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A self-sufficient mobile broadband seismological recording system for year-round operation in Antarctica

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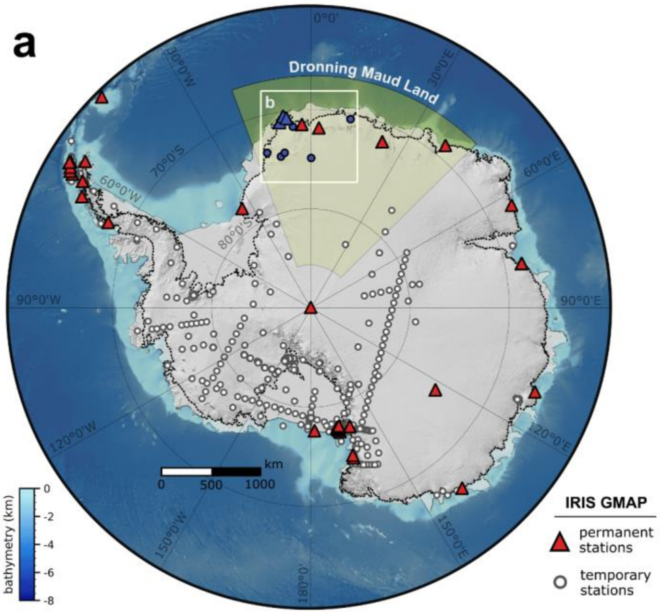
Abstract. Passive seismic measurements allow the study of the deeper earth beneath the thick Antarctic ice-sheet cover. Due to logistical and weather constraints, only a fraction of the area of the Antarctic ice sheet can be surveyed with long-term or temporary sensors. A fundamental limitation is the power supply and operation of the instruments during the polar winter. In addition, there is only a limited time window during the field seasons to deploy the stations over the year. Here we present a rapidly and simple deployable self-sufficient mobile seismic station concept. The station consists of different energy supply modules aligned according to the survey needs, measuring duration and survey aim. Parts of the concept are integrated into an already existing pool of mobile stations as well as in the seismological network of the geophysical observatory at Neumayer III Station. Other concepts and features are still under development. The overall goal is to use these temporary mobile arrays in regions where little is known about local and regional tectonic earthquake activity.

1 Introduction

A kilometer-thick ice sheet covers more than 98 % of Antarctica's surface. Therefore, the historical evolution, geological structure and tectonic activity underneath the Antarctic ice sheet are, for large parts, not well known. Continuous, year-round seismic recordings provide a remedy to overcome the direct inaccessibility of the Antarctic continent. The recordings of local, regional and teleseismic earthquakes have been used in various studies. Thus, our present knowledge of the structure of the earth's mantle, lithosphere, and crustal structure underneath the Antarctic ice cover is based on these records. (e.g., Knopoff and Vane, 1978; Nanesi and Morelli, 2001; Ritzwoller et al. 2001; Lawrence et al., 2006; Janik et al., 2014; An et al., 2015 and Lough et al., 2018). However, there is little on the Antarctic plate itself due to a low level of tectonic activity (Sykes 1978). Moreover, the low seismic activity is paired with a sparse distribution of seismic instrumentation in Antarctica (particularly in East Antarctica; Figure 1a) and is thus, difficult to verify. Only a few long-term seismic observatories exist. Most of them are constrained to the coastal region and in direct vicinity to research infrastructure (Figure 1).

Many seismic experiments, both using active and passive sources, require numerous seismic stations. The deployments often have to be done in remote and difficult to access areas with very limited power supply and servicing infrastructure. In particular, a long-term AC power supply is not available in most cases. For areas with moderate climatic conditions or when batteries can easily be changed or replaced in regular intervals, this is not a problem. Furthermore, state-of-the-art solar panels provide sufficient electrical power for efficiently charging batteries, enabling instrument operation almost throughout the entire year. In polar regions, however, significant challenges arise in terms of the geographical setting, remoteness and extreme weather conditions, which require a sophisticated power supply design. First, long periods of the dark polar winter with no sunlight available make it necessary to install an additional power supply. If sufficient backup power cannot be realized, it has to be taken into account that data acquisition will stop at some point during polar winter. Second, due to the low temperatures and high discharge of the batteries, it may occur that data acquisition cannot resume when sufficient sunlight is available after the winter break. Additionally, almost all types of batteries show reduced performance at low temperatures and show a substantially reduced adequate capacity. Therefore, energy-efficient and for low temperatures adapted renewable systems are required for a sustainable operation in polar environments (Tin et al., 2010).

