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New Pathfinder Technology for Ice – Ocean System Monitoring

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Summary

Recently, some advances have been made with multi-instrumented automated surface stations. These show promise of being able to monitor in situ conditions in both the surface (ice or sea ice) and subsurface (within glacier ice, and underlying ocean), and can transmit the majority of the collected data in real time, avoiding possible loss due to the dynamic installation environment. We describe here a pathfinder technology approach in support of eventual design selection for a group of intelligent up-linked stations and sensor components for monitoring outlet glacier ice-ocean interaction. Our working name for these stations is 'AMIGOS' (Automated Meteorology-Ice-Geophysics Observation Systems: Scambos et al., 2013 in press).

AMIGOS stations are fundamentally satellite telemetry (Iridium) –uplinked multi-sensor systems with the sensor components and system peripherals integrated and monitored by a specifically designed single-board computer. Weather and ice properties are measured by weather instruments, albedometers, snow-depth sensors, thermistors, and camera systems (visible and thermal infrared), and ice motion is measured by an integrated dual-frequency GPS. Ocean conditions are measured by a small CTD string or laser-stimulated optical fiber. The main system is designed to have very low power requirements, which reduces weight by reducing the need for large battery banks. Communications via the Iridium satellite modem is two-way, permitting changes to the data acquisition protocols, or, uplinking of stored high-resolution data that is not included in the daily uplink. Daily uplink data volume is on the order of 20 to 100 kilobytes, but could be upgraded to megabyte levels if power is not a concern (e.g. with more batteries, different battery technology, or in summer with abundant solar power).

Background, History, and Motivation

The interactions between ice sheet outlet glaciers and ocean circulation, or Arctic sea ice and the underlying ocean, have emerged as the most important controls on ice mass balance, both for sea ice and for ice sheets (e.g., Pritchard et al. 2012; Holland et al., 2009; Ngheim et al., 2012; Alexeev et al., 2012). Subtle changes in ocean circulation or heat content, driven by changing wind patterns or changing ocean layer densities or temperatures arising from global climate change, can have a profound effect on basal melt rates and, for glaciers, near-ice-front circulation. In turn, these have led to major increases in flow speed and mass flux from the ice sheets, for example along the southeast and northwest Greenland coast, and a northward retreat of sea ice in the Atlantic sector as well as significant sea ice thinning overall.

In situ telemetered observation stations for polar research have evolved considerably in the past few decades. Such observations began with Argos-system uplinked automated weather stations (AWS) developed in the late 1970s (Stearns, 1988). These have been considerably augmented in recent years to include a host of snow and energy-balance measurement sensors (e.g., Steffen, 2001; van den Broeke and others, 2010). Communications have improved by using larger-bandwidth telemetry available on the Geostationary Observing Earth Satellite (GOES). However, these communications are generally uplink only (i.e., station-to-observer). Moreover, the GOES satellites are unusable at the highest latitude areas because of their near-equatorial orbit.

