PLANETARY LAKE LANDER - A ROBOTIC SENTINEL TO MONITOR REMOTE LAKES

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ABSTRACT

The Planetary Lake Lander Project is studying the impact of rapid deglaciation at a high altitude alpine lake in the Andes, where disrupted environmental, physical, chemical, and biological cycles result in newly emerging natural patterns.

The solar powered Lake Lander robot is designed to monitor the lake system and characterize both baseline characteristics and impacts of disturbance events such as storms and landslides. Lake Lander must use an onboard adaptive science-on-the-fly approach to return relevant data about these events to mission control without exceeding limited energy and bandwidth resources.

Lake Lander carries weather sensors, cameras and a sonde that is winched up and down the water column to monitor temperature, dissolved oxygen, turbidity and other water quality parameters. Data from Lake Lander is returned via satellite and distributed to an international team of scientists via web-based ground data systems.

Here, we describe the Lake Lander Project scientific goals, hardware design, ground data systems, and preliminary data from 2011. The adaptive science-on-the-fly system will be described in future papers.

Key words: Titan Mare Explorer, deglaciation, limnology, autonomous science, ground data systems.

1. INTRODUCTION

The Planetary Lake Lander (PLL) project is a multidisciplinary study of the impact of rapid deglaciation at Laguna Negra (Figure 1), a high altitude alpine lake in central Chile [1], where disrupted environmental, physical, chemical, and biological cycles result in newly emerging natural patterns. Understanding this impact

Figure 1: Laguna Negra (33°39′S/70°07′W) is a 6 km × 2 km, 300 m deep glacial lake. In the background is the rapidly retreating Echaurren glacier. Deglaciation is associated with changes in meltwater discharge into the lake, whose implications for ecosystem and biodiversity have yet to be documented. The region is one of the main freshwater resources for the capital region of Santiago.

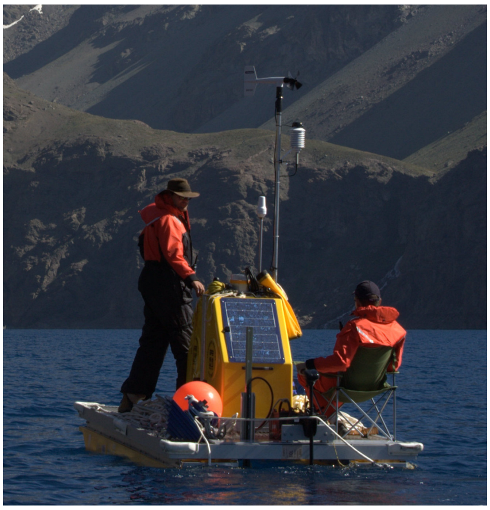


Figure 2: Deployment of Lake Lander 1.0 to Laguna Negra in December 2011

contributes to a better understanding of Earth's glacial lake ecosystems, and to how life and habitats adapted to past deglaciations of our planet. Glacially fed lakes, including Laguna Negra, are important sources of water for human economies.

Lake Lander (Figure 2) is a robotic probe designed to continuously monitor Laguna Negra for several years. It is built around a commercially available profiling system [2] that we anchored in Laguna Negra during the austral summer of 2011/2012 to collect baseline data (Figure 3). A winch raises and lowers a YSI 6600 water quality sonde through the water column to measure various parameters (temperature, turbidity, dissolved oxygen, chlorophyll concentration, pH, oxidation/reduction potential and conductance) from 1 to 50 meters 4 times a day. In addition, the probe carries a meteorological station (wind speed and direction, relative humidity, barometric pressure and air temperature), webcam, and attitude sensors.

In 2012 Lake Lander is being upgraded with computation, satellite communications, additional solar and wind power, camera imagers, and wireless data-link to nearby shore-based sensors. It will return to Laguna Negra for the 2012/2013 austral summer and remain there for two years, operating throughout all seasons, including winters when temperatures are below freezing and there is the possibility of the lake icing over.

Lake conditions can change rapidly following the onset of glacial discharge, weather activity (storms), seasonal state changes or unexpected stochastic events (e.g. landslides, hydrothermal discharge). Deducing the cause of these changes requires high rate measurements both before and after the change. Power, time, and communications constraints mean that Lake Lander cannot continuously acquire measurements at the desired spatial and temporal resolutions. Instead, an onboard intelligent adaptive science-on-the-fly approach is needed to focus resources on acquiring the most needed measurements.