In this article, we describe the concept of a mobile and self-sufficient seismological broadband station designed for the extreme demands of the Antarctic ice sheet. A focus lies on (i) the compact modular design and conception of an energy supply to operate under extreme temperatures between -20 to -40° C and (ii) to get the system through the sunless polar winter. This layout makes the system suitable for long-term operations over several years without regular maintenance and for shorter surveys. Some of the concepts presented here are already in use at numerous seismological stations in western Dronning Maud Land (East Antarctica) operated by the geophysical observatory of Neumayer III Station (Figure 1). Other concepts presented here represent extensions for current and future projects.



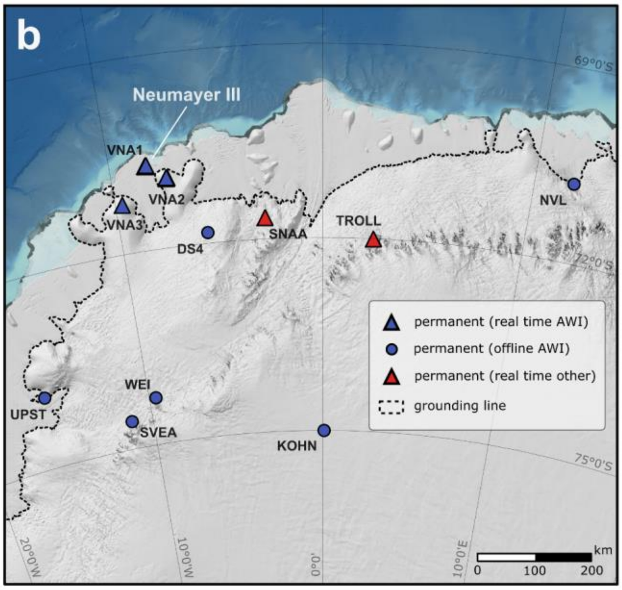


Figure 1: (**a**) Overview of permanent and temporary seismic station distribution in Antarctica (station locations obtained from IRIS GMAP, 2022). Panel (b) shows the distribution of real-time and offline permanent stations operated by AWI and others in western Dronning Maud Land. there are potentially more stations in Antarctica whose locations are either not published or where we don't have access to the coordinates.

2 AWI's regional seismographic network

The Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI), has been operating a local seismographic network for more than two decades in the vicinity of its permanent base Neumayer III Station (Figure 1b). One seismometer is located inside the geophysical observatory close to the station (VNA1), two other seismic stations (VNA2 and VNA3;) are deployed at ice rises at approximately 45 and 85 km distance off Neumayer III Station, all three are permanent stations (Eckstaller et al., 2007). The data quality of VNA2 and VNA3 is substantially better than VNA1 data because the former are stationed on ice lying over solid rock. Data is continuously transmitted to the base near real-time via high-speed data radio. This local network is supplemented by six offline remote semi-permanent seismic stations (Figure 1b; Novolazevskaya NVL, Kohnen Station KOHN, Svea Station SVEA, Forstefjell Nunatak DS4, Weigel Nunatak WEI and Utpostane UPST, respectively). So far several single mobile seismic stations or arrays have been deployed in the vicinity of Neumayer III Station for testing purposes and for geophysical surveys.

The motivation for developing and optimizing mobile stations is to use them for temporary regional array studies in Dronning Maud Land. The ambition is to use a moving array of seismic stations acquiring data for one to two years and relocate the instruments after that to a new site. Our scientific interests will focus on the analysis of the regional tectonic seismicity associated with a potential neotectonic activity and the analysis of receiver functions to determine the Moho depths and eventually resolve major structural features in the upper mantle in this region.

