

# SPLASHDOWN AND POST-IMPACT DYNAMICS OF THE HUYGENS PROBE : MODEL STUDIES

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## ABSTRACT

Computer simulations and scale model drop tests are performed to evaluate the splashdown loads of a capsule in nonaqueous liquids, in anticipation of the descent of the ESA Huygens probe on Saturn's moon Titan which may have lakes and seas of liquid hydrocarbons. Deceleration profiles in liquids of low and high viscosity are explored, and how the deceleration record may be inverted to recover fluid physical properties is studied.

## 1. INTRODUCTION

Saturn's moon Titan appears to be partly covered by lakes and seas of organic liquids [1]. The short photochemical lifetime of methane in the atmosphere, which is close to its triple point just as water is on Earth, suggests that its continued presence in the atmosphere requires replenishment from a surface or subsurface reservoir. Furthermore, the dominant product of methane photolysis is ethane, which is also a liquid at Titan's 94K surface temperature, and models predict that an equivalent of several hundred meters global depth of ethane should have accumulated over the age of the solar system. In addition to these photochemical arguments, there is observational evidence of surface deposits of liquid. First, near-infrared images that can penetrate Titan's hazy atmosphere show pitch-black regions, consistent with organic - and probably liquid - deposits. More recently, radar observations from the Arecibo radio telescope showing specular reflections from Titan indicate large (several hundred km in extent) areas which are smooth on the scale of a wavelength (12cm). A natural interpretation of these observations is seas : large, flat, dark deposits of organics.

There is, therefore, a significant chance that the Huygens probe may parachute down to a landing on a liquid surface.



*Fig.1 Impression of the Huygens probe descending to a splashdown in a hydrocarbon lake under Titan's ruddy sky. While the splashdown scenario may be realistic, the vista is not – Saturn will be on the other side of Titan during Huygens' descent. Artwork by Mark Robertson-Tessi and Ralph Lorenz. See <http://www.lpl.arizona.edu/~rlorenz/titanart/titan1.html>*

Little work, however, has been published on spacecraft splashdown dynamics since the Apollo era ; one notable exception being a study of the impact of the Challenger crew module after its disintegration after launch.

A previous review paper by the present author [2] explored various landing scenarios to estimate likely landing loads, including a splashdown. This paper is motivated by mounting evidence for surface liquids, the imminence and public interest in the event, and some recent laboratory experiments.

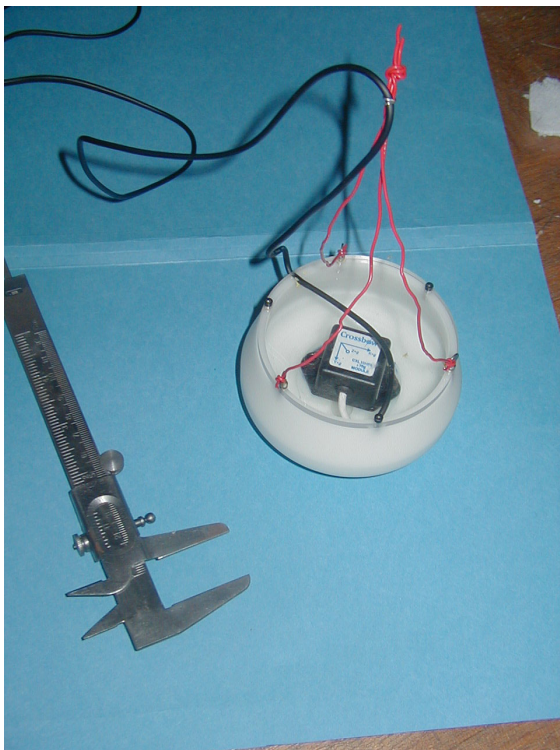
## 2. SCALE MODEL SPLASHDOWN TESTS

Two scale models (1/7 and 1/14) were manufactured with the external shape of the Huygens. The models were turned from a block of Delrin plastic, and had masses of 1205g and 205g. No attempt was made to model the rigidity of the real probe, nor to model deviations from the smooth base of the probe (notably the cavity of the Surface Science Package, and the spin vanes.) There are various appendages around the edge of the real probe whose influence is explored here.

These include the attachment points for the front shield, the flat antennae of the radar altimeters and parts of scientific instruments such as the camera head and the booms of the Huygens Atmospheric Science Instrument (HASI).

