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Deploying a Communicating Automatic Weather Station on an Alpine Glacier

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Abstract

The cost and effort of installing and maintaining an automatic weather station (AWS) on a glacier may be mitigated by the possibility of gathering sensor data in near real-time, and of controlling and programming the station remotely. In this paper we report our experience with upgrading an existing AWS, operating over an Italian glacier, from a mere datalogger into a networked sensing station. Design choices, energy constraints and power-aware programming of the station determined by harsh environment are discussed. Deployment operations and results are described. The upgraded AWS provides low-power connectivity from a remote location and is able to serve as a base station for a wireless sensor network working in the glacier.

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Keywords: Glaciers, Sensors, Power-aware, Autonomous systems, Satellite

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1. Introduction

In the last decades Automatic Weather Stations (AWS) have been increasingly used for process-oriented energy and mass balance measurements over glaciers. The high level of automation and the large memory of dataloggers allow scientists to investigate, with high temporal resolution, the micro-meteorological variables and processes that control the response of glaciers to climatic changes. Research-grade AWSs are also getting less expensive, making it feasible to deliver distributed measurements over glaciers, e.g. deploying a network of AWSs on different places of the same glacier, or in different glaciers, and perform real-time streamflow monitoring or modelling.

However, some aspects remain critical. AWSs must be periodically visited for gathering recorded data and for maintenance. As a glacier station can be typically reached only in summer, the major drawback for scientists is the unavailability of real-time sensor data. Moreover, harsh meteorological conditions occurring on glaciers (strong winds, icing, abundant snowfalls, lightnings) may damage or reduce the lifetime of the AWS structure or external sensors and lead to data loss. Communicating with the AWS is a mandatory solution to enable real-time data availability and timely detection of damages or malfunctions. Unfortunately, the effort of enabling communication in extreme environments is far beyond the one of everyday practice.

This paper reports how we upgraded with communication an AWS operating since 2007 over an Italian glacier, which is subject to direct mass balance measurements since 2003 (La Mare glacier in the Ortles-Cevedale group,

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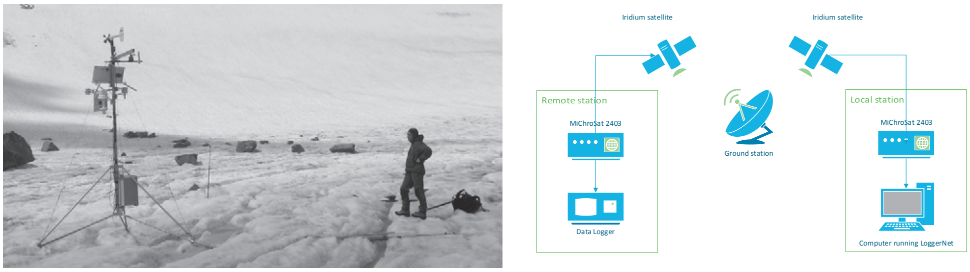


(a) The AWS, July 2012

(b) Satellite link through the MiChroSat 2403

Figure 1: The AWS as on July 2012 and modem connection schema.

Table 1: AWS components configuration and current drains.

Device type	#	Model	Description	Current drain (mA)
Anemometer	1	Young 05103-5	Wind speed and direction	Always < 0.01
Nivometer	1	Campbell Sci. SR50-A	Snow height, sonic sensor	Sleep 2.25; Active 250
Albedometer	1	Delta Ohm LP Pyra 05	Solar radiation, net between incident and reflected light	Always < 0.01
Thermo-Igrometer	1	Campbell Sci. CS215	Air temp. and relative humidity, passive ventilation shield	Idle 0.07; Active 1.7
Pirgeometer	2	Kipp & Zonen CGR3	Incoming and outgoing long-wavelength radiation	Always < 0.01
Thermo-Igrometer	1	Vaisala HMP45C	Air temp. and relative humidity, active vent shield	Sleep 0; Active 4
Thermistors	2	Campbell Sci. T-107	Temperature from both passive and active shields	Active < 0.01
Datalogger	1	Campbell Sci. CR1000	Datalogger unit	Sleep 0.6; Active 10
Modem	1	MiChroSat 2403	Iridium satellite modem	Sleep 15; Idle 150; Transmission 900

Italian Alps). The challenge was to figure out the suitable communication technology and to integrate it in an energetically sustainable way and without degrading the station's reliability. We discuss the issues related to design choices, energetic autonomy and power-aware programming of the station. The network architecture provides low-power connectivity from remote locations, making the AWS able to serve as a base station for a Wireless Sensor Network (WSN) deployed in the glacier.