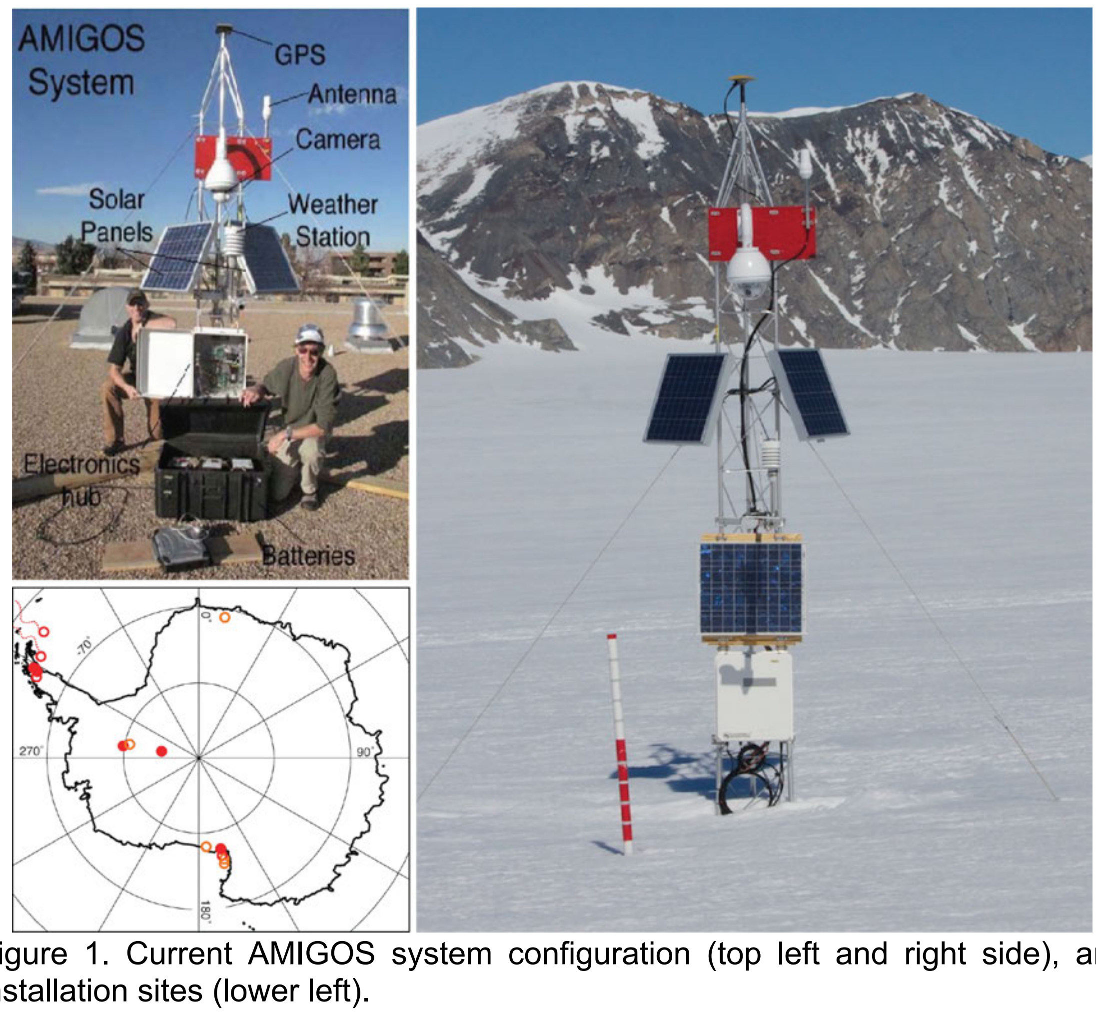

Figure 1. Current AMIGOS system configuration (top left and right side), and installation sites (lower left).

As more detailed information about conditions, processes, and environmental and ecological events is now desired, an increasing need for in situ image data and geophysical measurements has emerged. This requires a larger bandwidth than is available via Argos telemetry, and the complexity of managing power and data collection for year-round in situ observations requires two-way communications, i.e. the ability to change data acquisition protocols on the system from a remote location as well as the ability to send information from the observation site. On-board control of the communications system, data collection, and sensors also requires a more capable processing capability. To address this need for a group of related research objectives, an automated station configuration now called the Automated Meteorology – Ice – Geophysics System (AMIGOS) was developed over the past decade.

The AMIGOS set-up was originally created to support logistical needs at remote snow and blue-ice runways for a commercial company (Antarctic Logistics and Expeditions, ALE), but evolved into a multi-sensor geophysical and biological monitoring system for polar field work as well as logistical support. AMIGOS stations allow for year-round monitoring of Antarctic weather and surface conditions and, over time, compile information regarding changes in local patterns, sastrugi formation, melt and melt pond evolution, fracturing, ice flow, and climate changes (via firn temperature profiling). At present the AMIGOS design can combine weather and image data, precision GPS, solar flux and surface reflectivity, and thermal profile sensors, with a solar-panel – battery power system and, importantly, an Iridium satellite modem system for both data transmission uplink and system management downlink to the operating system. The improved two-way communication facilitates post-installation changes to the acquisition scheme, data download, internal software, or sensor configurations. Moreover, the Iridium system of near-polar satellites has connectivity at all latitudes.