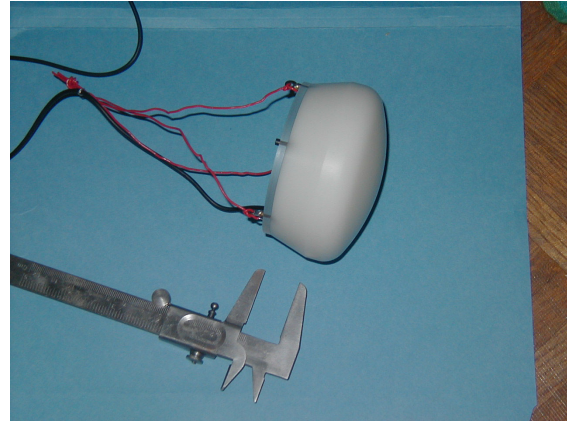
As an aside, it may be noted that the real Huygens probe has a rather low density. To manufacture a model from sheet would be rather laborious, but the manufacture by milling out a solid block with adequate rigidity led to a somewhat heavy model.

Additionally, for convenience and aesthetics, a plexiglass lid was used for the probe, to allow easy inspection of the installed instrumentation and to check for leaks etc. This lid probably made the probe somewhat top-heavy.



*Fig.2.. Small (1/14) Probe model. The jaws of the caliper are 2cm apart. Note the red wire suspension harness and the accelerometer.*

A Crossbow technologies CXL10HF3 accelerometer was installed at the center of the model. This device is a piezoelectric device with integral charge amplification, yielding a frequency response of 0.5 to 10,000 Hz. The range is +/-10g.



*Fig. 3. Side view of the small probe model, showing the non-spherical nose shape.*

Sample rates of some 5 kHz were needed to resolve the contact spike. (Note that the ACC-I sample rate on the Huygens Surface Science Package samples at only 500 Hz, but this will be adequate to characterize the impact as the length scales and hence times are proportionately larger at full scale.) Data was recorded with 16 bit precision using an Iotech Daq 216B PCMCIA data acquisition card on a laptop computer. Experiments were conducted at the author's residence.

The probe was dropped into a bathtub of water, and an aluminium jelly pan (25cm dia by 21cm deep). Although the latter probably suffers from some wave reflection/finite target effects, these were not severe. This pan was also used for tests into a hydrocarbon liquid (Kerosene).

In each case, the probe was dropped by hand – occasionally this led to tip-off errors (angular motion) or sticking/drag on release. A solenoid or melt-wire release system may be used in future tests.

The acceleration record for a typical drop is shown in figure 4. We observe first the near-square pulse of free-fall. From the integral under this part of the curve (and indeed, merely from its duration, since the acceleration may be considered essentially constant at -1g) the impact velocity may be calculated.

We then observe a very sharp spike in deceleration on contact. This is the classic splashdown deceleration pulse studied in previous work. Close inspection of the record reveals some high frequency oscillations, which are attributable to structural 'ringing'.

The inertial loading pulse at contact decays rapidly to almost zero - the vehicle continues to penetrate - the contact pulse removes only about 30% of the impact

velocity in this instance. The hydrodynamic drag forces appear in fact to be rather small.

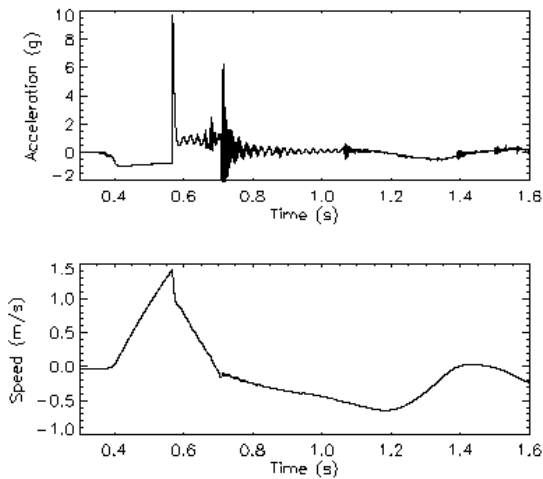


Fig.4 Deceleration record for a small probe drop into water. The integral of the record shows the speed - rising to impact at 1.45 m/s. Note the large deceleration spike at contact, and the onset of oscillations at 0.7s.

As the vehicle penetrates deeper, the buoyancy acting on it increases, leading a steady rise in deceleration. Since the vehicle floats only partially immersed, it follows that when fully immersed, the buoyancy exceeds the weight and thus there is an acceleration upwards.