2. AWS configuration

An AWS is typically composed of three subsystems: a datalogger, a power unit and a number of meteorological sensors. The term *automatic* underlines the system's main characteristic of enabling measurements from remote areas in unattended way. The operations of the datalogger are controlled by a microcomputer, that is in charge of toggling power to sensors and acquiring/storing data at given sampling rates. The challenge in AWS applications is to guarantee continuous and reliable measurements. When the AWS has no direct connection to electric power, rechargeable batteries are normally used as primary energy source for the system. Energy harvesting is usually obtained through solar panels and/or wind-turbines.

The AWS placed on La Mare glacier in Italian Alps is mounted on a 3 meters steel tripod (see Figure 1(a)). The datalogger is a CR1000 (Campbell Scientific) programmable unit based on a Renesas H8S 2322 16-bit CPU, running at 7.3 MHz [1]. The CPU, memory and Digital/Analog Inputs/Outputs are controlled by an operating system, application programs are written in CRBASIC language. The CR1000 is able to communicate with a PC or even with other CR1000 units by means of a serial connection RS232. The AWS is powered by a rechargeable 12 V – 24 Ah battery. A solar panel with a 20 W peak power output is connected to the battery through a power regulation circuitry; the small size of the panel (420 × 500 mm, weight 4.8 kg) is particularly suitable to windy conditions, typical of alpine glaciers. The datalogger and the battery are inside a weather-proof fibreglass enclosure, which is attached at the base of the tripod. To avoid burial by snow, the solar panel and the meteorological sensors are mounted on the top of the tripod. AWS components and their current drains are reported in Table 1. It should be noted that two redundant T-107 thermistors are used, one within the Vaisala HMP45C ventilated shield, the other within the CS215 passive shield. Sensors are powered by the CR1000 through always on or switched power connectors.

The AWS was installed by researchers of the Department of Land, Environment, Agriculture and Forestry (University of Padova, Italy), in the framework of a research project concerning the climate change effects on the hydrology and cryosphere of high-altitude catchments [2]. Until 2011, the AWS has been periodically inspected and maintained during summer visits. A range of new requirements arose during activity years, like remotely accessing the AWS with the aim of reducing field visits, programming maintenance and mass balance measurements, collecting and disseminating data.

3. Upgrading the AWS

Our goal is to upgrade the existing AWS with a communication facility that allows sensor data to be transferred daily and, occasionally, enables remote programming of the station (e.g., to change sensors' sampling rates and modem's duty cycle, or to recover from software bugs and instruments' faults). Such features can be enabled by satellite, radio telemetry and, recently, by exploitation of mobile telecommunication networks. The major issue with adding communication to AWSs operating in extreme environments is the impact of the needed hardware and software in the system's complexity and energy consumption. In particular, we are concerned with guaranteeing continuous data recordings, even in the case of communication failure. The challenge is to enable communication in an energetically sustainable way and without degrading the station's reliability. In the following, we discuss the issues and motivate the design choices related to the communication technology, the energetic autonomy and the power-aware programming of the upgraded station.

3.1. Communication

Telemetry can offer near real-time data transfer at relatively low cost. Enabling technologies are dedicated radio connection, WiFi, GSM/GPRS, or satellite connection. Advantages and disadvantages of different solutions must be carefully evaluated: a *radio bridge* requires the use of additional masts or poles with repeaters in order to reach the station; a *WiFi link* requires line-of-sight between the AWS and an Internet-enabled site (e.g., a mountain dew) and, again, some repeaters to have multiple relay hops functionality; a *GSM/GPRS connection* works only in the presence of a reliable network coverage, a condition often difficult to reach in high mountain; a *satellite connection* is ubiquitous but expensive.