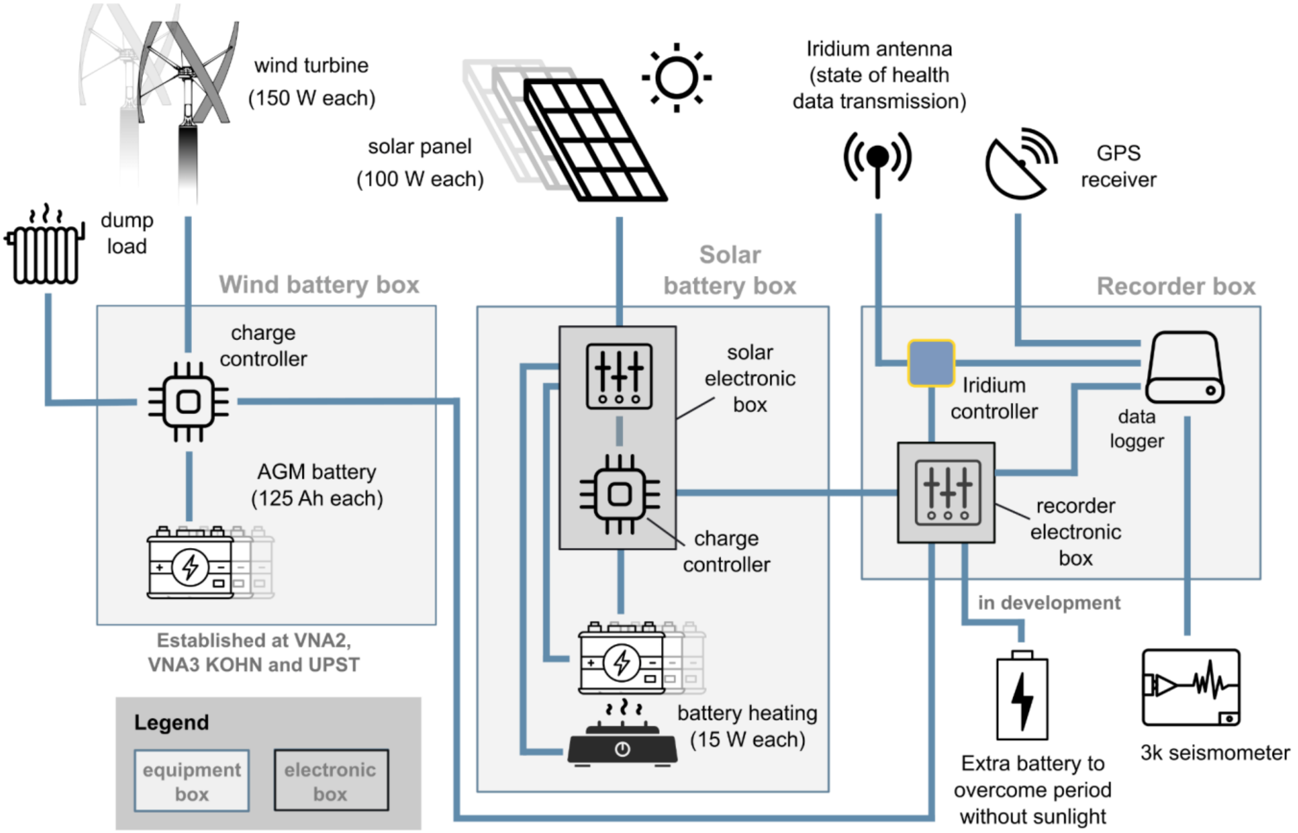


Figure 2: Schematic diagram of the instrument layout and power supply concept.

3 Concept and instrument design

Our requirements for the mobile seismometer stations must allow a rapid installation and be as modular and compact as possible to enable economic transport and fast deployment and recovery. A single mobile station comprises one recorder box and one to two battery boxes (Figure 2). We use “Eurocase" boxes for casing and transport because they are waterproof and mechanically stable (Figure 3).

Table 1: Specifications of instruments deployed with AWI's seismic stations.

