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From single point of measurement to distributed sensing in long-term glacier monitoring

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Abstract. Glacial environment monitoring is a key task in understanding natural phenomena related to global warming. For the last 30 years, Automatic Weather Stations (AWSs) have been spreading among the meteorological and geophysical community, and are on the way to become a *de facto* standard to perform long-lasting unattended data acquisitions in single localized points of interest. Sensor Networks (SNs), on the other hand, promise the possibility to perform measurements with a higher spatial density and lower cost. Designing and developing a SN for glacial environment face particular challenges for embedded electronics and sensor systems, which is why SNs are still under research and development in this field. This paper surveys the AWSs and SNs for glacial monitoring applications and compares their characteristics.

1. Introduction

Studying the evolution of glaciers became an essential task to follow global climate changes and its local effect [1]. Monitoring the state of glaciers (and in general of glacial environment) is important also for safety reasons. It enables early warning generation in case of an avalanche, or permafrost cracks and falls from mountains. Scientists today benefit from a broad range of technologies to better understand the phenomena in glacial environments. These means can be categorized based on whether they sense physical quantities remotely or locally.

Remote measurements can be carried out using satellites, planes or using ground-based devices, to take images in the visible light range (photogrammetry), or other spectral frequencies like infra-red (thermal imaging). Thermal imaging enables obtaining a temperature distribution image over the whole terrain or snow [2]. Laser or radar ranging allows to reconstruct 3D surfaces of the terrain, and compare two subsequent images to detect changes or movements. Local measurements, on the other hand, are carried out using sensing devices with output that varies based on proximal physical quantities. The sensors (temperature, water level, deformations, movements, etc.) are attached to devices able to store data (dataloggers).

Automatic Weather Stations (AWSs) are specialized measuring units, aimed at the monitoring of weather-related parameters. They are built around bigger dataloggers, that enable multiple sensors readings. In particular, AWSs deployed in glacial regions allow to investigate the micro-meteorological variables and processes related to glacier behavior caused by global climate changes. Establishing remote communication with the AWS is necessary to enable real-time data availability and timely detection of damage or malfunctions.

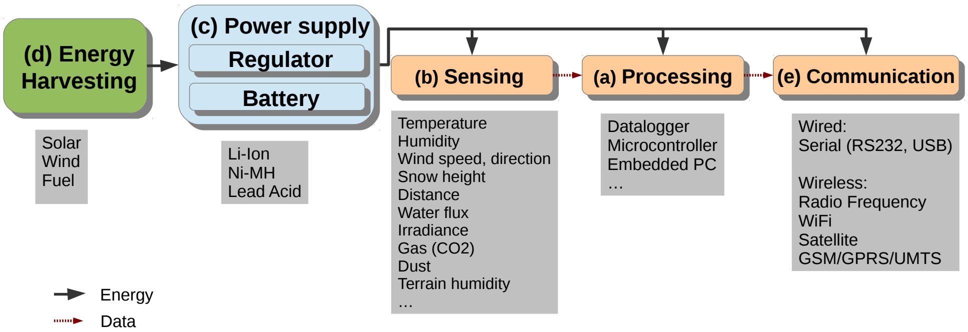

Figure 1. Scheme of typical components of an Automatic Weather Station

As the cost of hardware is decreasing, it becomes feasible to develop distributed measurements over glaciers. Deploying a network of spatially distributed sensing systems on different places of the same glacier, or in different glaciers, allows to perform real-time streamflow monitoring or modeling, enriched by dense environment data [3]. Sensor Networks (SNs), composed of multiple distributed wired or wirelessly communicating sensing devices, represent a possible enhancement to AWSs in terms of spatial resolution and costs. Open problems with SNs are related to their relatively complex setup phase and commercial availability.

A thorough study of existing literature showed the lack of a systematic overview of measuring devices used in glacial monitoring, particularly with respect to Automatic Weather Stations. These devices have been a common tool within a highly skilled community interested for measuring climate-related physical events and quantities. In this paper, we present an overview of AWSs, as they represent a standardized environmental monitoring solution. In addition, we analyse key opportunities and issues related to SNs, that could offer a higher spatial resolution of the AWSs measurements. Section 2 presents AWSs in glacial monitoring, from the hardware and software point of view. Section 3 discusses possibilities of using SNs to enhance the available solutions based on AWSs. Section 4 concludes the paper.

2. Automatic Weather Stations for glacier monitoring

A typical AWS is composed of a datalogger, sensors, a power supply, energy harvesting unit (optional), and a communication unit (optional). Fig. 1 shows a schematic view of an AWS, with the energy and data flow. Possible sensors, communication devices, harvesting and battery technologies are presented in the grey boxes in the figure. Energy harvesting unit enables replenishing the battery with energy from the environment (solar, wind, etc.), providing longer autonomy of the AWS. Communication unit enables remote access to the collected data and notifications in case of malfunctions of the AWS. Both enhancing autonomy and real-time data access are useful for geologists, since usually a glacier station can be reached only during short time slots during the year.