From previous field visits we realized that mobile telephony network coverage was very scarce and intermittent, thus absolutely unsuitable to our purposes. Then, considering the afore-mentioned problems of alternate solutions, we decided to use a satellite modem and investigated the following two options:

Geostationary: satellites operate in geostationary orbits (36.000 km). They are characterized by high data rates and low connection fees, communication requires directional antennas. This is often the right solution for connecting to the Internet sensor systems operating in remote regions. However, in our case, a directional antenna could not be used. The reason is that a glacier is continuously moving due to ice melting and basal sliding. As the AWS is floating on the ice surface and subject to significant tilting, the firm line-of-sight angle, required by a directional antenna to properly work, could not be ensured.

Low Earth Orbit: systems based on a constellation of high speed moving Low Orbit Satellites (LEO). The offered bandwidth is lower and costs are sensibly higher than with geostationary systems. However, as orbit radius are much shorter than geostationary one (e.g., Iridium's 780 km), the system may work with low power omnidirectional antennas.

The fact that LEO omnidirectional antennas can tolerate large angle variations from the initial (vertical) placement, perfectly fits with our deployment constraints. For this reason, we chose the Iridium LEO constellation and used the off-the-shelf modem MiChroSat 2403 [3]. The Iridium satellite link provides a nominal bandwidth of 2.400 bit/s. The modem can be connected to the CR1000 datalogger using an RS232 null-modem cable. The omnidirectional antenna was statically mounted on top of the AWS's tripod. The logical connection schema is depicted in Figure 1(b).

3.2. Energy constraints

The main concern with the integration of a satellite modem within a battery-operated AWS is the modem's impact on the energy balance. As can be seen in Table 1, the modem is a power-hungry device. If not carefully duty cycled, its energy consumption is likely to rapidly deplete the battery, even in the presence of energy harvesting [4].

The safest solution to guarantee continuous data collection would be to supply the satellite link separately, using an additional power reserve. However, this would require re-wiring of several parts of the system and, in our case, to replace the enclosure with a bigger one able to accommodate the new battery and circuitry. More importantly, the additional flat surface of a (possibly larger) solar panel would bring instability to the AWS, due to the strong winds blowing in the glacier. Thus, in the effort of changing the working station as less as possible, we had to verify whether, in the presence of the satellite modem, the battery and the solar panel already in place would have supplied enough energy to make the system self-sustainable. To this purpose, we sketched an analytical model of the AWS's consumption and used it to determine a setting of the modem's and sensors' duty cycles able to guarantee the desired lifetime. As visits to the glacier are planned only in summer, a reasonable AWS's lifetime is one year.

Basically, the analytical model makes a balance, over a time period Δt, between the energy consumed by all the components of the system, $E_{cons}(\Delta t)$, and the energy harvested by the solar panel, $E_{harv}(\Delta t)$. For each component, the contribution to $E_{cons}(\Delta t)$ is computed as the component's duty cycle multiplied by its current drain. For the modem, we considered three power states, *Sleep*, *Idle* and *Transmission*. For $E_{harv}(\Delta t)$, the model takes into account that the efficiency of the panel depends on solar radiation and battery voltage. Application constraints, in term of sensor data resolution and data transmission time, are considered to assign duty cycles to components. Any duty cycle assignment policy for which $E_{harv}(\Delta t) \geq E_{cons}(\Delta t)$ is said to be sustainable. Considering that energy harvesting depends on sunlight, a reasonable observation time is $\Delta t = 24\,\text{h}$.

Given the difficulty of testing the system thoroughly for a whole year, we conducted a conservative worst-case analysis based on historical data collected by the AWS during the last five years. We selected the days having lower battery voltage readings and used their temperature and solar radiation readings to find out a sustainable duty cycle assignment. The analysis led to a power-aware re-programming of the station, as described in the next section.

