FMGM 2018
INTERNATIONAL SYMPOSIUM ON FIELD MEASUREMENTS IN GEOMECHANICS
Rio de Janeiro - PUC-Rio, 16-20, July | 2018

Deployment Of Large-area Radio-enabled Geotechnical Monitoring Systems In Northern Mines

Vincent Le Borgne
GKM Consultants, Sainte-Julie, Canada, vleborgne@gkmconsultants.com

Alexandre Cosentino
GKM Consultants, Sainte-Julie, Canada

Jean-Marie Bréhé
GKM Consultants, Sainte-Julie, Canada

Stéphane-Éric Thivierge
GKM Consultants, Sainte-Julie, Canada

SUMMARY: Large-scale geotechnical monitoring programs of dikes and tailings dams in arctic and subarctic mines pose an array of unique challenges. Long distances, cold weather and rugged terrain make manual collection of instrument data difficult to carry out in the winter, lowering the return on investment of instrumentation. Running data cables between measurement points to minimize the number of collection points is not always cost-effective given the distances and difficult terrain. To address these concerns, wireless communications systems were introduced in arctic and subarctic mines. These systems deployed by GKM Consultants were used to connect geotechnical instruments such as piezometers and thermistor strings to follow immediate and long term behaviour of dams and dikes. Deployment of radio-enabled geotechnical monitoring systems at two large mines located in northern Canada. In both cases, data acquisition reliability, cost-effectiveness and consistent communications were required. The effectiveness of two solutions, one based on Campbell Scientific's data transmitters and one on Loadsensing transmitters, are compared. We show that there are trade-offs between the two technologies regarding upfront cost, flexibility and power requirements. In all cases, gains in reliability and amount of data for the cost can be made with respect to manual collection of data. We also compare with the more common approach of using standalone acquisition systems whose batteries are changed and data collected every few months. Furthermore, we discuss challenges associated with the installation of instruments under intense cold. Precautions have to be taken regarding handling and exposition to low temperature to ensure proper deployment.

KEYWORDS: tailings, arctic mines, radio communications, geotechnical monitoring

1 INTRODUCTION

Construction and management of tailings and dikes in arctic mines are still to this day a challenge

(Journaux Assoc. 2012). Because seepage can be a threat to the environment, to operations and to the safety of workers and because it can be a sign of dam failure, geotechnical monitoring systems in open-pit mines are often designed to provide critical information to the mine operators regarding water pressure and movement. Typically, seepage is caused by interaction between groundwater, mining activities, ground temperatures and the local geological makeup. Additionally, many open pit mines, such as one that will be discussed in this paper, operate under groundwater level and sometimes in lakebeds, presenting further difficulties for water containment.

Several instrument types can be used to follow the flow of underground water. The most direct and commonly instrument used is the piezometer. It gives direct measurement of pore water pressure. Other methods are occasionally used, such as thermistor strings and time domain reflectometry (TDR). In this context, underground temperature measurements play a dual role: temperature is affected by heat transfer between seeping water and underground ice, and increased temperature can affect the mechanical properties of permafrost (Lindholm 2014). Other instruments are also installed to follow secondary properties of the tailings and surrounding soil, such as dissolved oxygen probes and water concentration probes.

Historically, measurements with the instruments listed above have been, and sometimes still are, conducted manually. However, modern operations are often closely managed and thus require more consistent and real-time updates of the measurements. In large-area northern mines, the harsh weather, rough terrain and long distances make manual data collection unreliable and infrequent in the winter. Long term costs are also incurred by having staff regularly survey all instruments along kilometers-long dikes. Running instruments cables across harsh terrain, dikes and permafrost is cost-prohibitive and sometimes downright impossible.

These issues can be addressed with the use of a fully automated data acquisition system that relays its data to a central location through radio links. We have developed, installed and maintained complex networks of geotechnical instruments at several northern mines, including the Meadowbank mine in Nunavut, Canada and the Lake Bloom mine in Québec, Canada.