Data gathered by field scientists, the Lake Lander robot and other sensors is collected and visualized by an integrated exploration ground data system (xGDS) that supports interdisciplinary collaboration within the distributed science team by allowing easy comparison of multiple data sets and integrated modeling of physical and biological processes.

2. SCIENTIFIC MISSION

Ice is retreating worldwide. Glaciers and ice fields are expected to shrink significantly within a generation, and many of the lower-altitude glaciers could disappear during the next 10-20 years with significant effects on society, ecosystems, and biodiversity.

Deglaciation disrupts seasonal and inter-annual patterns, leading to the following questions that must be answered to improve our forecasting of the future of glacial lake habitats, ecosystems and biodiversity:

1. What are the disruptions associated with deglaciation, their frequency and magnitude?
2. What is their impact on metabolic activity, ecosystem and biogeochemical cycles?
3. What is the response of the glacial lake habitat, ecosystem, and biodiversity?

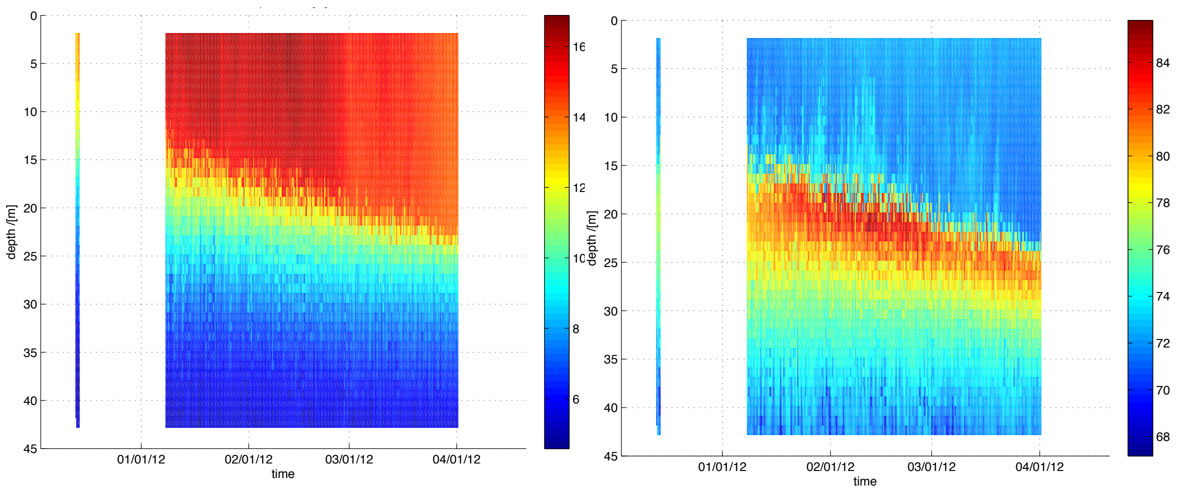
Glacial lakes are highly sensitive markers of environmental variability. Alpine and equatorial lakes are projected to be especially vulnerable to climate change because dissolved organic carbon (DOC) concentration, whether allochthonous or autochthonous, is strongly affected by lower and more acid precipitation, increased temperature and snow melting [3–5].

The International Panel on Climate Change [6] lists the Central and Southern Andes as particularly vulnerable [7]. Study of the Andean lakes in Chile has only begun recently [1, 8–14]. One relevant study is the High Lakes Project (HLP) funded by the NASA Astrobiology Institute (NAI) to explore early Mars lake environment analogs [14, 15]. HLP showed the impact of climate variability on the geophysical environment of several lakes located in the arid Andes (Bolivian and Chilean Altiplano and Andes 18-23.5°S). These lakes were formed by deglaciation at the end of the Pleistocene, but glaciers have disappeared since the onset of aridity 10,000 years ago. They are now barely sustained by limited and variable snow precipitation (30-90 mm/year) and experience strong negative water balance (-1,200 mm/yr). HLP demonstrated the domino effect of precipitation variability and intra-seasonal shifts. Those are associated with changes in temperature, cloud fraction and wind regime thus changes aerosol amount and nature that trigger a chain reaction in the lakes, changing water chemistry and transparency [14].

The study of deglaciation effects also applies to Mars habitability and life potential during comparable geological periods early in Mars history and later, during high-obliquity cycles when snow precipitation and glacier formation were possible.