Subsequently there are oscillations with a long period. This is simple bobbing. Spurious high-frequency signals are superimposed on the record from time to time - a notable feature is at 0.7s. This is interpreted to be where the back end of the probe crosses the waterline, and perhaps entrains a large bubble of water.

Peak decelerations for a set of drops into water and kerosene are shown in figures 5 and 6. Drops into water at an impact speed of 0.75-0.76m/s yielded decelerations of 1.82-1.96g while drops into kerosene at 0.76 m/s gave loads of 1.3, 1.57, 1.55g. Thus kerosene loads are ~80% of those for water.

The possibility of tip-off errors (i.e. angular motion prior to impact) and imperfect speed determination at impact means these results should be considered preliminary. It is notable, for example, that the water results in figure 5 do not quite follow the parabolic curve that would be expected (see section 3) and speed errors are suspected.

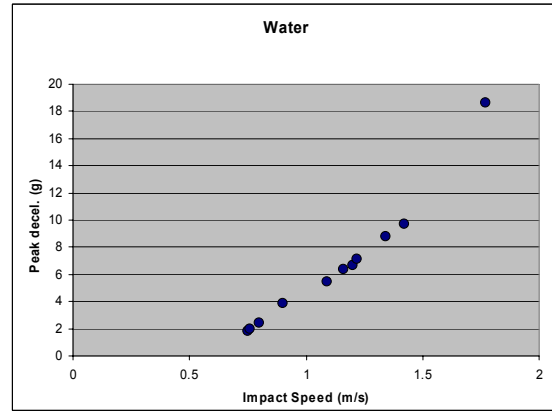


Fig 5. Peak deceleration for impacts into water. Due to poor speed determination, these results should be considered preliminary, particularly at the lower speeds (where perhaps impact speed has been overestimated – the results should fall on a parabola going through the origin).

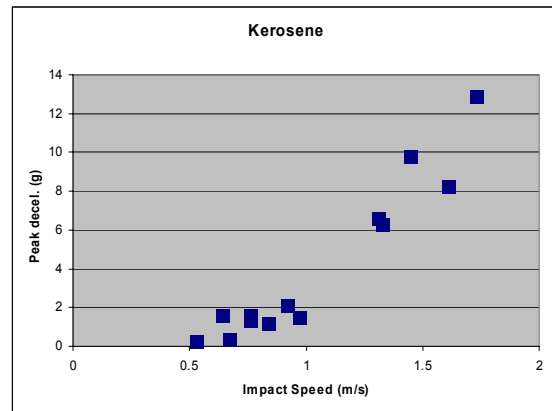


Fig 6. Peak deceleration results for drops into Kerosene. Again, these results should be considered preliminary, given the relatively inaccurate impact speed determination. It may be noted that these results seem to show the (correct) parabolic form of the peak deceleration rather better than for the results into water (fig 5).

### 3. MODELING OF SPLASHDOWN LOADS

Essentially conservation of momentum is applied, but this momentum is shared between the impacting spacecraft and some 'added mass' of water, with the added mass proscribed as a function of the spacecraft's penetration distance. The usual approach is to set the added (or 'virtual') mass equal to that of a hemisphere of water with a diameter equal to that of the spacecraft at the undisturbed waterline. Assume a mass  $M_0$  for the probe, at vertical impact velocity  $V_0$ . As it penetrates, it becomes loaded with a virtual mass  $M_v$

of liquid, with the probe/liquid ensemble moving at a velocity  $V$ .

Applying conservation of momentum and ignoring drag, weight and buoyancy

$$(M_o+M_v)V=M_oV_o \quad (1)$$

The virtual mass  $M_v$  is usually taken as a fraction  $k$  ( $\sim 0.7$ ) of the mass of a hemisphere of liquid with a radius  $R$  equal to that of the (assumed axisymmetric) body at the plane of the undisturbed liquid surface. Thus for a liquid of density  $\rho$ , the virtual mass is

$$M_v=2k\pi\rho R^3/3 \quad (2)$$

For a general axisymmetric shape  $R=f(h)$ , where  $h$  is the penetration distance, it is easy to show that

$$(dM_v/dh) = 2k\pi\rho R^2(dR/dh) \quad (3)$$

noting that  $(dh/dt) = V$  and  $(dV/dt) = a$

$$\text{hence } a = -\frac{V^2(2k\pi\rho R^2)dR}{(M_o+M_v)dh} \quad (4)$$

These equations are easy to solve numerically (indeed during the Mercury program, the computation was performed by hand) Terms for drag, weight and buoyancy could be added, but do not significantly affect the peak loads.