In the former, a thorough monitoring plan was set up with many instruments scattered over a large area but often concentrated in tight clusters. This system has a real-time component that requires an innovative approach combining manual readings, data loggers, and cabled or radio communications. Radio communications in this system were built around Campbell Scientific (CS) products (Le Borgne et al. 2017). In the latter, a network of instruments that was manually surveyed was upgraded to a modern system, based on the Loadsensing (LS) technology (Abanco et al. 2017). A custom-made visualization platform provides powerful tools to manage and understand the vast amount of data generated. In this case study, both technological approaches will be compared with regard to flexibility, power requirements, distances covered and advanced functionality.

2 OVERVIEW OF THE MINE SITES

2.1 MEADOWBANK MINE

The Meadowbank mine is an open-open pit gold mine located in located in the Baker Lake area in Nunavut, Canada. A series of three pits have been mined all within a 7 km distance of the processing plant. Water-retention dikes were built with a unique method to access the deposits located underneath Vault Lake and other nearby bodies of water. Extraction of a gold deposit under the water level require a larger amount of instrumentation than a regular open-pit mine because any type of failure could compromise both worker safety and operations. Extraction is done with a combination of drilling, blasting and truck and shovel methods. Inert rock waste is used for building purposes while acidifying waste is stored in ponds. To prevent acidifying, waste is isolated in permafrost where the low temperature and low water circulation prevent formation of acidic by-products.

The picture shown in figure provides an overhead view of the site. To the right (south), the main pit can be seen with the dikes holding back lake waters. In the middle, a large tailings pond is easily identified. The map also shows where the camp is located, as well as the two main radio towers. Figure 1 (c) shows typical terrain in arctic mines : jagged terrain, snow and -40 °C weather.

