsummer in 2017, winds are expected to be stronger and Cassini observations of the resultant waves are presently eagerly anticipated). The likelihood $P(>V)$ of encountering wind speeds higher than V (referred to anemometer height of 10 m) can be described by a Weibull distribution $P(>U) = \exp(-[V/C]^k)$, where k is a shape parameter and C is a scale speed—in this instance $k \sim 2$ and $C = 0.4$ m/s. This distribution is shown in Fig. 6. For context, the near-surface winds encountered by the Huygens probe²⁴ were in fact about 0.3 m/s, although evidently winds above ~ 1 m/s occur sometimes, as this wind speed is needed to form the sand dunes seen near Titan's equator.

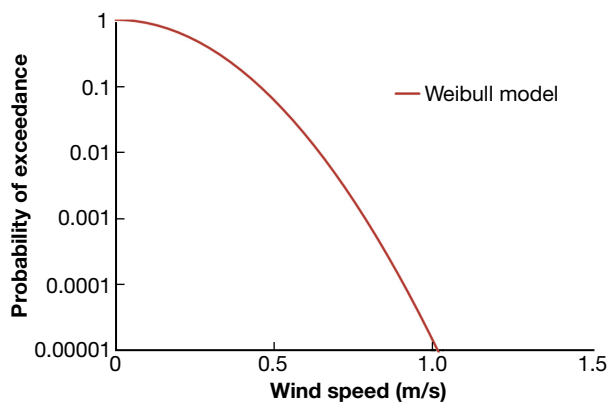


Figure 6. Weibull wind distribution for Ligeia Mare in 2023, chosen to exceed the predictions of all four global circulation models.

The relationship of wave height to wind speed and fetch (distance across the sea) is a complex one that was of practical interest^{25,26} on Earth long before computational capabilities could simulate wave growth explicitly. (Indeed, until the advent of wind speed instrumentation at the end of the 19th century, the relationship was itself the foundation of wind measurement at sea, wherein the wind speed was estimated from visual observation of the sea state; q.v. the Beaufort scale²⁶). Thus, terrestrial wave predictions are largely empirical (and hence are specific to 1 bar air, acting on water, in a 1-g gravity field—none of which apply in our application). A predictive framework for Titan had to be developed on physical principles, in some respects stepping back from modern wave studies to more fundamental and practical work in the 19th and mid-20th centuries.²⁷

In brief, the initially bewildering difference of all the atmosphere and liquid parameters as well as gravity can be decomposed into three steps: the formation of waves, their growth, and their ultimate wave height. First, the onset of small capillary and capillary-gravity waves at the smallest (centimeter) scale depends on the balance of wind energy (air density and wind speed) against viscous dissipation. The threshold^{16,28} depends rather critically on the viscosity of the liquid (which is five times smaller for liquid methane at 92 K than for water at 298 K but two times larger for liquid ethane), resulting in a wind speed threshold of ~ 0.4 m/s for methane and 0.8 m/s for ethane.²⁹ The formation of small waves is of high current interest in interpreting Cassini sunglint and radar data on Titan's seas, which at least until the last year or so have been dead flat^{30–32} but are now (3 years after the TiME study) perhaps starting to show hints of roughening,^{33,34} as expected. When these thresholds are compared with the wind model, it is seen that in fact for the TiME season of 2023, waves should be generated locally for only 1–13% of the time depending on the sea composition and thus threshold wind speed (although swells can propagate from other areas where wind is stronger). A feedback in the system, which has yet to be implemented in new generations of circulation models, is the extent to which the sea composition itself modifies the climate and thus the winds. For the Phase A study, an ethane-rich sea (giving stronger winds¹³) was assumed for conservatism.

Once waves form, they will grow to a limiting height (a fully developed sea), typically defined by the significant wave height (SWH), the average of the highest third of the waves. At a given wind speed, the wave heights grow downwind as the square root of distance, a result first recognized by the Scottish lighthouse engineer Stevenson in 1850. This growth rate depends on the liquid density and gravity, as well as the air density and wind speed. It emerges, however, that the fetch over which waves grow to their limiting height is in fact quite short on Titan.³⁵ This results from a couple of factors:

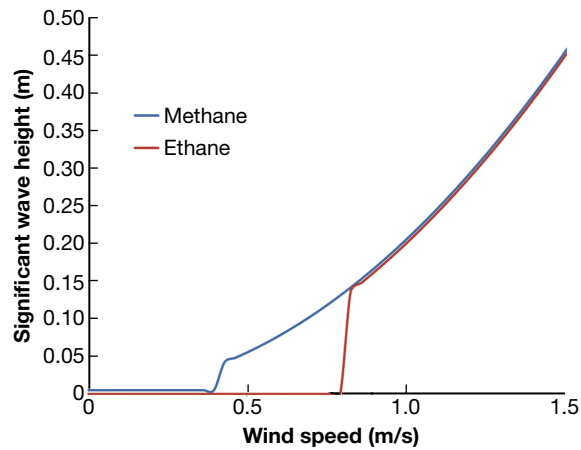


Figure 7. Limiting wave height as a function of wind speed. Note that no waves are present at winds below 0.4 m/s for any composition, and the presence or absence of waves 0.4–0.8 m/s depends on the ethane/methane amounts and the resultant viscosity. While the limiting wave height is the same for both compositions, wave growth will be slightly faster in methane because of its lower density.

First, as might be expected from the fact that the sea/air density ratio on Titan is only ~100, compared with 800 on Earth, Titan’s seas respond more quickly to atmospheric forcing. Second, in Titan’s lower gravity, waves propagate more slowly and thus have more time in a given fetch to extract energy from the wind. Model results suggest that the wave height approaches its maximum with a fetch of about 10 km, only a few percent of the width of Ligeia, so in general a fully developed sea should be encountered.

Perhaps of most obvious interest, then, is the limiting wave height. Essentially this is reached because of the finite steepness of waves—thus, as they get larger in amplitude, they grow in wavelength λ too. As the wavelength grows, so does the propagation speed ($c = (g\lambda)^{0.5}$), and thus the speed of the wave relative to the wind falls and the growth becomes self-limiting. (There are some important subtleties in the exchange of energy between waves of different periods, such that waves can in fact outrun the wind, but this is beyond the scope of the present article. Furthermore, these calculations all pertain to “deepwater” waves; further modeling would address the case of a shallow sea where the proximity of the seabed modifies the wave dynamics.) Hence, to a first order, the foregoing complications of different viscosity and air and sea density in wave formation and growth can be ultimately neglected and the final wave height H emerges as a simple function of wave speed and gravity $H \sim 0.2U^2/g$ (as, in fact, on Earth), where U is the wind speed and H is the wave height. (It may be noted that should pressurized habitats on Earth’s Moon ever be constructed with swimming pools, the corresponding wave dynamics may be representative of those in Titan’s

seas because the gravity is about the same!) Thus, for the strongest winds expected in this season, ~1 m/s, the wave height is a modest 0.2 m (see Fig. 7), a fraction of the height of the capsule. The corresponding wave period and wavelength are 4 s and 4.5 m, respectively.

Of course, ocean waves are neither regular nor sinusoidal but instead are trochoidal in shape, and in general many wave trains of different periods, heights, and directions are superposed. The height H above is an SWH, which essentially corresponds to what a visual observer would determine the wave height to be in an instantaneous observation. In reality the random superposition of waves typically results in a Rayleigh distribution of surface heights,^{36,37} so (for example) one in every thousand waves, typically, will be roughly double the SWH. Hence, for a given wind speed and thus SWH, one can calculate the interval over which one would need to wait before encountering a wave of a given height (typically a wave height needs to exceed about 1.5 diameters to capsize terrestrial discus buoys^{38,39}). One can convolve the Rayleigh wave height distribution for a given wind speed with the Weibull distribution of expected wind speeds to derive the ultimate wave climate—see Fig. 8. Expected wave heights are far too small to capsize the capsule.

Simulation Results

To evaluate the probability of given angular rates being exceeded, and to thereby establish the likelihood, for example, of a downlink being interrupted or an image being smeared, the capsule dynamics were simulated explicitly in OrcaFlex using a realistic pseudoran-