AMIGOS System Design

The main processing board, which we call the Triton CPU board, was developed by one of us (R. Ross) in 2004. Previous processor platforms in early pre-AMIGOS systems lacked a complete file system and the ability to call up the station and change parameters such as duty cycle and scheduling. In 2004, a custom processor board was designed and implemented, running a Linux operating system. The advantage of this approach is that simple built-in utilities such as telnet, FTP client/server, web server, shell scripting and a C cross-compiler would be available for both programming and remote trouble-shooting of the system. A single-board-computer module (TritonTM ETN) was selected from KARO Corporation of Germany as the host CPU. The Triton module is based on an Intel X-scale microprocessor chip, and has low power requirements (1.6W run mode, 120mW sleep mode). The modules are rated by KARO for low temperature operation (to -40°C) and are supplied with a 64 MB RAM and 32 MB flash memory, as well as KARO firmware. The module is compact with a footprint of just 3 x 7cm in a SODIMM-style design. A custom carrier board was designed for the Triton module which plugs into the carrier board and forms a single entity (hereafter, we refer to this combined pair as the "Triton board"; Figure 2). The Triton board accepts a range of input voltage from 12-15 volts and can route a total of 5A spread across the 10 regulated outputs. Precise voltage regulator output for peripheral instruments or components is set by a two-resistor combination. It has several I/O connections such as Ethernet, I2C, SPI, 1W, GPIO and a Compact Flash interface. The Triton board supplies regulated power to the module, has over/under voltage protection, reverse polarity protection, electro-static discharge protection and a 4-channel ADC for measuring input voltage & current draw. An array of linear and switching regulators surround the module, controlled by firmware embedded in the module's flash memory, that regulate and supply power to external sensors and peripherals.