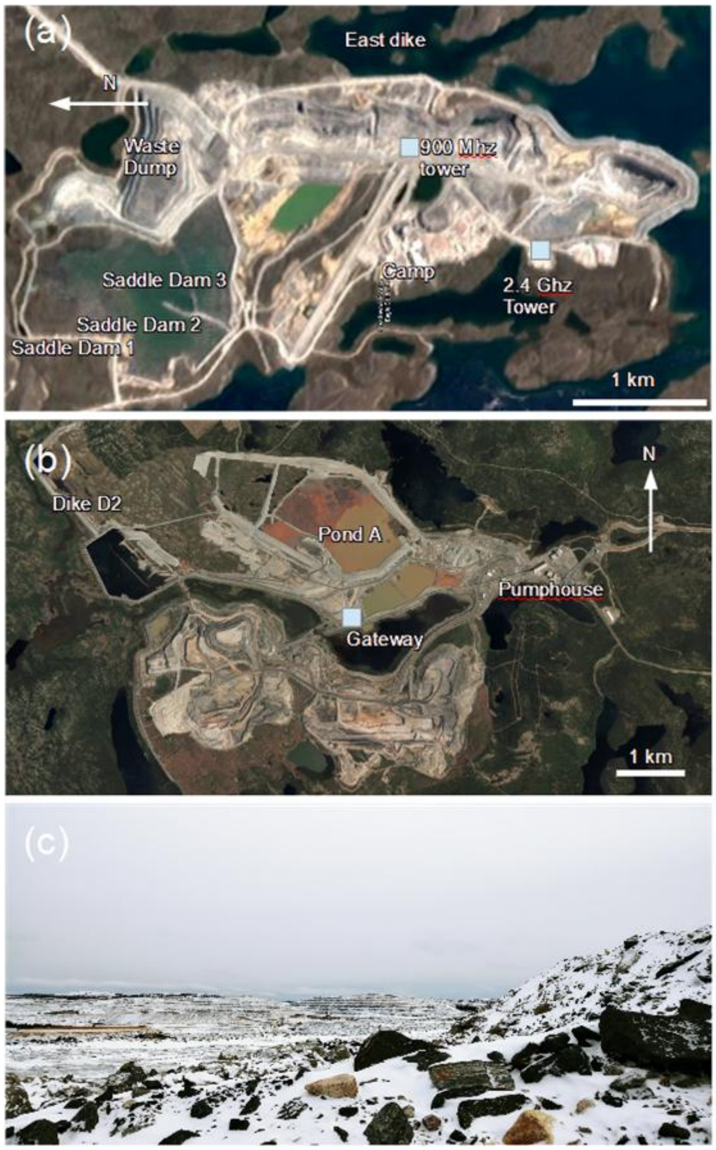

Figure 1 (a) Overhead view of the Meadowbank mine (b) Overhead view of the Lake Bloom mine. Relevant dams and ponds are identified on both figures. Locations of the radio base stations and gateways are identified with light blue squares. (c) Typical terrain found in arctic mines.

2.2 LAKE BLOOM MINE

The Lake Bloom mine is an iron ore mine is planned to produce 7.5 million tons of iron concentrate per year over a 21 year anticipated life-time. On-site concentration circuits raise the 30 % Fe raw ore to 60 % concentration. This concentrate is shipped out directly by rail with residue stored on-site. The mine owner conducted an upgrade to automatize the process and transmit data directly to the control center. Unlike the Meadowbank mine, extraction is conducted atop a hill thus the requirements to keep water out are less stringent. The mine's dewatering system has been put in place to contain water within the tailings ponds. The mine had been shut down in 2015 and prior to its reopening in 2017, all instruments that follow pore water pressure on and around the dikes were surveyed manually.

3 INSTRUMENTATION

3.1 MEADOWBANK MINE

The three main types of instruments were installed: thermistor strings, piezometers, and time domain reflectometers (TDR) to follow soil movements. Instruments can be sorted by the importance of obtaining fast measurements from them. *Background* instruments are usually read manually whenever possible. *Regular* instruments are often read by hand on a daily or weekly basis or have a standalone dedicated data logger. Finally, *critical* instruments are connected to a radio-enabled data logging system. These instruments are typically in the vicinity of dikes where failure could have major consequences on operations.

Table 1. Number of instruments installed in the scope of this project at the Meadowbank mine (as of 2017)

Instrument type	Number	Total cable length (approximatively, m)
Piezometers	>146	>5000
Thermistor strings	>20	>100
TDR	6	-

Thermistor strings, while a critical component of many arctic projects, can be difficult to install in temperatures below -20°C. Even cold-rated thermistor strings (or any electrical cable) can be manipulated slowly but any sharp movement or impact could break the sheath (Keane et al 2013).

Piezometers are installed in grouted wells, with several depths at each borehole, giving the opportunity of having a 2D mapping of water pressures away from dikes. Special care has to be taken regarding cable management and protection from freezing during installation. Indeed, piezometers should not be left to freeze while saturated with water without specific precautions.

The continuously changing configuration of the dikes requires creative solutions for extending cables and maintaining function of both thermistors and piezometers over many iterations. Piezometers and data loggers that were installed early in the project were in the way of new embankments and dikes, requiring the cables to be protected and spliced.

3.2 LAKE BLOOM MINE

The instruments required for the water management system of this mine were chosen and installed prior to the decision of implementing a radio-based system. However, as a cost-saving measure and to improve reliability and safety, the mine operator requested that the instruments be automated and all data be made available online automatically. Piezometers were entirely automated over an area of several square kilometers. In this project, all instruments can be classified as *critical* instruments.

4 DATA LOGGING AND NETWORKS

Figure 2 (a) shows an overview of the work site at the Meadowbank mine, with the main data logger locations identified as well as the locations of the two base towers (900 MHz and 2.4 GHz).

For this installation, data loggers are all built from CS technology. A typical data logger system is built from a central data acquisition system, one or two radio modules, a power system and data acquisition peripherals.

The network can be broken down according to the measurement requirements for each instrument category as described above. *Background* instruments are usually read and analyzed manually. They do not require any type of real-time component and their survey is infrequent. Regular instruments often have a small dedicated data logger whose data is regularly collected by a field technician. When the technician returns to base, the data is added automatically to a database for online visualization and analysis. While most regular instruments measurements are collected every week, some are in difficult to reach area that are only accessible in the winter and are left over the summer until water freezes again.