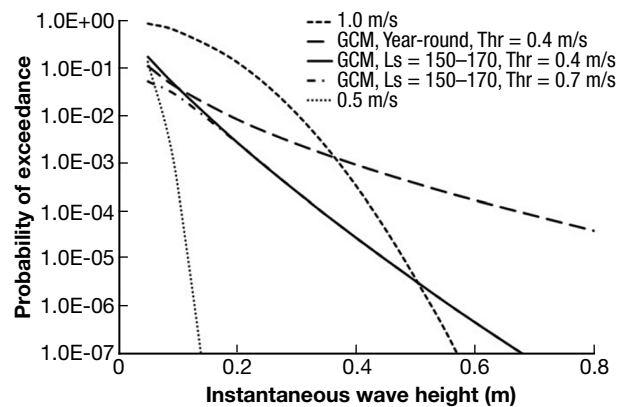


Figure 8. Wave climate predicted for the TiME mission and season (solid line), which was to last roughly 2 million wave periods (~3 months) and so might be expected to encounter a handful of waves 0.5 m or higher. The dashed and dotted curves show Rayleigh distributions for constant wind speed. The line with longer dashes shows how the wave climate would be more severe if a mission were to be conducted during the windier mid-summer in 2017. GCM, global circulation model; Ls, solar longitude; Thr, threshold.

dom wave train. An implicit time solver was used with a step size of 0.005 s (results were spot-checked against an explicit solver). These simulations were run for 20 min, similar to the data collection period of a terrestrial wave buoy.

The wave field was constructed assuming that waves could be described by linear, Airy wave theory. An irregular wave train is constructed by linear superposition of a number of linear wave components. OrcaFlex creates the components using an equal area weighting over the range of frequencies in the wave energy spectrum. The wave spectrum used was the JONSWAP (Joint North Sea Wave Project) spectrum, an empirical near fully developed spectrum, rescaled to the Titan wave period and significant wave height for a specified wind speed. An example is shown in Fig. 9.

Some example results of the vehicle dynamics simulations are shown in Fig. 10. An important result identified by the rapid “parameter sweep” capability afforded by our modeling approach was that the worst angular rates were not in fact associated with the strongest wind and largest waves. The maximum rotation rate encountered in a 20-min random wave train is plotted for several wave periods and wave heights in Fig. 11. It is seen that the maximum angular rate peaks sharply at around the 3-s period, even though the waves associated with that wind speed have an SWH of only 0.1 m. This is of course a classic resonant response in the rocking (pitch and roll) of the capsule.

As an analytic reality check, it is simple to calculate the characteristic bobbing period of a floating object (i.e.,

the natural modal period of heave motion). This motion occurs about the equilibrium flotation level—when displaced a distance x , the restoring force is simply $x\Delta\rho g$ —

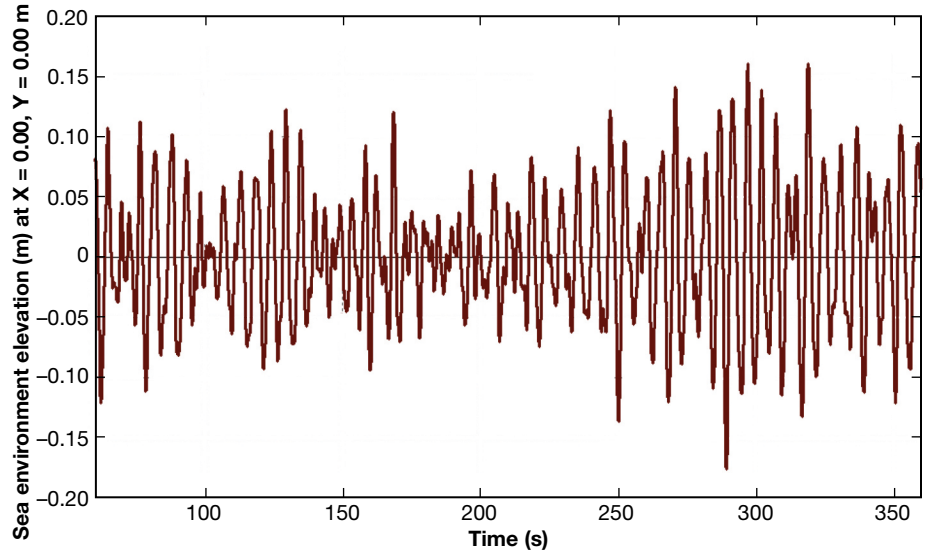


Figure 9. Candidate random wave sequence developed by rescaling a JONSWAP wave spectrum to Titan SWH and dominant wave period for 1-m/s winds.