Instrument type	Instrument specifications	Comment
Seismometer	Guralp CMG-3ESP	
	Kinemetrics Metrozet MBB2	
	Streckeisen STS-2	
	Lennartz LE-3D/20s	
Seismic recorder	Reftek RT-130	Favorised for temporary/mobile stations
	Quanterra: Q330 + baler or Q330S+	Favorised for permanent stations (Figure 3d)
Iridium controller	XI-202 (XEOS)	Module for Quanterra (Figure 3d)
	SeiDL (SeismicDataLink by SchwaRTech)	Custom-made module for RT-130
GPS receiver	GPS 16xHVS (Reftek)	
Solar charge controller	Blue Sky Solar Boost 3000i	Not used anymore
	Morning Star SunSaver SS-MPPT-15L	Preferred choice (Figure 4a)
Solar cells	Solara S405M36 Ultra 100W	Mounted on a standard rack (Figure 3a-c, h)
	Solara S300M36 Ultra 75W	Mounted vertically on a mast (Figure 3f)
Heating/temperature controller	Minco CT325 Miniature DC	
Wind generator	Twister KD-VK-10	Rotor blades are shortened to reduce rotation in strong wind regimes
Batteries (lead-acid)	AGM GPL31XT (12V, 125Ah)	
Boxes	Eurocase (EU080060-5010, EU080060-4010)	

We can equip our stations with two data logger types: 3-channels Reftek RT-130 and 6-channels Quanterra Q330S+ (or Quanterra Q330 + baler) recorders (Table 1). Both logger types can be deployed at permanent or temporary mobile seismic stations. We commonly use Guralp CMG-3ESP or Kinemetrics Metrozet MBB2 3-component broadband seismometers with a lower corner period of 120 sec and in some cases also Lennartz LE-3D/20s seismometers. The only exception represents UPST station, where we have deployed a Streckeisen STS-2 and a small short period tripartite array. The power consumption of the recorders is approximately 1 Watt and depends on the number of active channels, sample rate and desired GPS-clock operation. The seismometers require approximately the same amount of power, with a slightly lower consumption for the MBB-2 seismometers. Hence, recorder and seismometer require approximately 2–2.5 Watt continuous electrical power.

The solar-powered energy supply system consists of 100 W *Solara S405M36 Ultra* solar cells and a *Morning Star SunSaver SS-MPPT-15L* charge controller. Every seismic station is equipped with a state of health (SOH) transmitter that sends the station's operation status in regular intervals via Iridium satellite radio to AWI. The Q330 recorders operate with a XEOS XI-

202 controller. For the RT-130 we use a iridium controller developed by Arne Schwab (SchwaRTech, based near Bremen, Germany), which also uses the Iridium short burst data (SBD) technique. A complete list of the specifications of the instruments is provided in Table 1.

3.1 The battery box

3.1.1 Battery box configuration

Each battery box consists of two 125 Ah AGM (Absorbent Glass Mat) lead-acid batteries, a charging controller, and additional control electronics (Figure 3e). The advantage of AGM batteries is their good performance at low temperatures and that they are not categorized as dangerous goods for transport. The batteries are placed on an aluminum plate with two 10 or 20 Watt Silicone heating foils attached to its bottom side. The heating foils are underlaid with a thin heat resistant layer to prevent eventual melting of the insulation foam. The box is connected with one or multiple 100 Watt solar panels as input power. The solar panels can be mounted on standardized aluminum racks for deployment on snow and solid rock, which the AWI workshop had manufactured (Figure 3a). The racks are mechanically robust and can resist high wind speeds despite their lightweight if tied to anchors buried in the snow or stone bolts. We use *Alveo* polyolefine panels with a thickness of 5 and 10 cm as thermal insulators for the box interior. *Alveo* panels are available with two different densities. The denser and harder type is used for the bottom layer of the box. They can bear the heavy weight of the batteries without deformation. The material can easily be cut with a table saw into exactly fitting blocks. All electronic components, the charging controller, heating electrics and additional control electronics are installed inside a compact box (here referred to as the solar electronic box; Figure 2) that just fits besides both accus (Figure 3e and Figure 4a). All necessary electronic units are installed on DIN-rails, which allows compact and structured cabling.