For a spherically-bottomed vehicle with a radius of curvature  $R_N$  and a penetration distance  $h$ , this 'waterline' radius is given simply as

$$R=(2R_Nh-h^2)^{0.5} \quad (5)$$

and the equations can be solved analytically (Hirano and Miura, 1970), to derive the peak loads. For a spherical nose the peak deceleration  $a_{max}$  can be written

$$a_{max} = 0.491 F^2 \mu^{-0.667} g \quad (6)$$

The two dimensionless parameters here are a relative density  $\mu = (3M_o/4\pi\rho R_N^3)$  and the Froude number  $F=V_o/(gR_N)^{0.5}$ . The prefactor 0.491(= $256/243\pi^{-0.667}$ ) has no fundamental significance - Hirano and Miura [3] derive it on the assumption of  $k=0.5$ , and indeed their own experimental data show that this underpredicts the peak deceleration slightly.

It may be noted that while the instantaneous deceleration at a given penetration depth is proportional to fluid density, the peak deceleration is proportional to density raised to the two-thirds power

(at a given depth a more dense fluid will have decelerated the probe more strongly, so the speed at that depth is lower - hence the peak deceleration is sublinear with density.) The numerical simulations performed [2] bear this out - those calculations showed for a 207kg Huygens probe hitting at 5.2 m/s, the peak load is 8g for a 500 kgm<sup>-3</sup> ocean, but about 10.2 for a 700kgm<sup>-3</sup> ocean.

Applying the analytical model to the real Huygens probe ( $R_N=1.25m$ ,  $m=207kg$ ,  $V_o=5.2m/s$  and a 600 kgm<sup>-3</sup> ocean, we have  $\mu=0.042$  and  $F=3.5$ . Accordingly, we expect  $a_{max}=67 m/s^2$  (using the Hirano and Miura prefactor) or 6.8g - or more likely, 20-40% higher than this, taking into account a higher prefactor - consistent with the numerical results above.

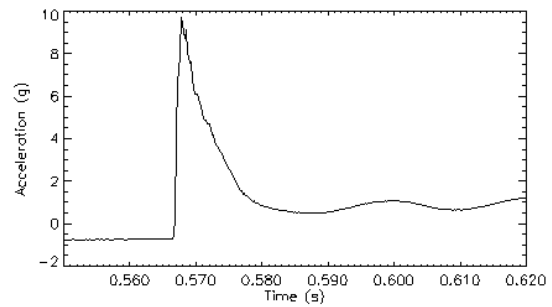


Fig. 7 Zoom in of figure 6 to show the approximately instantaneous rise and exponential decay of the contact pulse

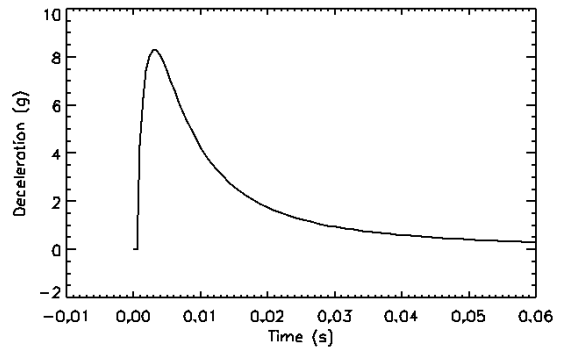


Fig. 8 Numerical model of the impact in figure 7 using the 'added mass' approach (but with an assumed hemispherical nose radius, rather than the actual probe shape - hence the numerical model decays less rapidly).

The density ratio between kerosene and water is 82%. We would expect density dependence of peak load to be proportional to density<sup>0.666</sup> or 0.87 times those for water, while the observed ratio (section 3) is around 0.80. It is believed, despite the preliminary nature of

the experiments, that this discrepancy is real. It may be a feature of the lower surface tension of kerosene compared with water, an effect that is likely to be less pronounced at larger scales.

#### 4. CONSIDERATIONS FOR THE REAL HUYGENS SPLASHDOWN

Several items of equipment protrude around the probe's equator, leading to an increase in projected area. These may be expected to cause some increase in deceleration when they contact the water surface. Although each component has not been modeled separately, protrusions with the same relative area have been attached to study their effect.

The spin vanes on the base of the probe, which are aligned very close to vertical, are not modelled. The irregularities on the top platform such as the antennae and parachute container would not be expected to affect the splashdown profile and are not modelled.