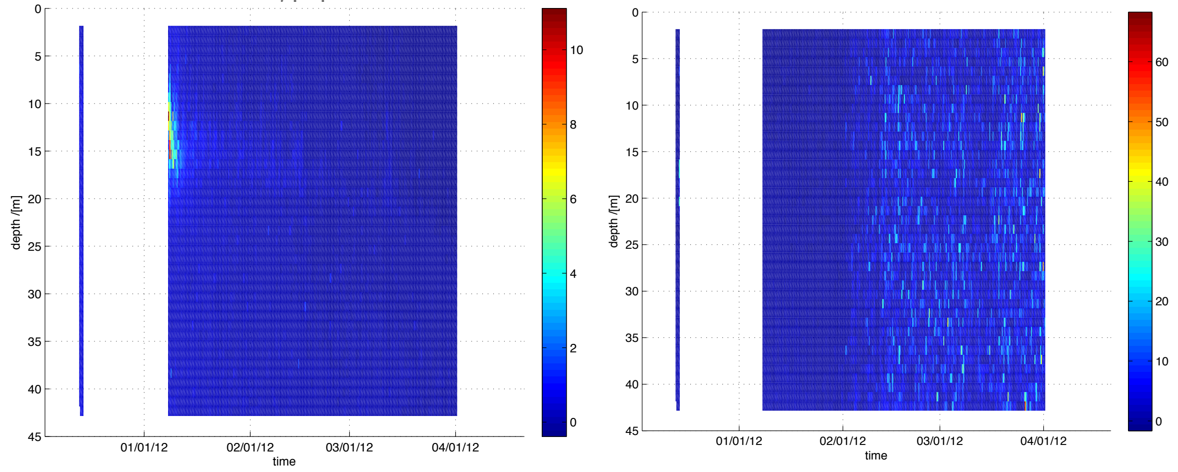
The existence of ancient glaciers and lakes on Mars is now supported by multiple lines of evidence [15–18]. Planetary Lake Lander, thus, also gives a window in time to better understand the rapidity and types of physical, chemical, and possibly biological processes that could have taken place in Mars history during similar climate transitions. Ultimately, the data collected will inform us on life's adaptation potential (or lack thereof) and will teach us how to recognize the geological, mineralogical, and biological signatures of past deglaciation on Mars.

From a robotic planetary exploration perspective, investigating this lake confronts us with challenges analogous



(a) Temperature (C)

(b) Dissolved oxygen (%)



(c) Turbidity (NTU)

(d) Chlorophyll

Figure 3: Lake Lander profiler data. Water quality paramters (temperature, turbidity, etc) from the surface to deep within the water column are plotted against time (December 2011 - April 2012). Summer warming of the lake is evident in the gradual lowering of the thermocline (a). It is hypothesized that photosynthetic organisms cluster around the thermocline as evidenced by the increased concentration of oxygen there (b), however there is no clear relation of the chlorophyll signature to depth (d). The tail end of a turbidity spike resulting from the discharge of summer time glacial meltwater is visible in (c).

to those faced by future missions to the lakes and seas of Titan [19,20], thus affording us an opportunity to develop and test exploration strategies for such planetary lake lander missions.

3. HARDWARE

3.1. Commercially Available Hardware

Lake Lander is built around a commercially available vertical profiling system for harsh marine environments. We are adding additional sensors, computation, communications, and power subsystems.

The vertical profiler, procured from YSI Integrated Sys-

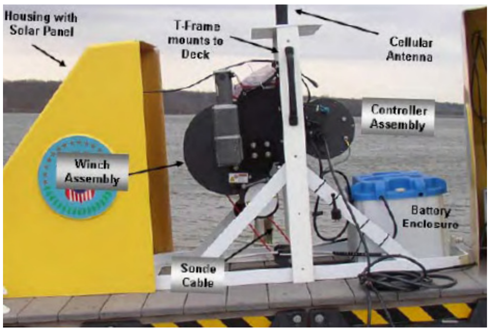


Figure 4: The vertical profiler assembly, with the covers removed to show the winch assembly and watertight enclosures for the electronics.