Programming the behavior of battery-powered acquisition systems, in terms of sampling and communication rates, impacts on storage, energy and transmission. A higher acquisition rate causes higher energy consumed by the sensors, requires more storage resources and more data transmission. Wireless data communication also causes high energy consumption and, if using GSM or satellite connections, non-negligible financial costs. This motivates researchers to adapt sampling rate and use compression algorithms to obtain energy awareness in the system, enabling better usage of energy and financial budget.

A Glacial Automatic Weather Station (GAWS) can be considered as standardised within the scientific community, that accepted and adopted the basic composition of GAWS introduced

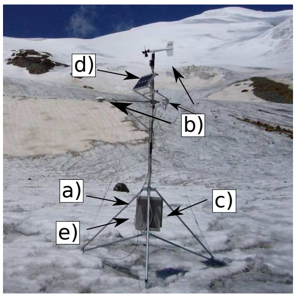

Figure 2.
a) Datalogger: MCU, EPROM, ADC
b) Sensors: temperature, wind, humidity, snow height, irradiance
c) Power supply: battery (Li-Ion, lead acid), charge regulator
d) Energy harvesting: photovoltaic panel
e) Communication device: satellite

Producer	Product	Temperature range	Sleep, Active Power	Enclosure
Gemini	TGP-4020 [5]	-40°C ... +85°C	0.5mW Average	Waterproof
Campbell Scientific	CR1000 [6]	-25°C ... +50°C	6mW, 15mW	Simple
Vaisala	QML201 [7]	-50°C ... +60°C	< 60mW Active	Simple
Delta-T Devices	DL2e [8]	-20°C ... +60°C	Not documented	Simple
Aanderaa	3660s [9]	-40°C ... +60°C	0.5mW, 150mW	Simple
MSR Electronics	MSR145 [10]	-20°C ... +60°C	Not documented	Waterproof
LSI-Lastem	e-log [11]	-20°C ... +60°C	2.4mW, 240mW	Simple
IMAU	i-AWS4Polar [12]	Not documented	Not documented	Waterproof
SensorScope	DS3 [13]	Not documented	Not documented	Waterproof

Table 1. Specifications of most popular dataloggers

in the 1990s by IMAU [4]. A typical GAWS is composed of 5 main subsystems: datalogger, energy harvester (solar panel), communication device (satellite, RF, WiFi), sensors, battery. The sensors of a GAWS are: snow level, wind speed and direction, temperature and humidity, direct and indirect irradiance. In Fig. 2 a typical GAWS is presented. Since the datalogger is the main component of an AWS, we will deepen the analysis of its features and compare the most used models.

2.1. Dataloggers

Table 1 reports about commercially available complete systems for the development and deployment of AWSs. The comparison should give a quick overview of systems and producers, to speed up the process of choosing a particular one. From the specifications of reported loggers and producers, it is extremely difficult to understand which producer is using which software architecture or programming language. The only producer that is documenting hardware and software of dataloggers is Campbell Scientific (CS). Their CR1000 datalogger (as well as other dataloggers from the same family) executes an operating system (OS). The OS is not directly accessible, but they allow to code scripts in CRBASIC (a Basic dialect) to manage the acquisition, processing and communication policies. Other producers don't enable programming of their products. The absence of fine grained programmability in the majority of products is an advantage for the primary customers (field scientists). Although most of the dataloggers are nowadays based on programmable microcontrollers, often the producers offer only preconfigured solutions, without the possibility of programming the system independently. So, for researchers interested in experimenting with different sensing, processing and communication policies, the possibilities offered by CS remain the only viable solution.

2.2. Software and data management

Programming the datalogger of an AWS often only requires setting some variables in a graphical interface on a PC connected to the datalogger, or to regulate physical handles on the housing

Institute	Location	Producer	Hardware	Time
Universities (ITA) [14]	Italian Alps	Campbell Scientific	GAWS+Sat	2004-present
IMAU (NED) [15]	Worldwide [12]	Campbell Scientific	GAWS	1995-present
Universities (ITA) [16]	Italian Alps	LSI-Lastem	GAWS+GSM	2007-present
University (CHI) [7]	Himalaya	Vaisala	AWS	2000-2010

Table 2. Some AWS deployments (with datalogger producers). Acronyms: Italy (ITA), China (CHI), Netherlands (NED).

of the logger, that set the sensors acquisition rate. Measurements taken on dataloggers are typically stored as simple log files, containing the raw sampled values. In some cases, the data is preprocessed before being logged, performing some kind of aggregation (e.g. averaging, min, max) on it, in order to reduce the amount of stored samples. Stored data are collected manually during field visits to the AWS or, if the system is equipped with some transmission device, like RF or satellite, data can be remotely sent to a computer (telemetry).

