PLANETARY LAKE LANDER: ADAPTIVE SCIENCE INITIAL RESULTS. T. Smith[1], S. Y. Lee[1,2], L. Pedersen[1], H. Seddiqi[1], N. A. Cabrol[3,4], E. A. Grin[3,4], R. Lorenz[5], J. Moersch[6], E. MacLennan[6], V. Parro[7], E. W. Smith[8], P. Sobron[3], C. Tambley[9], C. Thompson[10], D. S. Wettergreen[11]. [1]NASA Ames Intelligent Robotics Group, Moffett Field, CA 94035. Email: trey.smith@nasa.gov; [2]SGT Inc., Moffett Field, CA; [3]SETI Institute Carl Sagan Center, 189 Bernardo Ave., Suite 100, Mountain View, CA 94043; [4]NASA Ames Space Science Division, MS 245-3, Moffett Field, CA 94035; [5]Johns Hopkins University Applied Physics Lab., MD, 20723-6099; [6]University of Tennessee, Knoxville, TN 37996; [7]Centro de Astrobiología, Madrid, Spain; [8]Aqua Survey Inc., Flemington, NJ 08822; [9]Campoalto Operaciones, Santiago, Chile; [10]University of Guelph, ON N1G 2W1, Canada; [11]Carnegie Mellon University Robotics Institute, Pittsburgh, PA, 15260.

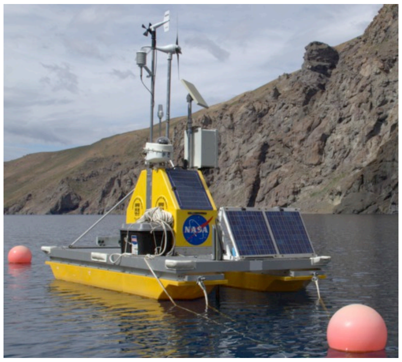

Fig. 1. The lake lander in Laguna Negra.

Introduction: The PLL robotic probe, an analog to future probes on the lakes and seas of Titan, autonomously learns about its environment, and uses that information to focus its limited resources on the most relevant phenomena, improving science impact. Autonomy is particularly compelling for Titan missions, where round trip communication delay to Earth is over two hours and limited power tightly constrains downlink data volume. Our general approach is to enable the robot to learn probabilistic models of the environment that improve over time, and use those models to sample at the most interesting times and places, downlink the most interesting samples, and further reduce data volume through smart compression.

Background and Objectives: The PLL lake lander is deployed at Laguna Negra (33°37'25"/70°03'35W) in the Central Andes of Chile, at 2700 m elevation in the region of the Echaurren glacier.

PLL's primary science objective is to characterize lake physical, chemical and biological processes, and how they are disrupted by rapid deglaciation that affects inflow to the lake. Its primary technology objective is to develop and field test operational scenarios and systems relevant to future Titan missions, in particular to the Titan Mare Explorer (TiME) mission [1].

Platform: The lake lander (Fig. 1) is a pontoon buoy carrying a sensor suite and avionics to support adaptive science. It is powered by solar panels and a wind turbine, with batteries for energy storage. Sensors include: (1) *Water quality:* A sonde, suspended from a winch that can lower it to 50 m maximum depth, measuring oxidation/reduction potential, dissolved oxygen, turbidity, chlorophyll, blue/green algae, conductivity, and temperature. (2) *GigaPan:* A pan/tilt/zoom camera to capture and stitch 360-degree panoramic imagery. (3) *Weather:* Wind speed and direction, air pressure and temperature, and relative humidity. (4) *Depth sounder:* Measures depth with sonar.

The lake lander has operated in two main configurations: (1) When moored, the lake lander has operated unattended for months at a time. (2) During our Dec. 2013 field campaign, the lake lander performed transects across parts of the lake (drifting, or piloted with a trolling motor when necessary).

Storm Detection: Storms are interesting due to their effect on lake processes. For example, precipitation runoff can increase nutrient inflow, and windstorms can blow soil into the lake. Storms may also be rare and important events in Titan lakes, enabling study of Titan's methane cycle.

When the lake lander detects a storm, it responds by taking a burst of high-rate samples and sending an alert email to the science team. A storm is defined as a precipitation or high-wind event. Without a rain gauge, high relative humidity is used as a proxy for precipitation. Keeping the initial approach simple, manual detection thresholds (RH > 85%, wind velocity > 10 m/s) were selected by observing past data.

The past few months with the simple storm detector emphasize the importance of context sensitivity and relative thresholds in event detection. First, of nine detected storms, three were judged to be false alarms—afternoon wind may indicate a storm in winter but is normal in spring. Second, a strategy that takes into account the system energy constraints (e.g., lowering the response threshold on a sunny day with nearly full batteries) could safely collect more opportunistic samples. Initial work in classifying weather states using an HMM also appears promising.