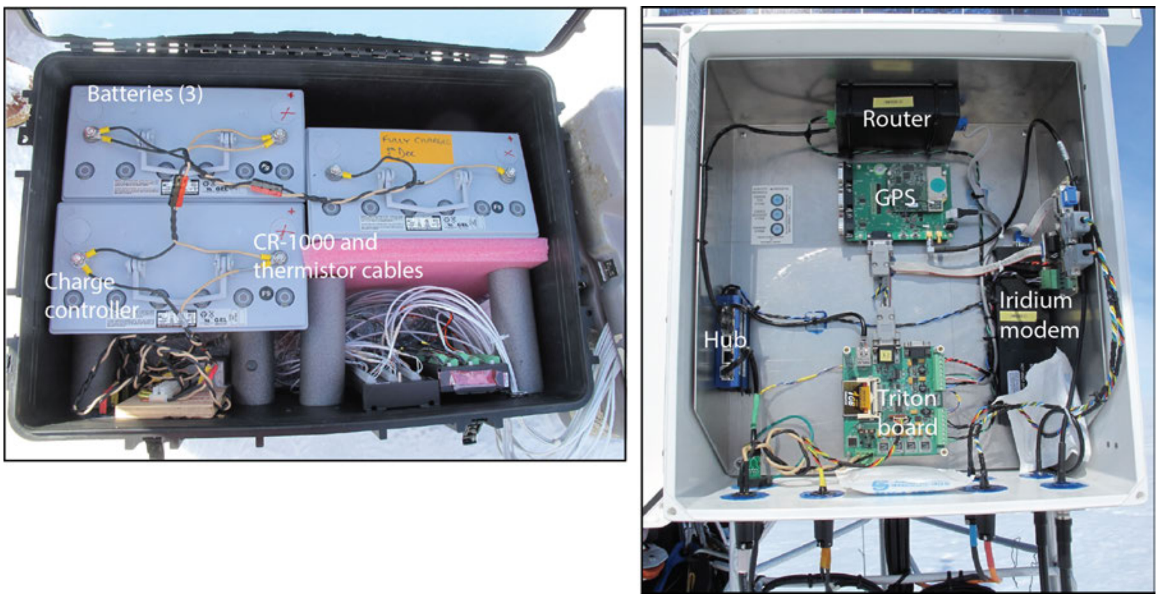

Figure 2. View of main electronics enclosure (right) and battery box (left).

A key requirement is the need for the module to be reset externally and automatically in the case of a software crash, i.e., a 'watchdog' functionality. A basic microcontroller was added to the carrier and programmed for this watchdog function. When the system is running properly, the Triton module pulses ('pets') the microcontroller watchdog every minute. The absence of a pulse from the CPU initiates a hard reset of the CPU.

The core firmware for the Linux operating system (version 2.6) is stored on the internal flash memory of the Triton module. Our custom programs and code for the sensors and instruments are stored on compact flash, along with acquired data. Currently a 2GB SLC compact flash is used. Once the Triton has booted and configured, all tasks performed by the software are executed through a scheduler that runs every minute. Shared resources such as the Iridium modem are controlled through a system of software flags. For example, for a typical task (e.g., read the weather sensor every hour), the scheduler will launch the software task to turn on power to the sensor, read the data from the sensor, turn it off, timestamp and format the data, and append it to a 24-hour log. For most AMIGOS systems these data will be transmitted by the Iridium modem as a SBD message to an email recipient. A previously launched task may already be using the Iridium and therefore a software flag will postpone a task until the resource is available. If not in use, the software will turn on the modem, send the message to the modem and execute the transmission. Some tasks do not complete due to Iridium transmission breaks. In this case a record is kept for future attempts to clear backlogs. Once a task is completed, the modem is switched off to conserve power. Operation of the modem is among the largest power-consuming functions (the other major power consumer is camera operations).

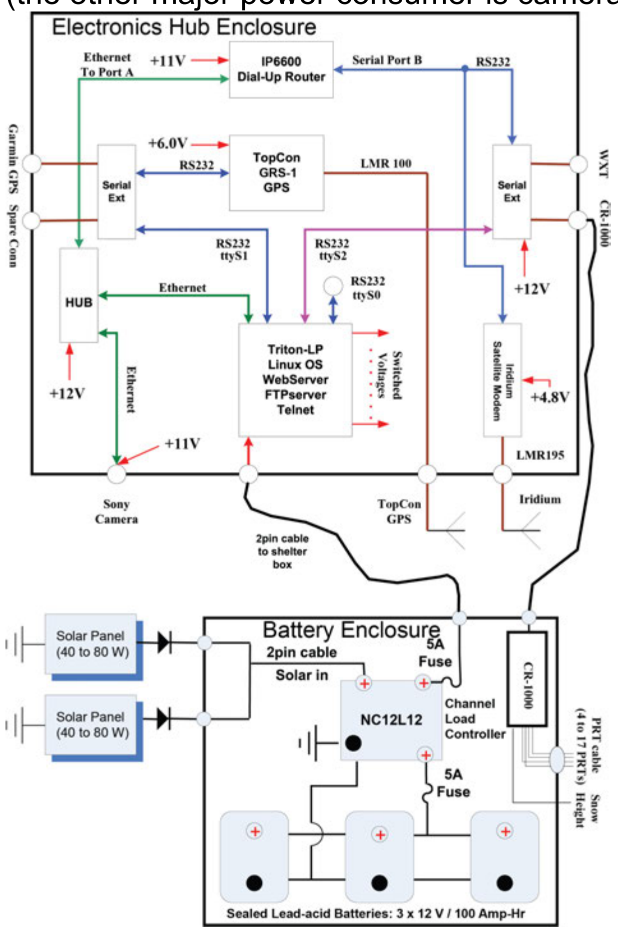

Figure 3. Block diagram and description of current AMIGOS configuration and components.