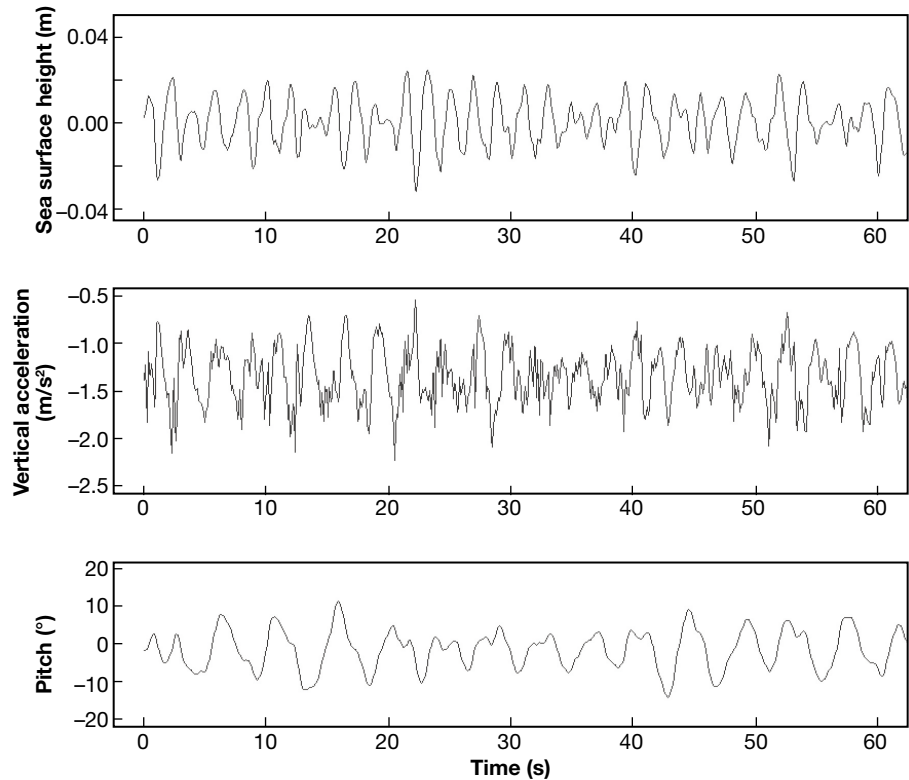


Figure 10. The vehicle response in acceleration and pitch to random wave forcing by rather small waves. The acceleration curve is generated by numerical differencing of a velocity history and thus appears somewhat noisy, but it is evident that even a simple accelerometer can measure the wave motions. The pitch history in this instance is dominated by the natural period of the vehicle rather than the forcing.

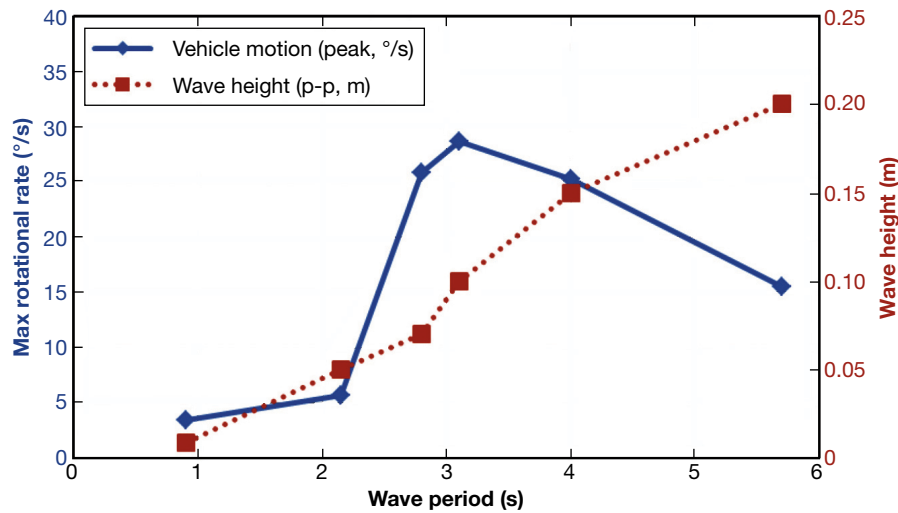


Figure 11. Random wave OrcaFlex simulation results of TiME capsule. The maximum rotational rate of the capsule is shown in blue and plotted against the dominant wave period. The significant wave height of the random waves is shown in red.