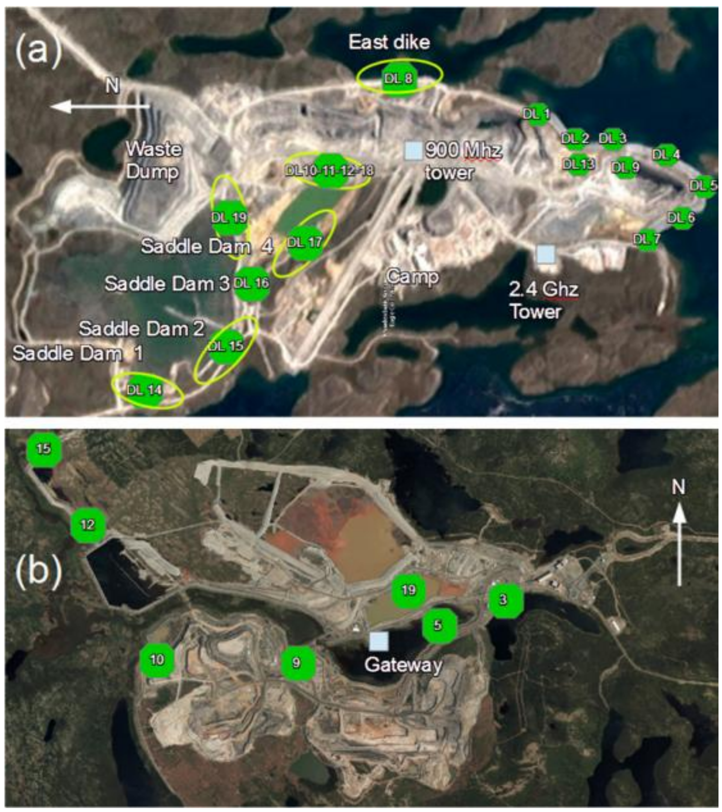

Figure 2 : (a) Main data logger locations at the Meadowbank mine (c) Overview of selected data logger locations at the Lake Bloom mine.

Critical instruments, who require real-time monitoring, are cabled back to local data loggers. They comprise a single data logger with one or several multiplexers that allow it to read a large number of instruments. The yellow ellipses in Figure 4 (a) show the approximate area from which instruments are directly cabled to each data logger. The data loggers are connected back to the base station through a radio link to transmit readings that are automatically integrated into the database for visualization.

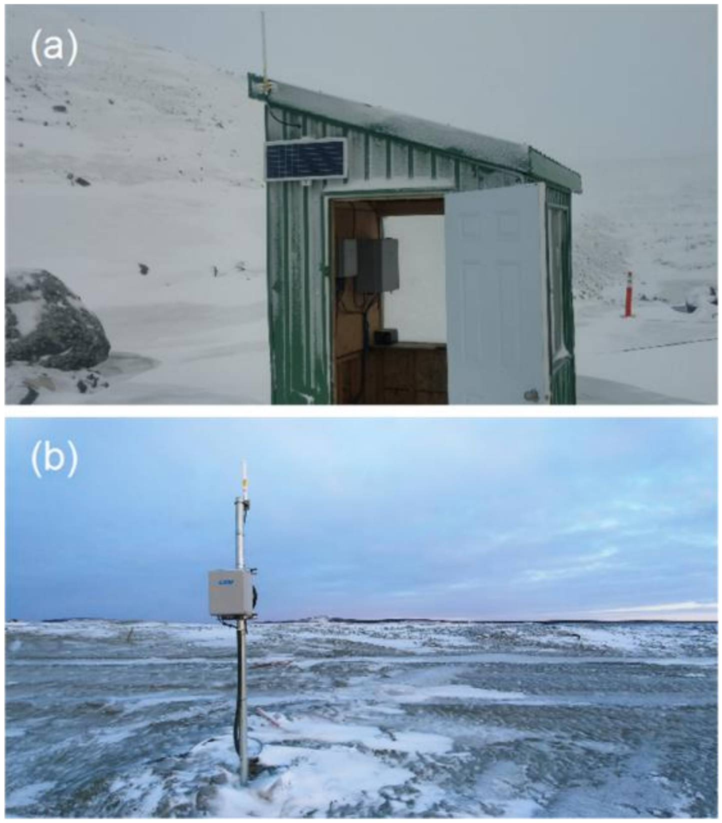

Figure 3 (a) Typical installation at the Meadowbank mine (b) Typical installation at the Lake Bloom mine