Figure 5: YSI 6600 multi-parameter water quality logger sonde. Note the sensor port cleaning brushes. The manufacturers estimate the sensors will remain calibrated for up to 3 months in pristine alpine waters. The sonde can also operate by itself using its own data-logger and batteries

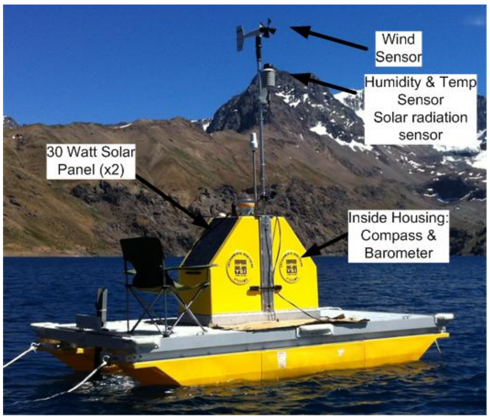


Figure 6: Meterorology sensors on vertical profiler

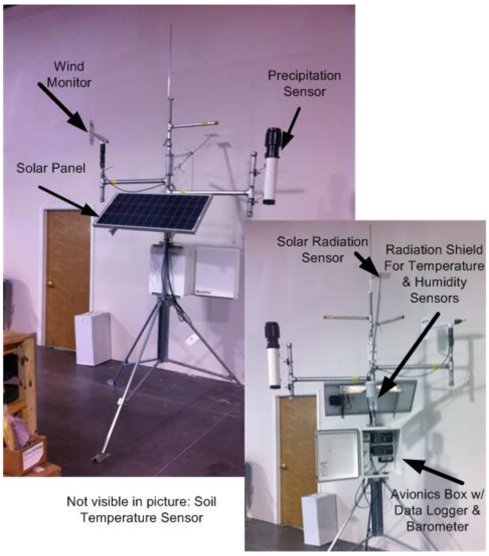


Figure 7: Shore based meteorology station located near the vertical profiler, with additional sensors to measure rainfall, solar insolation, soil moisture and lake level

tems and Services, consists of a winch system on a pontoon (Figure 4). Suspended from the winch is the YSI 6600 multi-parameter sonde (Figure 5) with temperature, dissolved oxygen, turbidity, pH/ORP, conductivity, chlorophyll, blue/green algae and depth sensors. The sonde is equipped with cleaning brushes and anti-foul coatings for sustained operations in between cleaning and re-calibration. Above water the vertical profiler has a standard meteorology sensor suite (air temperature, wind direction and speed, barometric pressure).

The vertical profiler is controlled by two Campbell Scientific CR1000 data loggers, one for the sonde and winch control, the other for the meteorology sensors. The data loggers have 4 MB memory and some limited computation, sufficient for computing running averages of sensor data and moving the sonde up or down. A serial connection to the outside world allows a Windows computer, running Campbell's LoggerNet software, to retrieve data from either data logger or install operating software.

Additional serial ports connect to an Iridium 9522 satellite transceiver, and a Microhard Nano IPn920 RF serial and ethernet modem for connecting to the profiler from NASA Ames or from the lakeside base camp respectively.

The vertical profiler is powered by two opposite facing 30 Watt solar panels attached to a 95 Amp-hr lead-acid battery.

A shore station (Figure 7) also based on the CR1000 data logger and with the same meteorological sensors plus a rain gauge, soil moisture sensor and lake level gauge is located on a beach across from the vertical profiler mooring point.

3.2. Avionics Upgrades

During the 2011 austral summer field season of PLL, the profiler and all the sensors were controlled directly by the CR1000 data loggers. The loggers were pre-programmed to run four profiles per day and take measurements with the sensor at set intervals. This was sufficient to collect baseline data and to see how the system runs for long periods of time; however, the loggers alone are not capable enough to intelligently adapt to sudden unexpected changes in the environment, support cameras, or initiate communications back to California, and must be manually reset in the event of complications, such as momentary power loss. The iridium satellite link, which initiates as a 2400-4800 *bits*-per-second analog modem dialup link from California proved too unreliable to retrieve data or even check system health.

To address these shortcomings we have built a new avionics subsystem (Figure 8), based on a FitPCi [21] with 500 GB SSD drive and running Linux. This ultra-low-power computer controls the communication between all the devices as well as analyzes the data. If the computer records an interesting event it may trigger more sensor measurements, following adaptive measurement rules devised by the science team.

The primary communications channel is a BGAN 9502 [22] satellite transceiver that provides a globally routable Internet connection through the geosynchronous Inmarsat service. The FitPC is configured as a router for external access to all devices on the local area network. Microhard Nano IPn920 radios extend the LAN to the shore station and to base camp. A Quake Global Q-Pro modem provides a backup communication channel over Iridium's SDB service for short messages between the FitPC and mission control.