The World Glacier Monitoring Service (WGMS) is a unique place to store standardised observations on changes of mass, length, volume, area of glaciers over time [1]. It is a kind of a database, but its consistency and meaning are maintained by people. It would be a great advantage to automate at least some of the steps needed to populate the WGMS, e.g. through systems like Global Sensor Network (GSN), that ease the job of managing sensors data and process them using the notion of virtual sensor. In that way, it becomes possible to have real-time elaboration and storage of sensor data [2].

2.3. Deployments

Table 2 presents a selection of AWS deployments in glacial environments. The first three are maintained until today, while the last one has been implemented using mobile AWS (transferred from place to place every few days), to perform measurements in different places on Himalaya. Automatic Weather Stations represent a stable technology and, as we can see from Table 2, they have been used for the last 20 years in different parts of the world and by different organizations. However, recent glaciologist conferences show that there is a growing interest in spatially distributed measurements in such harsh environments [12]. In the following section, we will discuss main challenges in designing and deploying Sensor Networks that need to be reliable, easy to use and robust, just as AWSs are today.

3. From Automatic Weather Stations to Sensor Networks

Automatic Weather Stations, built around dataloggers, are a well known and widely used measurement systems for monitoring glacial environments. They are robust and reliable, but as a drawback, they represent a single point of measurement and a single point of failure.

During the last decade, in the scientific community a new requirement emerged: enhancing single points of measurements with spatially distributed measurements. Small rugged dataloggers, like the TinyTag2 [5] or the MSR145 [10], have been used for years by scientists to acquire temperatures and humidities during long periods. They are much cheaper than AWSs. The data from the sensors is stored and collected manually afterwards. Distributed Thermal Sensors (DTS), on the other hand, allow to monitor temperature along fiber-optical lines, with a spatial resolution of about 1 m. Some experiments even use DTS to measure soil moisture [17].

A technology enabling distributed measurements and communicating data to the user in an automated fashion is Sensor Networks [18]. The architecture of a sensor node comprises the

[1] World Glacier Monitoring Service - http://www.wgms.ch/about.html
[2] Global Sensor Network - http://www.swiss-experiment.ch/index.php/GSN:Home

Project	Locations	Nodes	Number of nodes	Time
SensorScope [13]	Switzerland	TinyNode	~ 15	2007
PermaSense [23]	Switzerland	TinyNode	~ 25	2006-present
GlacsWeb [24]	Norway, Iceland	GWNode	~ 20	2004-present

Table 3. Some WSN deployments on glaciers

AWS	Centralized	Single point of failure	Established	Easy to use
WSN	Distributed	Redundancy	New	Complex

Table 4. Key characteristics of AWSs and WSNs

same components like an AWS (Fig. 2), only in smaller scale. The sensors are connected to a microcontroller, that controls the acquisition, storage, processing and communication of the acquired data. The microcontrollers are often programmed using standard languages (C/C++), thus it is possible to develop new behavioural paradigms by computer scientists or electronic engineers.

In wired sensor networks, nodes are connected with wires to the base station, like in [19]. An interesting commercial solution is Thermistor Chains RBR [20] — cables with termistors attached, that can be used in water, cement, ice, etc. In a Wireless Sensor Network (WSN), sensor nodes communicate wirelessly, usually containing a radio in GHz or MHz frequency band, using WiFi, ZigBee or similar standardized protocols.

WSNs have become a hot topic in the last 10 years. The biggest challenge in WSNs is to provide enough energy to the node to enable autonomous operation [21]. Another challenge is to obtain reliable wireless communication in harsh environments (with water, ice, etc.), often requiring using lower communication frequencies (MHz or lower). Those are key reasons that WSN applications in glacial environment are still under development.

There are few successful deployments of WSNs in glacial environment. Table 3 shows most popular ones. Comparing with Table 2, we notice that some WSN deployments lasted almost as long as some AWS deployments. It is necessary to emphasize, though, that WSN deployments were part of multidisciplinary research projects and experienced operation outages (of the whole network or only of particular nodes), requiring often maintenance and modifications during the years. On the other hand, AWSs are based on mature and commercially available technologies and have had a more stable operation, although they were deployed directly by field scientists. PermaSense and GlacsWeb deployments are still active and under development. In [22], we compare those two projects and introduce possibilities of performance enhancements.

WSNs represent an interesting opportunity to enhance measurements of AWSs. Nowadays, programming and electronic skills are still needed to configure, deploy and maintain WSNs successfully. In order to become an established technology, they need to be improved in terms of simplicity of usage and robustness.