3.3. Power-aware programming

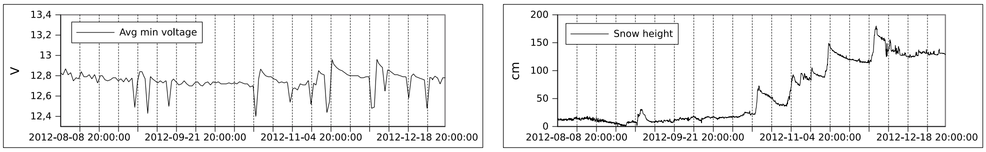
The program running on the datalogger, written in CRBASIC, has been modified to integrate the satellite modem. Also, it has been significantly reviewed to achieve a more power-aware control of the station. Duty cycles of meteorological sensors have been adapted to the constraints resulted from the energetic analysis (for example, the duty cycle of the nivometer was reduced to one sampling per hour). The amount and frequency of data logging was also optimized: to avoid frustrating the AWS's mission with possible data loss due to energy shortage, raw data are always logged to the local solid-state memory of the station, from where they can be eventually read out manually.

To determine the duty cycle of the modem we proceeded as follows. The average length of a communication session was estimated by calculating the amount of data collected daily. Given the sampling rates of sensors, such amount is roughly 28 KBytes. At the nominal modem's connection speed (2.400 bits/s), the transmission takes about 100 seconds/day, to which a connection overhead (360 s) must be added. The length of the modem's power-on time window was set to 30 minutes. This allows the remote server several chances for successfully establishing a working satellite connection with the AWS. For fault-tolerance operations and remote programming of the station, a spare time window of 30 minutes was also provided. To have better light conditions onto the solar panel, the two daily windows were scheduled at 11.00 AM and 1.00 PM, respectively.

The energetic analysis confirmed the system's sustainability. Nevertheless, to prevent deep, potentially unrecoverable discharge of the battery, we devised an adaptive control of the modem based on battery voltage readings. We observed that when the voltage level $V_{battery}$ drops below a minimum threshold, even though the datalogger can still sample and store data, the start up of the modem could completely exhaust the battery and stop the system. To prevent such a situation, the modem is NOT turned on at the scheduled time if $V_{battery} < 11.5\,\text{V}$. In this case, to let the battery reach a safe charge level, the modem will not be turned on until $V_{battery} \geq 13\,\text{V}$. This simple hysteresis-based control of the modem, enabled by the *SW12V* programmable power supply pin of the datalogger, allowed us to secure the system's lifetime at the tolerable cost of a delay in data transmission.

4. Deployment and preliminary results

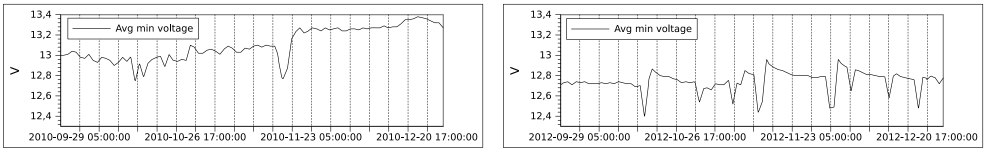
Considering the short time available for in-situ deployment and the high cost of fixing possible errors due to changes applied to the AWS, it is strongly advisable to carry out a thorough laboratory simulation of the installation procedure. To this purpose, we preventively arranged materials, tools and methods and tested them using a clone of



(a) Average minimum (over 24h) voltage of battery

(b) Snow height

Figure 2: Relation between the battery voltage and the snow height, August-December 2012



(a) Before (2010)

(b) After (2012)

Figure 3: Average minimum (over 24h) battery voltage, before and after modem installation

the station. Satellite maps and pictures of the AWS were used to devise the right placement of the antenna and the modem. We repeated the installation check-list several times in order to reduce the probability of errors and to be prepared to operate as quickly as possible once into the harsh glacial environment.