Figure 3: Photographs of the station design from several deployments in western Dronning Maud Land (Antarctica). Panels (a-c) show the setup of the mobile stations on the ice surface. Panels (d) and (e) show the recorder and solar battery boxes from the inside. The permanent real-time station setup of VNA3 is shown in (f) for the ice surface and in (g) for the ice cave. Panel (h) shows the station layout of DS4, which is deployed on a rock base. Photo credits: (a,b, d-h) Jölund Asseng; (c) Steven Franke.

3.1.1 Self-discharge protection

The key feature in the solar electronic box in our battery boxes is a special control electronics (solar control; Figure 4a) to guarantee that battery charging will resume after the several week-long break during polar winter. Due to the inevitable self-discharge (if not connected to a power source), battery voltage can drop below a critical value of approximately 8–9 V. A voltage level below this threshold implies the risk that the charging controller cannot resume operation again. Without the power supply from batteries, charging controllers cannot operate with the solar panels' output. Additionally, even in standby mode when the LVD (low voltage disconnect) control disconnects the recorder and seismometer, the controller continuously drains current from the batteries which can cause additional voltage decrease. Therefore, our control electronics will disconnect the charge controller from the batteries when dropping below a critical value, which we set to 11.0 V. At the same time, the solar panels are directly connected to the batteries (Figure 2). This enables the batteries to be charged directly with the electric power of the first sunlight after the winter break. When the battery voltage rises above the threshold of 13.0 V, the charge controller is reconnected to the batteries. At the same time, the solar panels are reconnected to the charge controller. This principle enables a safe return to the normal operation mode. The solar control and its electronics were designed and manufactured by Erich Lippmann (LGM) and inserted in a small green enclosure inside the solar electronics box (Figure 4a).

3.1.3 Battery heating

All kinds of batteries show better performance and higher capacity if they are not exposed to too cold temperatures. Therefore we realized the option for battery heating if sufficient power is available. Battery heating will only be enabled if the battery voltage has exceeded an upper threshold value of 14.5 V and will be disabled if falling below the lower threshold value of 13.0 V. This is accomplished by using a voltage guard relay from MRS Electronic. The threshold voltages can be freely programmed and set to desired values. The module is designed for automotive applications and is thus very robust and reliable. For heating control, we use the Minco CT325 Miniature DC Temperature Controller, which can switch 6 amperes of heating current. This is sufficient for the heating foils under the bottom of the aluminum plate where the batteries are placed on. The sensor is a PT-100 element that is inserted into the drilling hole of an aluminum bar that is attached to the aluminum plate. We set the desired battery temperature to +20 degrees Celsius. This temperature may only be reached during summer, but it will then keep the batteries during this period relatively warm.

3.2 The recorder box

The recorder box is of the same type as the battery box, with slightly lower height and is thermally insulated in the same way (Figure 3d). Besides the data recorder and the SOH control modem, there is an recorder electronic box containing a backup battery management controller (BBat-controller) for battery box management (Figure 4b). Two solar rechargeable batteries and one backup battery can be connected. For two connected solar battery boxes the BBat-controller acts as two ideal Schottky diodes which are switched opposite to each other and power comes only from the battery box with the higher voltage.. In case both voltage levels are equal, the two battery boxes provide the same amount of current. If both solar batteries boxes are disconnected by their own internal LVD or both voltages drop below approx. 8.9 V, the power supply will be almost simultaneously switched to the backup batteries. It will switch back to solar batteries if one of the voltages rises back again above 10.7 V. This MOS-Fet based switching electronics was designed and manufactured by Erich Lippmann and utilizes the LTC4416 controller chip which is widely used for backup power supply systems. Furthermore, our circuit design prevents the flow of current from one battery box to the other. The current drain is max. 0.3 A, thus extremely low and does not play any significant role in the total power consumption considerations. With some additional minor modifications, even cascading backup batteries can be realized.