It has been noted in previous work that the ideal predicted loads for a perfectly flat liquid surface and normal impact are larger than in the case of a more realistic wavy surface, or if the probe is tilted at impact.

On the other hand, it must be observed that the model tests typically employ, and the mathematical models assume, a perfectly rigid probe fore dome. In reality, the probe will deform, flattening on impact. This may have the effect of increasing the peak loads.

Thus some care will be required in interpreting the impact signature to recover ocean density - at the ~10-20% level required to discriminate ocean compositions, these nonideal effects will be significant.

#### 5. OCEAN DYNAMICS TESTS

Some preliminary experiments have been conducted in post-impact dynamics with the Huygens probe configuration. It should be emphasized that while the shape of the probe is representative, the mass distribution is not, the model being somewhat top-heavy due to a thick plexiglass lid. This may lead to rocking modes being less heavily-damped than on the real probe.

The probe model was instrumented with a Crossbow CXL04LP3 3-axis accelerometer (somewhat more sensitive than the splashdown unit, and with a DC response). This was driven by a 5V regulated supply powered with a small 9V battery, and the analog output sampled at 50 Hz with a Pace Scientific XR-440M 4-

channel 12-bit datalogger (a unit 120x61x24 mm). This unit has enough memory capacity to store about 2 minutes of data at this rate, enough to disconnect the system from a data management laptop computer and transport the package into the sea and perform about a minute and a half of sensing operations. The fourth channel of the logger was connected to a Sharp AD12D02 infrared proximity sensor which yields an analog voltage that relates (nonlinearly and nonuniquely, but reproducibly) to the distance of a reflecting surface.

The tests were conducted in the Pacific Ocean at Mitchell Cove near Santa Cruz, California in June 2003, in depths of 0-1.5m, within about 20m of shore.

An attempt to record the actual wave-height profile contemporaneously with the accelerometer was unsuccessful: buffeting by wave loads and the difficulties of the experimenters' moving smoothly across the uneven seabed meant the sensor could not be held steadily. A video record was obtained of some of the tests.



*Fig. 9 1/7 Scale Model in the Pacific Ocean*

The top-heavy nature of the model was such that the probe occasionally inverted during deployment, or on encountering a breaking wave.

It was impossible to determine whether a persistent ~1.4 Hz signal in the record was due to the wave spectrum itself, or to bobbing, or rocking motions.

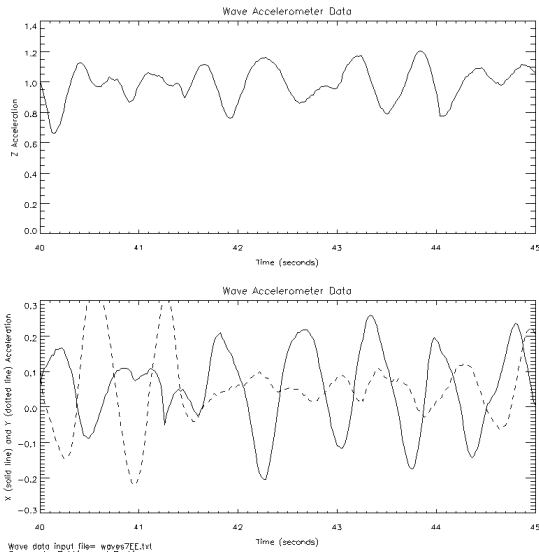


Fig 10 Bobbing and rocking motion. It is, with these model data alone, rather difficult to discriminate bobbing from rocking motion.

As noted in [4] the Huygens shape is such that the bobbing and rocking periods are a function of ocean density. The bobbing period would be about 2.95s for a  $450\text{kgm}^{-3}$  ocean and 2.3s for  $650\text{kgm}^{-3}$ : these periods were based on an early mass for the probe of 170kg – since the probe mass at impact is now anticipated to be  $\sim 200\text{kg}$ , the bobbing period will be  $(200/170)0.5=1.08$  times longer than these values. [4] predicted rocking periods of 3.7s for  $450\text{kgm}^{-3}$  ocean and 3.1s for  $650\text{kgm}^{-3}$  – presumably the as-built probe has a longer period, although the details will depend on the moments of inertia (the Huygens User Manual indicates moments of inertia  $I_y=24.5\text{kgm}^2$  and  $I_z=22.9\text{kgm}^2$ , thus the period depends on the azimuth of the rocking axis.) The figures above are undamped periods – damping may lead to a slightly longer period.