i.e., the weight of the displaced or missing fluid. Thus the acceleration is xAg/M , where M is the vehicle mass and A is the cross-sectional area at the waterline. For the usual parameters and a vehicle properties $M \sim 700$ kg $A \sim 4.5$ m², we find an acceleration of 0.05 ms⁻² (~ 4 mg) for a 1-cm displacement in liquid ethane. The bobbing period is $T = 2\pi(M/A\rho g)^{0.5} \sim 2.6$ s. Similar calculations show a similar period for rocking (pitch) motions. The proximity of these natural motions to the wave forcing period means that the damping characteristics of the capsule, which can be tuned by relatively modest hull features such as bilge keels, can be important in the behavior of a capsule on Titan and that detailed model-

self-righting. The wave height/diameter ratio that could lead to capsize for TiME was presumably lower than for similarly shaped terrestrial disc buoys³⁹ because of the modest static stability permitted by the assumed mass distribution: in practice, ballasting could improve the static stability, and bilge keels or other damping measures might be introduced to improve dynamic stability depending on the risk posture adopted. The challenge would be in affordably implementing such measures alongside the demands of hypersonic entry stability, power source accommodation, and other spaceflight factors not normally demanded of maritime systems. It must be stressed that the 3.5-m/s winds required for such

ing of the type we have outlined here is necessary.

Toward the end of the study, a simulation was conducted to deliberately try to capsize the capsule, in part to validate the modeling approach and to establish some idea of safety margins. It was found that a 1.8-m significant wave height random wave field with a dominant 8.5-s period would cause the capsule to capsize within 60 s of the simulation start (although a purely sinusoidal forcing did not cause inversion). The capsule could also be reverted upright, so it had a 50% chance of continuing operation after such a violent storm. The capsule, like catamarans and some other craft on Earth, was not

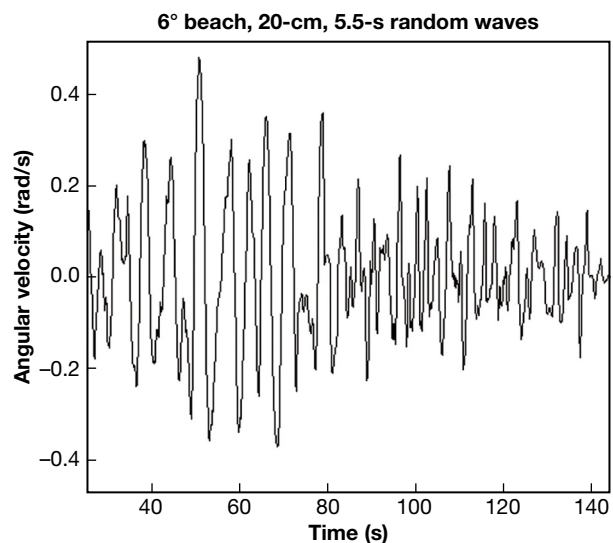
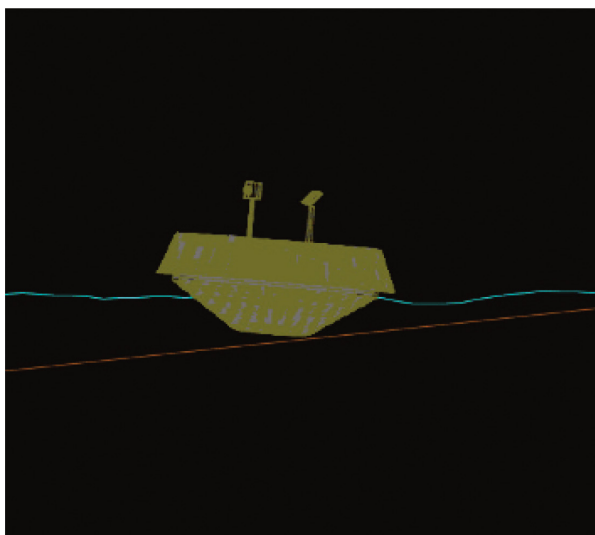


Figure 12. A bottom interaction model was introduced into the OrcaFlex simulations to examine beaching dynamics. In the time history shown, bottom contact occurs at about 80 s, and the motion becomes of lower amplitude but with more rapid variations.

waves are in any case far in excess of the winds predicted by global circulation models.