Figure 3 shows typical installations at both sites : (a) at the Meadowbank mine and (b) at the Lake Bloom mine. A large number of instruments and instrument types can be connected to a single data logger in the first case, justufying the expense and trouble of building a larger shack: it comfortably houses all the required accessories and peripherals and shelters the workers during installation and maintenance. Commisionning is greatly facilitated when workers are sheltered from the wind and intense cold of arctic winters. For the Lake Bloom mine, the small number of instruments at each location makes installing a small box and antenna sufficient.

The network topologies can be seen on the schematic of Figure 4 : instruments (yellow circles) are connected to multiplexers (pink triangles). The multiplexers can be cabled directly to the data loggers or connected through a short range radio link, typically less than 500 m. The data loggers are then connected directly to the base stations according to their chosen frequency through radio links and the base stations are connected to the mine's servers through regular optical fiber connections. The basic standalone configuration for *regular* instruments is also shown in the bottom left.

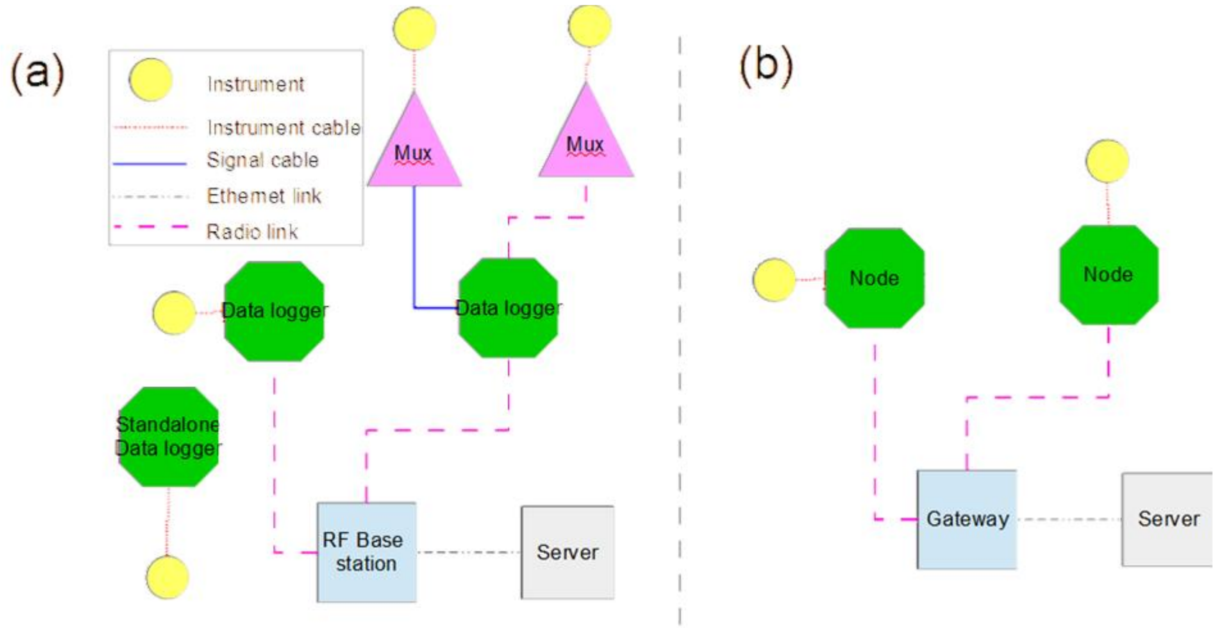

Figure 4 (a) Schematics of the of the network topology of the system deployed at the Meadowbank mine (b) Schematics of the network topology at the Lake Bloom mine