The design philosophy is to minimize any changes to the well-tested vertical profiler system and to preserve the manufacturer-supported methods of connecting with it, even in the event of other hardware failing. Consequently, we have retained the profiler hardware (including Iridium modem and serially connected Microhard radio) and could continue using it as originally designed in the event of catastrophic failure of the avionics subsystem.

An ethernet adapter is added to the profiler data loggers so that we can access them from any point on the LAN (including both the FitPC and the shore station), or through the BGAN satellite connection.

The FitPC runs a software package called LoggerNet Server Linux, that provides a text-based interface to all connected CR1000 data loggers with the same capabilities as the Windows GUI based LoggerNet program normally used to retrieve data. Python scripts enable us to automate control of the data loggers (on both the profiler and shore station) from the FitPC.

3.3. Power System Upgrades

Constrained power is the biggest hurdle to operating reliably withot interruption for an entire year. The unmodified system is sufficient for operating the profiler a couple times a day during the summer months, but not for the additional avionics in winter, although much care was taken to choose low power components. The additional power required for Internet devices is judged worthwhile for the design flexibility afforded. The 1140 Wh battery provides only 3.8 days of power reserve. Consequently, an additional 30 W solar panel and Air Breeze wind turbine are being integrated, so that we may keep the FitPC and communications channels running continuously (Tables 1,2).

4. GROUND DATA SYSTEMS

The Exploration Ground Data Systems (xGDS) Project in the NASA Ames Intelligent Robotics Group is developing a web-based software platform that handles mission data for science operations [29] [24]. The platform includes tools for planning, monitoring, visualization, documentation, analysis, and search. xGDS has supported

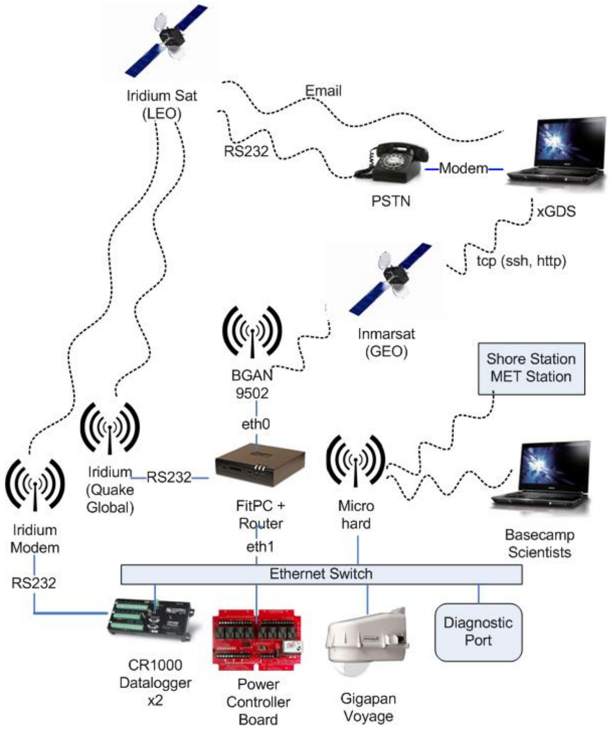


Figure 8: Detailed Communication System diagram

Table 1: Power Requirements

Component	*Power [W]*	*Hours / day*	*Wh / day*
FitPC	6.0	24	144.0
Microhard Radio [23]	0.01	24	0.24
Gigapan Voyage [24, 25]	18.3	1	18.3
Ethernet Switch	2.5	24	60.0
Winch	26.4	0.8	22.1
Power Controller Board [26]	1.2	24	28.8
Quake Global Comm. Tx [27]	6.6	0.5	3.3
BGAN	0.4	24	9.6
CR1000 electronics	0.7	24	16.8
Total			**300**

Table 2: Estimated Power Available

Component	*Power [W]*	*Hours / day*	*Wh / day*
Built In Solar Panel (x2)	30.0	4	120
Additional Solar Panel	15.0	4	60
Wind turbine [28]	30.0	6	180
Total			**360**

Data set	*Characteristics*
Water quality	18 time series, 2 platforms, variable depth, 3 months of data
Weather	19 time series
Probe health	7 time series
Biology samples	71 samples, 3 teams recording different sample parameters
Geology samples	6 samples
Map layers	13 map layers, several sources
GigaPan imagery	10 gigapans, 15 gigapixels