Beaching Simulations

While the TiME mission would be expected to complete its science objectives during the multi-Tsol (several-week) drift from its splashdown point to the shores of Ligeia, the prospect for operation during and after shoreline encounter (if it occurred) was of obvious interest. Because modeling shows that Ligeia Mare has a tidal range of a few tens of centimeters,¹⁰ the capsule might become comfortably beached in low-slope depositional environments such as beaches or tidal flats.

A bottom interaction model was constructed using terrestrial materials as a guide (the familiar appearance of many of Titan's landforms such as dunes, mountains, and river channels attests that while the chemical composition of Titan's surface is very different from that of Earth, under the low-temperature, low-gravity conditions on Titan, the mechanical properties end up being

rather similar). Values of bottom slope of 1° and 6°, typical of sandy shores on Earth, were examined.

A notable dynamical signature of shoreline encounter, of interest for autonomous detection of beaching (which might, for example, trigger optimized scientific observation sequences such as an imaging panorama), is a reduction in the angular rates, but much more rapid changes in those rates (see Fig. 12). This is readily interpreted as the base and corners of the lower hull bouncing on the bottom: the random waves progressively push the capsule higher on the beach, depending on the friction coefficient chosen, and intervals of rest are punctuated by refloating events. Because wave-breaking and tides were not included in the simulations (and of course the shoreline characteristics of Titan as a whole, let alone the location of beaching, are not known), no formal evaluation was made of these results, but they demonstrated the capability to address the problem and were reassuring overall. Some of these bottom interaction signatures were also seen in field tests⁴⁰ (performed after the TiME study concluded, in support of NASA