We had the opportunity of installing the modem on August 1st, 2012. The day before we walked to Refuge Larcher in the Mt. Cevedale area, where we stayed overnight. Early in the morning, a 2-hour climbing was necessary to reach the AWS location in the La Mare glacier, at about 3000 mt asl. All the needed stuff was backpacked and carried by the six members of the team. The first operation was to place and test the omnidirectional antenna. The signal strength was measured running Hayes AT commands on a laptop connected to the modem via RS-232. Before finalizing the connection of the modem through a major re-wiring of the station, logged data were manually downloaded into the laptop, hopefully for the last time. Next, the datalogger firmware was upgraded and the new CRBASIC program installed. At the scheduled time window the modem turned on successfully and, with the help of a handheld transceiver, we talked with the operator at the refuge that confirmed the acquisition of the first dataset by the local station. The installation took about 4 hours, during which we also did some scheduled maintenance. The scrupulous care we took in the pre-deployment preparation proved to be worthwhile, as all the installation steps were executed successfully and the satellite connection started working immediately.

Since the date of the first installation we have been collecting and analysing data, not only with the purpose of monitoring the microclimate of the glacier, but also to have a feedback of the actual AWS's behaviour and power state. Figure 2 shows the relation between the battery voltage (a) and the snow height (b) over the period August–December 2012. It should be noted that, starting from autumn, snowfall accumulated on the solar panel caused episodic reductions of the minimum battery voltage. In contrast, when the snow melted, the higher albedo due to increased light reflection of fresh snow caused a significant rise of battery voltage. Figure 3 shows the impact of communication on the overall energy status. Comparing the average minimum voltages taken during the same period (October-December) of years 2010 (a) and 2012 (b), respectively before and after the modem installation, it can be noted that, apart from effects due to different climate conditions (autumn 2010 was particularly dry), the use of the satellite modem caused only a slight lowering of the mean value of the battery voltage.

Intuitively, we would expect a higher voltage in summer than in winter, when weaker sunlight and lower temperature are likely to produce less battery charge. However, this guess revealed in contrast with real data shown in Figure 3, where the battery voltage tends to increase when the cold season approaches. This odd condition can be explained by the fact that, to prevent snow accumulation, we mounted the solar panel almost vertical, so as it receives more solar energy in winter when the sun is low over the horizon.

5. Related work

Literature about real installations in harsh environments is relatively small, and only few groups in the world work in the field of glacial monitoring. Corke et al. [5] wrote an extensive review on environmental wireless sensor networks, but no mention about satellite communication is given. The work "Glacial Environment Monitoring using Sensor Networks" (GSN) reports about Glacsweb [6], describing design, implementation and results of an experimental installation of WSN nodes in a glacier. The PermaSense [7] remote monitoring infrastructure is a joint project between geophysics and computer science, to study how climate change impacts on permafrost. Neither GSN nor PermaSense talk about satellite links. The problem of monitoring energy consumption by software in WSNs is addressed in [8].

6. Conclusions and future work

The AWS installed on La Mare glacier had no possibility to communicate, so that periodic site visits, at least once a year, were needed for maintenance and data gathering. To enable near-real-time data communication, timely assessment of the correct functioning and remote programming of the datalogger, we decided to upgrade the station with a satellite link. The harsh glacial environment forced us to carefully investigate the impact of energy constraint and of time-varying climate conditions on sensing operations and communication. An in-depth study of the available technologies, energy harvesting concepts and battery characteristics was necessary. The new deployment required us a power-aware re-programming of the system. The AWS is currently transmitting data every third day. This allows scientists to study glacial dynamics with a higher temporal resolution, to monitor energy and weather variables continuously, to act timely in case of ordinary and extraordinary maintenance interventions, and to plan visits to the AWS with a more accurate knowledge of site weather conditions.

Currently, we are working at enriching sensor readings with metadata complying with recognized standard like the one proposed by the GSN project [9]. Metadata should be entered into digital files to accompany and facilitate web-based dissemination of sensor data. We are also developing a tool for assisting scientists in power-aware remote re-programming of the AWS. A more complete energy model of the station is under development, with the goal of making the station's behaviour self-adaptive to environmental data. Finally, we plan to use the AWS as a gateway to a WSN deployed nearby in the glacier and connected to the station through a low power listening wireless MAC [10].

7. Acknowledgements

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