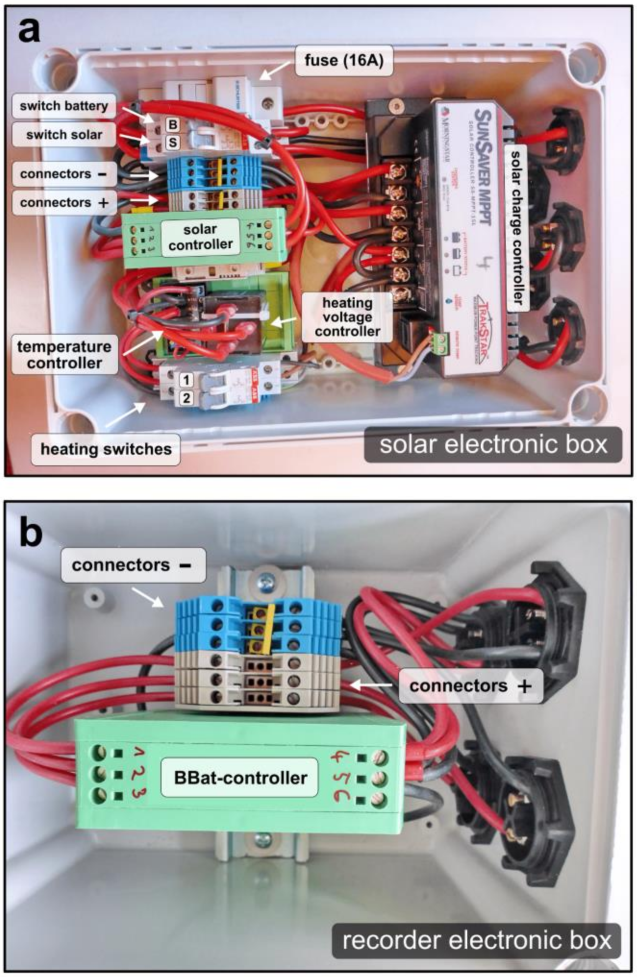


Figure 4: Electronic boxes indicated in Figure 2 and Figure 3d,e. Panel (a) shows the solar electronic box containing the solar charge controller, the solar controller and additional electronics. Panel (b) shows the recorder electronic box and contains the backup battery management controller (BBat controller).

All necessary connecting cables are connected with the connectors on the rear side of the recorder box. We decided to use the so-called *Reftek standard* for sensor input, which means that the pin configurations of the sensor connectors correspond to Reftek specifications. If using a Quanterra Q330, make sure that the cable from the rear sensor connectors has the appropriate connector for this recorder. This will allow the connection of both of our sensors without needing an extra connector or adapters for the specific recorder, which allows higher flexibility, reduces the deployment time and susceptibility for errors.

4 Discussion

4.1 Overcoming the polar winter gap

The absence of the sun in the polar winter creates a supply gap of input energy, which usually leads to a data acquisition gap if solar cells are the only energy source and the battery capacity is not high enough to provide energy for several weeks. We have developed a concept for our mobile stations to restart the data recording after the polar winter reliably. Beyond, there are different ways to bridge this period, and the advantages and disadvantages of these systems are discussed below.

4.1.1 Backup batteries

Assuming a deep discharge level of 30% for one 100 Ah battery can provide power for approximately 14 days at polar winter onset. Hence, using AGM 2 batteries will not ensure recording for more than 4 weeks without recharging. This implies an inevitably long recording break during polar winter unless high capacity backup batteries are additionally added. These could either be high capacity battery types, such as Lithium Thionyl Chloride (LTC) primary cells or rechargeable LiFePO4 accumulators. The reasons why we prefer a Li-based battery with a high energy density to the use of additional AGM batteries are the following. First, the number of AGM batteries needed to last through the polar winter would be very high and add a lot of transport weight. Theoretically, of course, these could be recharged over the summer. The problem, however, is that at the end of the polar night, there is little light and thus little current flow available to charge a huge total capacity. This can result in the entire system being very slow to get above the minimum voltage to start data acquisition, and thus extending the data gap period.