The RF base station is connected to a server that makes all data available to the relevant parties, as will be discussed in section 6. Each data logger acts as an aggregator for several radio-connected multiplexers while the two base stations act as the main integrator for all the data loggers. This deployment can be seen as an extended star network. In network topology, a star network is a network in which each spoke (data logger) is connected to a central hub (base station). An extended star network is a star network in which some of the spokes contain repeaters to extend the range of the star network (Sosinsky 2009). Star networks provide a good compromise between complexity and reliability. They are somewhat more complex and more reliable than daisy chain or bus network topologies but are easier to implement and deploy than the more complicated mesh networks.

Figure 2 (b) shows an overview of the worksite at the Lake Bloom mine with the main data logger locations identified. Up to 4 piezometers are connected to each single node. The nodes are then connected through a radio link directly to the gateway. In this system, all instruments are automated and is thus not a hybrid system that combines manual readings, standalone data loggers and radio-connected data loggers.

LS networks work under a pure star topology built on a gateway-node structure. The gateway acts as an aggregator for all nodes. The nodes themselves are a small datalogger that can transmit their data back to the gateway.

5 DISCUSSION

There are three areas to focus on when selecting and designing a radio-enabled data acquisition system. The system's flexibility and how it ties in to cost of deployment, radio power and range, and power requirements.

5.1 FLEXIBILITY

Vibrating wire is an instrumentation technology common in geotechnical monitoring due to its ruggedness, durability and low power requirements (Dunnicliff 1993) but is less known so in other fields. Therefore, the options for compatible data loggers are limited to a few manufacturers. CS-based systems are entirely programmable and they provide the opportunity to connect many different instrument types with various requirements in a single data acquisition system. Furthermore, they are expansible with the addition of multiplexers. Therefore, a large number of instruments in a small area is a good situation for automating acquisition with CS-based technology. For instance, at the Meadowbank mine, some locations along one of the main dams have up to tens of thermistors and up to 16 piezometers, fully taking advantage of the options offered by multiplexers.

Conversely, LS-based data loggers are less flexible : each node model can either connect vibrating wire, analog signal (e.g. 0-10 V) or digital data (e.g. RS-485). Each model has a comparatively small number of ports and no possibility for expansion. They are however individually several times cheaper than most CS-based systems and, unlike CS-based systems, they are best suited for smaller number of instruments in a given location. As discussed earlier, a typical location at the Lake Bloom mine has 2 piezometers in a single borehole. This small number of instruments at any given location precludes the need for a complex systems with multiplexers.

LS-based systems do not have programming capabilities beyond configuring each instrument's acquisition mode and frequency. Not only can CS-based systems be programmed, they can be reprogrammed remotely through the radio links. The greater flexibility of CS-based systems allow for on-the-fly adjustment of measurement settings and for remote diagnosis if any data is missing or faulty.

5.2 RADIO COMMUNICATIONS

Radio power and range are major considerations in the deployment of a radio-enabled system. A more powerful radio will usually communicate over longer distances than a less powerful radio, at the cost of more electrical power consumption. Furthermore, lower frequency radios have lower path loss than higher frequency radios (Johnson 1984), provided the Fresnel zone is kept clear of obstacles (Ahmadi 2016). The Fresnel zones are ellipsoid volumes between two antennas that seek to represent the combination of the emitting antenna's radiation pattern, the receiver antenna's reception pattern and the dispersion of radio waves caused by air, suspended water, rain etc. It is generally accepted that 40 % of the first Fresnel zone, given by equation (1) should be kept free of obstacles to maximize transmission range.

$$F_n = \sqrt{\frac{n\lambda d_1 d_2}{d_1+d_2}} \tag{1}$$

Where F_n is the nth Fresnel zone radius, d_1 is the distance from one end, d_2 is the distance from the antenna and λ is the wavelength (see diagram underneath).