Table 3: PLL 2011 Data Sets Accessible Through xGDS

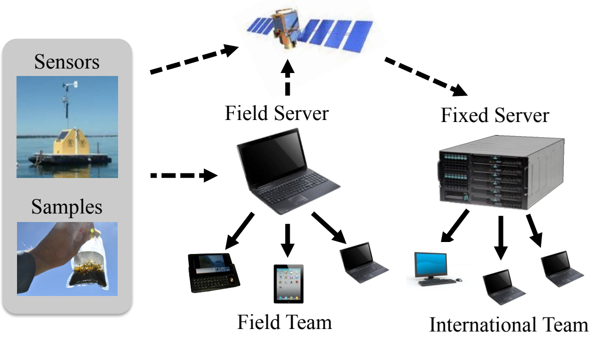


Figure 9: xGDS Data Flow

diverse operations ranging from rovers and astronauts at the Haughton Mars Project and Desert RATS to submersibles and divers at NEEMO and the Pavilion Lake Research Project.

We were able to establish a unified xGDS repository of PLL science data (Table 3), thanks to strong support from the science team. PLL science themes concern correlations between different data sets (example: turbidity and chlorophyll), so making it easy to visualize and analyze all data through a single interface is a major benefit. The system helps us track what data sets have been collected, ensure proper backups, and establish common meta-data standards to support search (uniform sample numbering, GPS locations, timestamps, attribution, and so on). Users interact with xGDS primarily through a web browser, so we can make the whole data repository available to the international science team with minimal overhead for software installation and maintenance.

Data flow is a concern given our reliance on limited satellite bandwidth. Figure 9 shows the anticipated flow for 2012 operations. During the field season, data will first be collected and annotated at a server in base camp where the field team can access it, and will then be sent via satellite to a fixed server where the rest of the science team can access it via the Internet from their home institutions. After the field season, the Lake Lander will send its data back to the fixed server directly. During our first field season in 2011, we used a simplified version of this data flow with only one server active at a time.

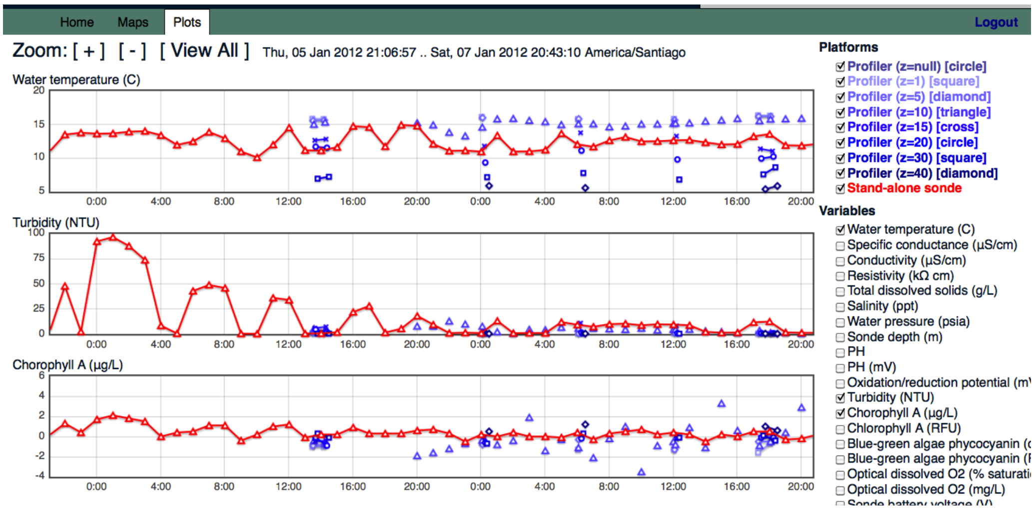
To visualize PLL time series data, we added a new section to the xGDS web interface (Figure 10). The sidebar has a menu of 37 time series variables available for plotting. Some variables are available for multiple platforms (both stand-alone sonde and Lake Lander) or at multiple depths (Lake Lander winch). The user can select which variables to display together, scroll forward or backward in time, and zoom the time resolution in or out to visualize processes at time scales ranging from minutes to months. Scrolling or zooming the time axis of any plot adjusts all the plots in the same way.