The power bridging concept during the polar winter gap with backup batteries has been so-far only applied in a proof-of-concept testing period with AGM batteries. The usage of Li-based batteries has not been implemented so far. The main reason for this is that the transport and storage of these batteries are restricted as they have to be treated as dangerous goods. Especially transport by aircraft may sometimes become almost impossible. The second reason is that they are still very expensive unless they are produced in higher quantities or if further developments make them more affordable. However, in principle all our mobile stations could also be equipped with Lithium based backup batteries. Since the lithium batteries cannot be recharged, this solution is suitable for temporary applications designed for 1–2 years.

4.1.2 Additional wind generator

Wind generators are an alternative energy source that is independent of the light conditions in the polar winter. This option has been implemented for other non-permanent seismic stations (e.g., Anandakrishnan et al., 2000; Contrafatto, et al., 2018) as well as for long-term seismic stations in our network (VNA2 and VNA3; Figure 1b and 3f). The principle in all versions is that when the batteries are fully charged and the remaining energy is dissipated through resistors (dump load; Figure 2 and

3g), the rotation is reduced simultaneously. In general, this option can be easily integrated into our mobile stations and could enable data recording over the entire year. However, this concept has several disadvantages, especially for the recording of seismological data. The vibrations caused by the wind generators are transmitted to the ground or snow and thus recorded by the seismometer. Depending on the coupling between the wind generator and the ground and the distance between the wind generator and the seismometer, the seismological data may be disturbed or even unusable. In addition, wind generators are mechanically very susceptible to these extreme conditions and the strong Antarctic winds. However, they are currently indispensable for a long-term energy supply over many years. In addition, the time required to set up a seismological station increases significantly with the installation of a wind generator. Wind turbines can, in principle, also be used for effective battery heating during the polar night. This requires, however, additional equipment (and thus cargo) and represents another source for system failure.

4.2 Choosing the appropriate solar charge controller

In the development stage of the mobile stations, we used two different solar charging controllers, a *Blue Sky Solar Boost 3000i* and a *Morning Star SunSaver SS-MPPT-15L*. Both controllers are maximum power point trackers (MPPT), which show high efficiency and can produce sufficient charging current even at weak or diffuse daylight conditions. The SB 3000i offers a variety of features and needs careful programming for a proper setup. It can display battery voltage and charging current and the maximum charging voltage among other features. The specific temperature coefficient for AGM batteries can be programmed, and the LVD can be arbitrarily chosen. However, the variety of available settings and vulnerability to incorrect programming leading to total system failure, is a problem if the mobile stations are not installed by trained personnel. Moreover, we experienced during our testing period, that some SB 3000i controllers lost their programming when battery voltage was very low during winter. Therefore we have chosen not to use Blue Sky charge controllers for our mobile stations to minimize the susceptibility to errors during programming, installation or in the polar winter to enable also less-trained staff to deploy the stations. For all mobile seismic stations, we, therefore, use the simpler Sunsaver MPPT charge controllers. They offer two LVD voltages to choose for recorder shut down at low voltage conditions. Until now, we had an excellent experience with these controller types, which have been proven to work at very low temperatures properly

4.3 The electrostatic charge problem

If the mobile stations are placed on the ice and not on the few outcropping rocks, the system is vulnerable to static charging. Since snow, firn and ice are very poor electrical conductors, there is almost no possibility to find a suitable mass to prevent electrostatic charging. The electric charge itself is caused by all station elements positioned outside the snowpit (solar cells and their racks, GPS and Iridium). For the GPS, it is possible to operate it under a limited snow cover thickness. However, the solar cells and the iridium must necessarily be installed on the surface. In our testing period, we attempted to create a mass for the electrical compensation with large metal elements, which we have buried in the snow, but only with moderate success. The problem currently remains and can cause long-term damage to electrical equipment or, in rare cases, system failure.