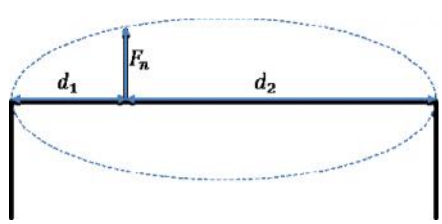

Figure 5 Fresnel zones

It is often more convenient to compute the maximum value of F_1's radius and use that as a reference, as given by equation (2)

$$F_1 = \frac{1}{2}\sqrt{\frac{cD}{f}} \quad (2)$$

where c is the speed of light, D is the distance between the two antennas and f the radio frequency. For instance, for antennas located 2 km apart for 900 MHz frequency radio waves, the radius of F_1 is approximately equal to 12.9 m. It follows that in this specific application, antennas should be 5.1 m (i.e. 40 % of 12.9 m) off the ground for an acceptable transmission quality. As seen in the pictures of Figure 3, antennas were rarely installed more than 3 m off the ground. The limitations imposed by the Fresnel zone were circumvented by several different methods. First, directional antennas were frequently used at the Meadowbank mine. Though they are still limited by the Fresnel zone, they boost transmission power in the desired direction. For evident reasons, only the data logger antennas are directional ; the base station antennas should be omni-directional. A second method is to keep distances as small as possible. The Fresnel zone diameter increases as a function of $D^{1/2}$ so closer antennas do not need to be as high. Received power is also inversely correlated with distance. Though this is highly-site dependant choosing strategic locations and multiplying the number of base stations can be critical. Finally, in both cases, the base station or gateway antenna is installed significantly higher. For instance, the gateway antenna at the Lake Bloom mine was installed atop a silo as shown in the picture of Figure 6. Despite these precautions, the radio link of a few nodes are difficult to maintain. At a glance, it appears obvious that nodes as far as node 15 (>4 km) would have more issues transmitting data than node 5 located less than 1 km away. The following table summarizes this information for selected nodes. Node 5 provides very strong and consistent signal. Node 15, over 4 km away, has acceptable signal strength (-120 dBm being the cutoff) and very few, if any, messages dropped. However, node 10, located approximately 2 km away from the gateway has very poor signal and a very high fraction of messages dropped. This can be explained by the topology of the site. The silo where the antenna is located was chosen in part due to its central location, but it has the drawback of being at a lower elevation than other parts of the mine. For node 10, both the node antenna and the gateway antenna are lower than the summit of the pile located between them, blocking line of sight and the Fresnel Zone. To address this issue, the acquisition frequency of node 10 is multiplied by 6, ensuring that enough data reaches the gateway in all conditions.

Figure 6 Gateway Antenna installation

Table 2 Comparison of signal quality for selected nodes at the Lake Bloom mine

Node	Signal strength	% message dropped
10	-120 dBm	30%
15	-118 dBm	<1 %
5	-78 dBm	<1 %

At the Meadowbank mine, both frequency bands were used : 900 MHz and 2.4 GHz whereas the LS systems only work in the 900 MHz range. The basic setup of CS radios with omnidirectional antennas provide a range of 1600 meters in normal conditions, but this can be significantly improved by using directional antennas and by increasing the antenna heights. However, when longer distances need to be covered, more modern protocols, such as the lpwan protocol used by Lora radios (the radio technology behind the LS radio communications) provide a more cost-effective solution.

5.3 POWER REQUIREMENTS

Power requirements are also a major component to take into account when selecting a technology in the design process. The harsh weather and long winters of arctic mines put stress on solar and battery-powered systems. For instance, the Labrador city airport (located close to the Lake Bloom mine) has an average of 2 hours of bright sunlight during day during the winter. At the Meadowbank mine, days can be as short as 4 hours in the winter. Though days are longer in the Labrador city region, it tends to be cloudier, thus providing less direct sunlight to solar panels. Due to the low sunshine and intense cold, battery packs should be designed to last at least several months, and to be recharged over summer by a solar panel. A typical CS-based system requires 1.5 mA at 12 V in standby and up to 220 mA when performing a measurement. With 4 measurements per day, this is an energy requirement of 50 Wh per month. It should be noted that the cold weather (< -20 °C) cuts in half the available charge of batteries (Hutchinson 2004) which further increases battery requirements when compared to installations in warmer climates. However, the low temperature greatly decreases the self-discharge rage of lead-acid batteries, allowing for easier long-term installation than in applications in warm climates. With these parameters, a 26 Ah lead-acid battery is required to last through the winter months with a 30 W solar panel. This adds additional costs to ship and install the battery and solar panels system.