Figure 12: 360° GigaPan taken near Lake Lander mooring (2.5 Gigapixels)

We collected a wide variety of PLL map layers in a repository on our server, to aid in operations planning and data analysis (Figure 11). Users launched the map view by clicking on a web link that loaded the map from the server and launched the Google Earth map viewer on their computer. The sidebar listed all the map layers, allowing the user to choose which layers to display together in the map. The viewer automatically refreshed the map display at an adjustable rate to show the latest data. Layers included sample locations, bathymetry, vegetation and geology maps scanned from previous studies of the watershed, topography, landmarks, and multi-spectral remote sensing.

We collected several wide-area gigapixel-resolution panoramas around Laguna Negra (Figure 12). We used a GigaPan, a robotic mount that takes hundreds of photos in a regular pattern that facilitates stitching them into a single panorama [30]. These geolocated survey panoramas will support detailed before-and-after comparisons in case of landslides or other environment changes.

In future work, we plan to make the xGDS system available for offline use in the field through a mobile device such as a phone or tablet, what we call a “digital field assistant”. The primary benefits of this approach are improved management of data collection and improved field safety through shared trip planning and live position tracking. In 2011 we did a preliminary assessment of the benefits of live tracking using Garmin Rino GPS-enabled handheld radio transceivers. The units functioned well, were used for most field operations, and got positive feedback from our safety officers.



Platforms

☑ Profiler (z=null) [circle]
☑ Profiler (z=1) [square]
☑ Profiler (z=5) [diamond]
☑ Profiler (z=10) [triangle]
☑ Profiler (z=15) [cross]
☑ Profiler (z=20) [circle]
☑ Profiler (z=30) [square]
☑ Profiler (z=40) [diamond]
☑ Stand-alone sonde

Variables

☑ Water temperature (C)
☐ Specific conductance (µS/cm)
☐ Conductivity (µS/cm)
☐ Resistivity (kΩ cm)
☐ Total dissolved solids (g/L)
☐ Salinity (ppt)
☐ Water pressure (psia)
☐ Sonde depth (m)
☐ PH
☐ PH (mV)
☐ Oxidation/reduction potential (m
☑ Turbidity (NTU)
☑ Chorophyll A (µg/L)
☐ Chlorophyll A (RFU)
☐ Blue-green algae phycocyanin (
☐ Blue-green algae phycocyanin (
☐ Optical dissolved O2 (% saturati
☐ Optical dissolved O2 (mg/L)

Figure 10: xGDS time series plots

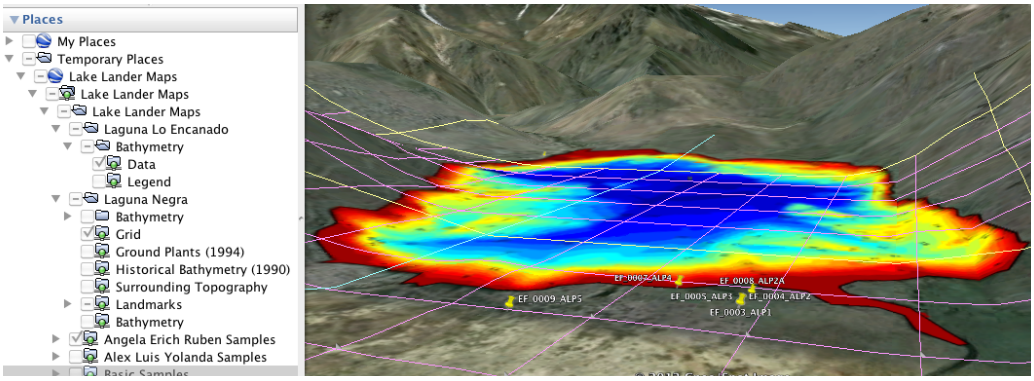


Figure 11: xGDS map display showing sample locations, grid marks, and bathymetry (courtesy of Chris Haberle)

5. CONCLUSIONS

This paper describes the scientific rationale for the robotic exploration of alpine lakes, and their scientific relevance to Martian astrobiology. Field tests to acquire baseline data established that the commercially available systems are by themselves insufficient for the demands of this mission. We describe the hardware design being built for continuous monitoring of the lake for two years beginning in November 2012, and the ground data systems built to support it.

ACKNOWLEDGMENTS

This work is funded by NASA's Astrobiology Science and Technology for Exploring Planets (ASTEP) program. Thanks to xGDS team members Matt Deans, David Lees, and Tamar Cohen for their continuing support.

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