Adaptive Depth Sampling: The lake lander sonde samples one depth at a time. Raising and lowering the sonde takes a significant part of the lake lander's total energy usage. If the goal of sampling is to reconstruct conditions throughout the water column, what is the optimal sampling strategy?

A relevant insight is that some parts of the water column are more predictable than others. The largest temporal variations are often observed near the thermocline, a sharp temperature gradient marking the boundary between near-surface and deeper waters. This observation suggests a strategy of sampling more frequently at the less predictable depths near the thermocline, and carrying forward the predictable values at other depths using an environment model.

This concept was tested in simulation using historical data. Sampling strategies in simulation were restricted to use less energy than was available on the real lake lander, thus could only collect a subset of the samples from the historical data set, and were evaluated on their ability to reconstruct the entire data set. Two strategies were compared (Fig. 2): The baseline strategy periodically took full profiles (samples at all depths). The adaptive strategy took less frequent full profiles and more frequent partial profiles centered on the thermocline. Using the adaptive strategy reduced the error of the temperature reconstruction from 1.22 C to 0.63 C (RMS). The adaptive strategy is now being evaluated onboard the lake lander.

Adaptive Shore Approach: The TiME mission lander would splash down in a Titan lake and drift passively until running aground on the shore. The approach to the shore could be a brief and unique opportunity to image shoreline features and sample in the shallower parts of the lake.

During the Dec. 2013 field test, the lake lander performed several near-shore transects, and demonstrated increasing its sampling rate when it approached the shore, as detected using a simple depth threshold. In future work, these transect data sets will be used to develop more sophisticated adaptive behaviors, such as controlling the GigaPan camera pointing to optimize coverage of shoreline features.

Novelty Detection: Statistical novelty detection is useful for identifying unusual events. Response to such events includes prioritized downlink of data collected around their occurrence and follow up data collection.

We use Hidden Markov Models (HMM's) [2] to model both weather data (over time) and water quality parameters (along a traverse). The HMM is learned from unlabeled data which is then classified by it to a finite set of abstract states. Transitions to rarer states are flagged as novelties.

This approach successfully flags storm events (in weather data) and stream discharges into the lake (Fig. 3) as novelties *without any prior knowledge* of the environment.

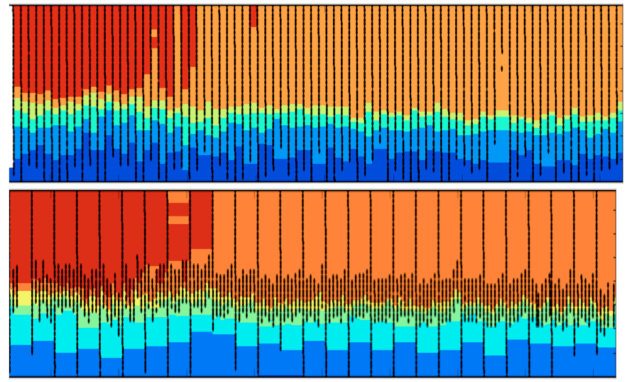

Fig. 2. Adaptive depth sampling. Color indicates reconstructed temperature (redder is warmer). Black points mark sample locations. (Top) Baseline strategy. (Bottom) Adaptive sampling thermocline tracking.

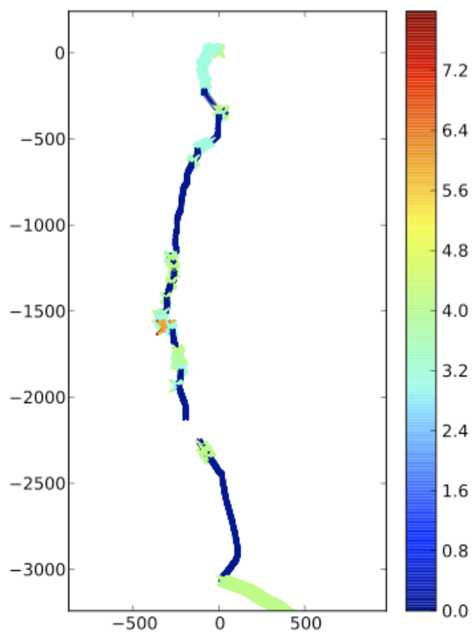

Fig. 3. HMM classification of water quality measurements taken along the western shore of Laguna Negra. Color scale indicates number of standard deviations of state mean from base state (blue). Several of the high-novelty areas correspond to stream inflows.

References: [1] Stofan, E. (2009), *Titan Mars Explorer (TiME): The first exploration of an extraterrestrial sea.* Presentation to the NASA Decadal Survey. [2] Thompson, D. R., et al. (2008) "Information-Optimal Selective Data Return for Autonomous Rover Traverse Science and Survey." In *Proc. ICRA*.

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