4. Conclusion

In this paper we survey the technologies for sensing in glacial environments, in order to help: a) glaciologists — to choose equipment for their application and deploy it with minimal effort and engineering skills; b) engineers — to understand the field requirements and design standardized solutions that would be easy to maintain, interoperable and scalable, in terms of software and hardware. We describe the characteristics of Automatic Weather Stations, and discuss their benefits and drawbacks. In addition, we discuss the possibilities to use sensor nodes (wireless or wired) to obtain dense spatial resolution of the measurements. The wireless sensor networks present a promising advantage for spatially distributed measurements in remote areas, but, as summarized in Table 4, they still need to be improved in terms of robustness and simplicity of usage.

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References

[1] Oerlemans J 2005 *Science* **308** 675–677

[2] Light J, Parthasarathy S and McIver W 2012 Monitoring winter ice conditions using thermal imaging cameras equipped with infrared microbolometer sensors *Procedia CS* vol 10 pp 1158–1165

[3] Abbate S, Avvenuti M, Carturan L and Cesarini D 2013 Deploying a communicating automatic weather station on an alpine glacier *3rd Internat. Workshop on Sensor Networks for Intelligence Gathering and Monitoring (SNIGM)* ed Springer

[4] Box J E, Anderson P S and van den Broeke M R 2004 Lessons to be learned: Extended abstracts *Automatic Weather Stations on Glaciers* (Univ. Utrecht, The Netherlands)

[5] GeminiDataloggers Tinytag plus 2 logger URL `http://www.geminidataloggers.com/`

[6] CampbellScientific Campbell scientific cr1000 datalogger URL `http://www.campbellsci.com/`

[7] Vaisala Qml201 datalogger URL `http://www.vaisala.com/`

[8] Delta-T Devices Dl2e - data logger URL `http://www.delta-t.co.uk/`

[9] AAnderaa Datalogger 3660s datasheet URL `http://www.aadi.no/Aanderaa/`

[10] MSR-Electronics Msr 145 datalogger URL `http://www.msr.ch/`

[11] LSI-Lastem URL `http://www.lsi-lastem.it/`

[12] 2011 *Workshop on the use of automatic measuring systems on glaciers.* (Univ. Utrecht, The Netherlands)

[13] Ingelrest F, Barrenetxea G, Schaefer G, Vetterli M, Couach O and Parlange M 2010 *ACM Trans. Sen. Netw.* **6** 17:1–17:32 ISSN 1550-4859 URL `http://doi.acm.org/10.1145/1689239.1689247`

[14] Carturan L, Cazorzi F and Fontana G D 2012 *Journal of Glaciology* **58** 467–486

[15] Shepherd A, Ivins E R, Geruo A, Barletta V R, Bentley M J, Bettadpur S, Briggs K H, Bromwich D H, Forsberg R, Galin N *et al.* 2012 *Science* **338** 1183–1189

[16] Diolaiuti G, Senese A, Mihalcea C, Verza G, Mosconi B and Smiraglia C 2011 AWS measurements on glaciers in the Italian Alps *Workshop on the use of automatic measuring systems on glaciers.* pp 31–35

[17] Steele-Dunne S C, Rutten M M, Krzeminska D M, Hausner M, Tyler S W, Selker J, Bogaard T A and van de Giesen N C 2010 *Water Resources Research* **46** URL `http://dx.doi.org/10.1029/2009WR008272`

[18] Hart J K and Martinez K 2006 *Earth-Science Reviews* **78** 177–191

[19] Mohamed N, Jawhar I, Al-Jaroodi J and Zhang L 2010 Monitoring underwater pipelines using sensor networks *12th IEEE Internat. Conf. on High Performance Computing and Communications (HPCC)* pp 346–353

[20] RBR Xr thermistor chains URL `http://www.rbr-global.com/`

[21] Abbate S, Avvenuti M, Cesarini D and Vecchio A 2012 Estimation of energy consumption for TinyOS 2.x-based applications *Procedia CS* vol 10 pp 1166–1171

[22] Jelicic V, Cesarini D and Bilas V 2013 Enhancing performance of wireless sensor networks in glacial environments using wake-up receivers *IOP Sensors & Their Applications XVII (accepted for publication)* (Dubrovnik, Croatia)

[23] Beutel J, Gruber S, Gubler S, Hasler A, Keller M, Lim R, Thiele L, Tschudin C and Ycel M 2009 The PermaSense remote monitoring infrastructure

[24] Martinez K, Basford P J, Jager D D and Hart J K 2012 A wireless sensor network system deployment for detecting stick slip motion in glaciers *IET Internat. conf. on Wireless Sensor Systems 2012* URL `http://eprints.soton.ac.uk/339176/`