In contrast, an LS node can be powered for over 10 years on its internal lithium batteries without a solar panel, lowering long term maintenance expenses. In locations where logger maintenance is difficult or cost-prohibitive, long battery life is an effective method of reducing lifetime costs.

In LS nodes, the internal radio is almost always turned off and significant amounts of electrical energy is saved. Indeed, LS-based systems can only initiate communications from the node to the gateway and turn on the radio module only at that time.

6 DATA VISUALIZATION

A common pitfall of ambitious data collection plans is that there is so much that some of it gets ignored. While data visualization is not part of the monitoring hardware discussed so far, it is nonetheless a crucial components to optimize the return on investment of the monitoring system. Relying on manually plotting all data would somewhat defeat the purpose of constructing automated systems in the first place. For both projects, online visualisations were built to provide tools required for taking the right decisions. Visual indicators on plans show the values of specific instruments on a map with a color status, giving workers a quick overview of their worksite. Properly designed time graphs are another powerful tool to analyse data over long periods of time.

Finally, section visualizations are used to understand soil temperature data.

7 CONCLUSION

Water management in open-pit arctic mines requires solution to face challenges inherent to their location. Manual surveying of instruments have inherent problems such as a low turnaround, having to send people on-site regularly for this specific task, and the difficulty of data collection during winter months. Some of these issues can be alleviated with regular standalone data loggers, but running instruments cables in this harsh environment is cost prohibitive. We have shown how using radio-enabled data loggers are a good avenue to solve these issues in two remote mines in Canada. Two technologies and approaches were compared : a hybrid topology based on CS radios and a star topology based on LS systems. The CS based systems offer the greatest flexibility as far as what instruments can be read and is easier to scale up. On the other hand, the LS based system offer good value for the price when there is a smaller number of instruments distributed over a very large area. Power requirements were also discussed, and though both systems draw very little power, LS-based radios edge out CS-based systems for autonomous systems with battery life over a decade.

REFERENCES

Abancó, C., Pérez, J. and Gómez, D. and Mwagalany, H. (2017). Wireless monitoring of pore-pressure and dewatering activities in the Aitik Boliden Mine in northern Sweden, *Geo Ottawa 2017 conference*,

Ahmadi, J. (2016). The effects of Fresnel Zone in communication theory based on radio waves Bulletin de la Société Royale des Sciences de Liège, Vol. 85, p. 729 – 734

Dunnicliff, J. (1993). Geotechnical Instrumentation for Monitoring Field Performance, *John Wiley and Sons*, New York, NY, USA. 577 p.

Hutchinson, R. (2004). Temperature effects on sealed lead-acid batteries and charging techniques to prolong cycle life. *Sandia report* Sand2004-3149

Johnson, Richard (1984). Antenna Engineering Handbook (2nd ed.).: *McGraw-Hill*, New York, NY Inc.

Journeaux Assoc. (2012). Engineering challenges for Tailings Management Facilities and Associated infrastucture with regard to Climate Change in Nunavut. *Goverment of Nunavut*.

Keane, B., Schwarz, G. and Thernherr, P. (2013) Electrical equipment in cold weather applications, IEEE October 2013, WP083007EN

Le Borgne, V. and Bréhé, J.-M. (2017). Deployment of a large-area geotechnical monitoring system in an arctic mine, *CSCE 2017 annual conference proceedings*, CSCE, to be published

Lindholm, M. (2014). Advanced Topics in Mine Water. CMS Project.

Sosinsky, Barrie A. (2009). Networking Bible. *Wiley Publishing*, Indianapolis, 916 p.