Some unanticipated, but enlightening, observations were made in the surf zone. In particular, a very clear signature, which one would hope we will not encounter at Titan, of breaking waves is apparent in the accelerometer record. This is shown schematically below.

Two other distinct signatures were detected in the littoral zone. One (which again we would hope not to encounter; the chances of successful data reception in such an instance are in any case small) is of rolling. The Z-axis acceleration falls to near zero, while there is a 1-g sinusoidal signal on the X axis, echoed with a 90 degree phase lag on the Y axis.

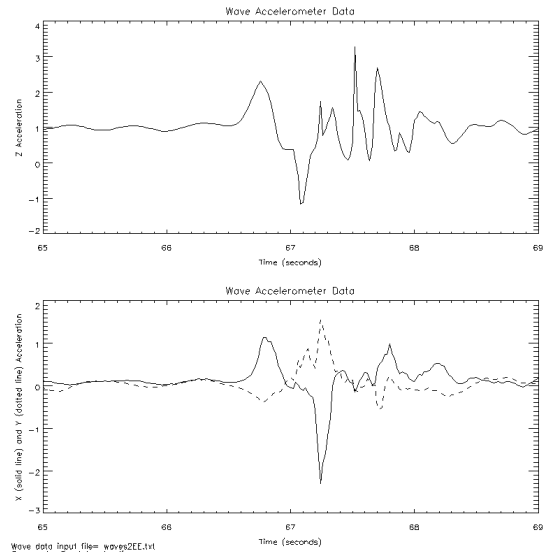


Fig. 11 Probe is gently bobbing on smooth surface when caught in a breaking wave. Note the first signature is 'upwards' acceleration (actually the probe tilts and is accelerated forward) then becomes inverted before tumbling several times and eventually ending upright.

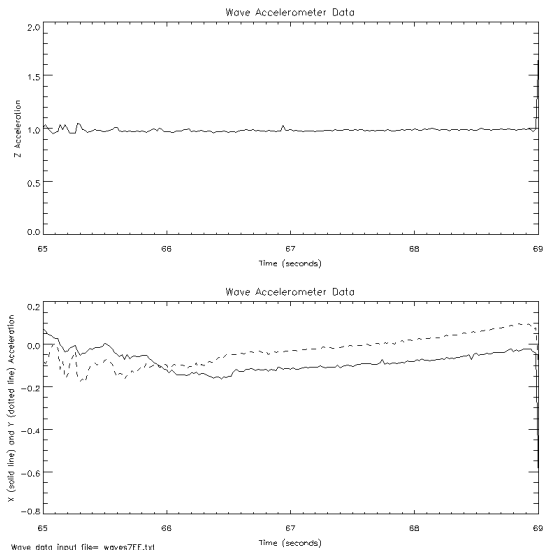


Fig. 12 signal during beaching. Note the steady, decaying X- and Y- axis deceleration, while the Z-axis remains constant at 1.0 (indicating no vertical motion)

The second littoral signal was encountered when the probe was beached and subsequently pushed by swash. Z-axis stays constant at 1g, while a modest but persistent X-Y signal decays to zero. Subsequently a

spike is encountered and normal ocean motion (with bobbing and rocking) resumes.

## 6. FUTURE WORK

The canonical 'hydrocarbon ocean' on Titan is assumed to be a mix of methane and ethane, although more detailed models include nitrogen dissolved in the methane, and a number of minor solutes such as propane. Large amounts of suspended materials are also possible. The haze that drizzles down from the stratosphere comprises fractal aggregate particles of only a fraction of a micron in diameter, the density contrast between the haze and the liquid is modest, and Titan's gravity is very low. These three factors conspire to make sedimentation velocities very small, and likely much smaller than the likely liquid motions due to wind stress and tidal effects. Thus Titan's 'oceans' may be in fact rather like sludge or mud.

This possibility motivates consideration in future experiments of studying splashdown loads in rather viscous liquids. The damping influence of viscous liquids on bobbing and rocking motion may be significant.

The tests will be repeated with fluids of different density and viscosity, and perhaps surface tension, with improved release controls and speed determination. The accelerometer record between the contact phase and the re-emergence and bobbing may be useful in constraining the viscous properties of the fluid.

The effects of the mass distribution will be considered, in an effort to recover the actual wave height profile from the accelerometer or tilt sensor record- the probe acts as a buoy.

## 7. REFERENCES

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