The instruments and Triton board are connected by local Ethernet links and serial ports. The computer enclosure includes an Ethernet hub, router, and the Iridium modem, as well as the Triton board (Figure 3, top, and Figure 4 top; Table 1b). It also includes the precision GPS system (if installed), and the main shelter box can be modified to hold the DSLR high-resolution camera and precision pointing stage as well. The power box (Figure 3, bottom) contains three or four 100 amp-hr batteries, a solar power controller, and the CR-1000 data logger supporting the thermistor string and sonic ranging sensor (if installed).

All AMIGOS systems incorporate an Iridium modem for both SBD and dial-up uplink and downlink communications. Recently installed systems use NAL Research Corporation A3LA-XA modems for more reliable low-temperature operation. These modems provide a data rate of 1200 baud in dial-out mode. Transmissions in SBD mode are single bursts of up to 2000 bytes. A key feature of the AMIGOS platform is the ability to call up the system at pre-scheduled times via the modem and re-program the system software or the peripherals that are Ethernet connected to the Triton board. Typical changes include redirecting the camera or changing operational duty cycles to conserve power in winter. Modem parameters themselves have been changed remotely when Iridium dial-up numbers or receive-site settings have been changed by external service providers. This feature makes the AMIGOS system both versatile and adaptable to on-site geophysical or off-site communication changes, within limits.

Planned Improvements for Ice-Ocean and Sea Ice Monitoring

We are planning to continue development of these in situ multi-sensor stations. Improvements in the computation and communication of the stations will center on better processing capability, more memory, and a greater uplink bandwidth. We have already designed an updated Triton CPU board. The new board can host a 400MHz ATMEL ARM9 processor (or a lower-power 200MHz version). The new features of the carrier board are support for OTG, full speed and high speed USB ports, Ethernet 10/100, CAN bus, LIN bus, 5 serial ports, 8 channel 12bit ADC, 10 switched regulated outputs, on board temperature, humidity, pressure and accelerometer sensors. Also new for this carrier is a real-time external clock to support a flexible sleep state for very low power low duty cycle modes. Both CPU modules run Linux 2.6 OS, with Perl and Python installed, flash memory up to 1GB and 256MB of RAM on the higher performance module. The 400MHz processor allows support for greater on-board processing of data streams, facilitating a reduced uplink requirement by sending more compressed data, or uplinking information extracted from data rather than raw data. Onboard analysis of sensor data could be used to trigger a shift to different modes of operation, for example, automatic reduction of data acquisition and uplink when solar power decreases in late fall; or, transition to a far greater rate of acquisition and uplinking when sensors indicate an unusual event is occurring. For data uplinking, the current Iridium modems are capable of sending greater amounts of data, but the required power greatly increases the logistical cost because of increased battery weight. A secondary concern is a larger solar array and the support structure required for it. For example, continuous systems operated by UNAVCO (University NavStar Consortium) in Greenland and Antarctica typically send 4 to 7 megabytes of data per day, but require up to 10 100 amp-hour lead-acid batteries (typically 32 kg each) to provide continuous power to the Iridium system through the polar winter. A key improvement in battery technology, such as re-chargeable lithium batteries, could provide higher energy density at lower weight, and thereby present an opportunity for greater uplinked data volume.

In our planned designs for sensor configuration, we will aim to expand the capabilities of AMIGOS installations by adding some important sensor improvements. The success of the high-resolution cameras and precision pointing stages shows that there is value in incorporating them at more of the sites. We are also planning to upgrade to dual weather stations at different heights — for example, at 2 and 4 meters above the initial snow surface — to determine wind and thermal gradients, which can be significant on polar ice sheets. At glaciological sites, a pair of thermal radiometers measuring both sky thermal emission and snow surface skin temperatures would facilitate surface energy balance studies. Sites overlooking floating ice front areas could benefit from a sensitive thermal infrared camera, to record ocean surface temperature variations at the front in summer (allowing the detection of warmer currents emerging from the sub-shelf cavity, or solar warming of sea-ice-free ice front water). An upgrade being discussed for indigenous species observations is a directional microphone, to receive penguin or seal calls.