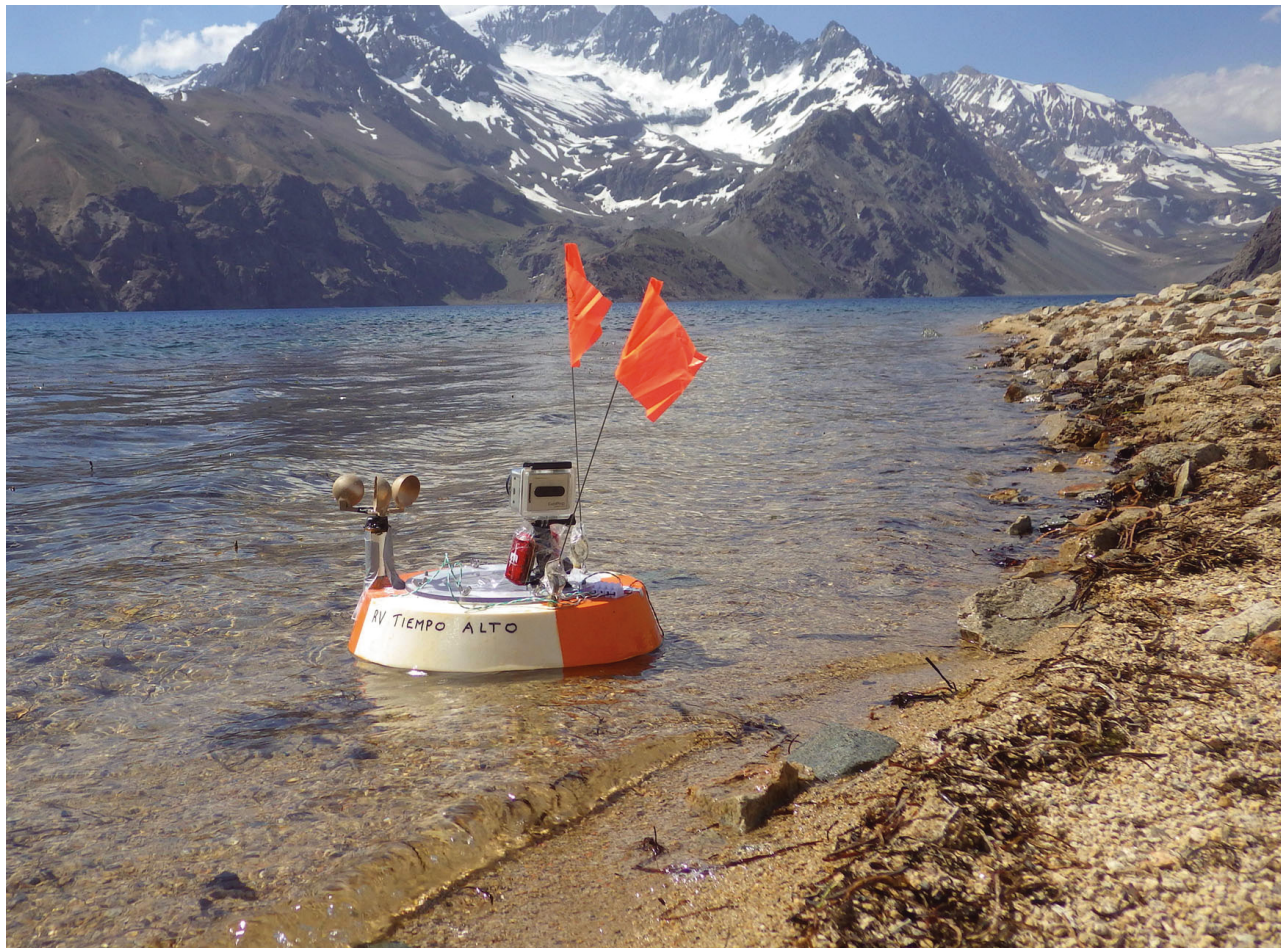


Figure 13. A field test of a 1/8-scale model (~35 cm diameter) of the TiME capsule at Laguna Negra. A small GoPro camera demonstrated the utility of imaging for shoreline morphology as well as the dynamics in waves. The tests shown here showed distinctive accelerometer signatures of beaching. The red flags aided in recovery of the test article.

onboard science autonomy experiments) with a scale-model capsule at Laguna Negra in the Chilean Andes (Fig. 13). It was noted that the acceleration waveforms became spiky and asymmetric compared with bobbing and rocking motions; a simple running calculation of skewness and kurtosis of the signal could likely be used to autonomously detect beaching.

CONCLUSIONS

We have outlined the approach adopted in evaluating the motion of a floating capsule in an extraterrestrial (methane/ethane) sea. This required careful specification of several aspects of the Titan environment and the adaptation of conventional seakeeping modeling tools. More elaborate investigations via CFD and/or scale model trials were required to anchor certain model parameters, but with these determined, the overall results were considered robust in the project reviews by NASA, retiring any perceived risk on the ability to acquire the desired scientific measurements.

The seakeeping performance of any future Titan vehicle will rely on the wave climate, which depends on location and season, as well as on the specifics of the vehicle hull shape and mass properties, but the results reported here can serve as a basis for expectations and a benchmark for simulations. It is a result of classical mechanics that floating vehicles on Titan (which must have a density somewhat less than that of the liquid) that are a few meters across—as are most spacecraft—will have natural periods of a few seconds, which is uncomfortably close to the characteristic wave periods on Titan. Detailed evaluation of the seakeeping characteristics of any future proposed vehicle is therefore required.

EPILOGUE

The ASRG power source around which the TiME mission was conceived failed its flight development review in July 2012, prompting a restructuring of the ASRG management team.⁴¹ A month later, shortly after the successful landing of the Curiosity rover, NASA announced the selection of the InSight mission as the next Discovery mission for launch in 2016. The opportunity to perform DTE communication from Titan's seas, thereby enabling TiME's cost-effective architecture without a relay spacecraft, expires around 2025 when Earth becomes prohibitively low in the sky as Titan moves into northern winter.⁴² More southerly splash-down sites in Kraken Mare, now mapped by Cassini since TiME was proposed, extend the window only by another year or two. With trip times to Titan of ~7 years, realistic implementation of such a DTE mission on a development schedule traditional for competed missions is no longer possible. Missions with relay orbiters, such as the 2007 Titan Explorer flagship⁴³ concept developed

by APL, and the Titan Saturn System Mission (TSSM) flagship concept that followed, could be launched any time, as could missions that address the wide range of science elsewhere on Titan, such as hot-air balloons,⁴⁴ unmanned aerial vehicles,⁴⁵ and equatorial landers. The appeal of Titan's seas, however, is only likely to grow as Cassini observations continue to come in as we move toward northern midsummer in 2017, and interest in their future exploration remains high, as evidenced by ideas for floating capsules on international missions⁴⁶ and even ideas for more ambitious vessels such as submarines. The innovative and imaginative TiME project, drawing on APL's maritime as well as space expertise, will rightly be seen as the setting where the challenges of sailing the seas of another world—an enterprise perhaps first considered by Titan's discoverer^{12,47}—were first seriously confronted.

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