4.4 Comparison to and lessons learned from other seismic surveys

The development of self-sufficient seismic stations has been strongly promoted for the extreme conditions of the polar regions in the last two decades. The component design and the available resources of various temporary or long-term year-round surveys in Greenland (e.g., Dahl-Jensen et al., 2010) and Antarctica (e.g., Hansen et al., 2015) are partly very different. However, some of the concepts have gained acceptance and many useful recommendations for future campaigns and networks have emerged from numerous scientific publications and field reports over time. Our concept of a fast to deploy, compact, modular self-sufficient mobile seismic station is based on many of the experiences described in the literature, which we discuss in the following.

Since 2009, the GreenLand Ice Sheet monitoring Network (GLISN), has been initiated to monitor all types of earthquakes with broadband seismometer stations in Greenland (Dahl-Jensen et al., 2010). Four of the 33 stations are deployed on the ice-sheet interior (Veitch and Nettles, 2012). Here, the power system of one of the stations consists of a large amount of batteries and solar cells (26 6V AGM batteries and nine 80W 12V solar cells) to ensure long-term operation (Toyokuni et al., 2014). This configuration enables a year-round operation but requires a large amount of heavy equipment. Moreover, a large portion of the batteries are not required for summer operation but consume high logistical capacities. A smaller number of batteries in combination with solar cells, wind generators (and a dump load for excess energy if the batteries are fully charges) as well as a low-voltage disconnector to protect the batteries from deep discharge has been used in a survey with six broadband seismic stations in West Antarctica in 1998 (Anandakrishnan et al., 2000). Although during the first year of deployment the total time of data recording was only 50 %, some of the stations were able to operate through the year. The authors suggest that longer uptimes can be achieved by improving the insolation of the battery boxes, which is a concept that we have implemented in our system. A similar approach in system design is introduced by Contrafatto et al. (2018). Major advancement in continuous seismic recordings in Antarctica came with the deployment of the 30-station Gamburtsev AntarcticMountains Seismic Experiment (GAMSEIS) array on the East Antarctic plateau (Hansen et al., 2015). The novel station design was developed by IRIS-PASSCAL for polar applications (Johns et al., 2006) and enabled the deployed stations to operate year round with the usage of lithium backup batteries in the winter. This setup enabled a total data recovery of 93 % (Heeszel et al. , 2013). With regard to our station design, our goal is mainly to achieve the recording of continuous and high-quality seismic data with a minimum amount of equipment. Therefore, we (i) avoid the usage of wind generators for non-permanent stations, (ii) operate at the moment with a data gap in the polar winter but with a setup that allows to resume data acquisition reliably again and (iii) will incorporate (already developed) Li-based backup batteries to bridge the polar winter gap in the future.

5 Future visions

In addition to the concepts currently under development, we also have ideas for subsequent developments. Above all, we see much potential in optimizing battery management and input energy management. For example, a multiple-battery option would be desirable, in which individual batteries are charged step by step after the polar winter when the current flow is low so that a high voltage is available quickly. It would also be desirable to disconnect deeply discharged batteries from the overall system. In terms of input energy management, a variant is conceivable in which a wind generator is switched on exclusively in the polar winter. This would close the energy gap in the polar winter (with the acceptance of increased noise in the data) and generate no noise during the summer season while recording data. Another possibility to reduce the noise influence and material stress of the wind generators would be to switch on the wind generator only for a particular time when the total voltage of the batteries drops below a certain range.

6 Summary and conclusions

We have presented a fast and easy to deploy modular, compact, mobile and self-sufficient seismometer station concept. Due to its modular design, it can be used in various ways, for example, for short-term deployment as an array over 1–2 years or as a long-lasting permanent station. The energy supply can be adapted as required using the modular cascading of battery boxes, wind generators, solar cells or backup batteries, which enables optimum use of limited resources. The stations' modules are designed so that only the cables have to be connected in the field. The plug connectors are designed to be unique to avoid the possibility of mixing them up. Parts of the concepts presented here are already in use as part of the extended seismology network of the Neumayer III Station. Our system concept is not specifically limited to the application to seismology stations (except for noise suppression). It is a suitable system managing the power supply for all types of self-sufficient measuring systems in polar regions.

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Author Contributions

AE, JA and EL led the development of the energy management concept and mainly manufactured the mobile seismic stations. AE and SF wrote the manuscript with contributions of JA.

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