Augmented AMIGOS systems for sea ice monitoring would include the same suite of weather, snow, motion, and camera instruments. In particular, the snow depth sensors and GPS data would be highly valuable for calibration – validation of satellite mapping of ice thickness (from, e.g., CryoSat-2 data) and ice motion mapping. Of key importance would be an examination of sub-ice ocean properties to at least 40 meters below the base of the ice, and preferably 200 meters (to the base of the halocline if possible). Constructing a multi-sensor CTD string to this depth and integrating it with the main on-ice surface station hub is possible, but costly. Alternate technologies have been tested in several polar sites using a laser-illuminated fiber optic cable (which returns a temperature-only data set sampled at ~1 to 10 meters along the length of the cable). Exploring the integration of this technology with the AMIGOS would be a key goal of instrument development over the next two years.

On the glaciological side, a major current topic of interest is ice-ocean interaction, i.e., the effect of ocean circulation on ice fronts, particularly for large and deep-keeled ice sheet glaciers. These systems are known to be highly sensitive to oceanographic circulation changes driven by changing climate patterns. Monitoring such sites, over the long term and covering the several environments (glacier, ice shelf, sub-shelf, and ice-front ocean) would require a system of AMIGOS-like stations that are linked, or a hub-and-spoke array of simpler sensor instrumentation sites with a main station housing larger data storage, processing, and high-bandwidth uplink capabilities, as well as a suite of sensors of its own. Sensor sites would be linked to the main hub by a wireless network capable of spanning several (~5 to 20) kilometers. Sensor array sites would include GPS, meteorology and geophone units, long thermistor strings for ice shelf or glacier temperature profiling, and ocean measurement systems. These may initially be ocean conductivity-temperature-density (CTD) sensors that are mounted on a cable extending through the shelf ice, with a surface station for data relay and weather measurements. Main station sites might best be located on aircraft- or ship-accessible areas that have a broad view-shed of the ice-front study area, and would include both high-resolution visible and thermal infrared cameras, seismic monitoring, and the other AMIGOS instrumentation previously discussed. The main facility of the central hub, however, would be communications, data storage, and high-bandwidth data uplink. This would likely be accomplished by multiple linked Iridium modems configured in an aggregating mode.

An important advance for installation, maintenance and repair, or upgrading automated multi-sensor stations will be a more modular design, both in the tower structure and in the sensors, CPU, and power systems. Modularity is particularly important for stations (or hub-and spoke systems) installed in snow accumulation areas, where periodic re-visits are necessary to re-set or remove the systems before burial. More significantly, a modular approach should facilitate integration of new sensors, replacement of broken sensors, augmenting sensor arrays, or adding to the power-supply components.

The overall goal of such installations would be understanding the processes that govern ice mass balance for the major ice sheets, and in particular those aspects of the ice-ocean system that are not easily monitored (or too infrequently monitored) by remote sensing. For sea ice, the goals are monitoring ice drift, verifying snow depth in support of satellite-based ice thickness mapping, and understanding the dynamic ice-ocean interactions, both dynamic and thermodynamic. The AMIGOS stations, and in-situ sites with similar multi-sensor and imaging capabilities, expand our ability to assess polar areas of interest and are a needed complement to the current observational methods of remote sensing and human-operated field methodologies. These criteria arise from several informal meetings among glaciologists and oceanographers at recent conferences (NSF-sponsored polar technology conference in August 2010; Fall AGU 2010; IGS Symposium on Ice-Ocean interaction, June 2011; and Polar Tech meetings in 2011 and 2012.)

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