Automatic Weather Stations on Glaciers: Lessons

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1. Introduction

Automatic Weather Stations (AWSs) have been deployed over a wide variety of glaciated surfaces, for example, on: continental ice sheets; valley glaciers; sea ice; and ice bergs; and have a variety of applications, including: climate variability assessment; in support of operational weather forecasting; model validation and in avalanche information support. AWS applications share a common challenge of obtaining continuous and reliable measurements both unattended and often in extreme environments. AWS have facilitated growth in the branch of *glaciometerology*. The 1st AWS On Glaciers Workshop, hosted by J. Oerlemans of The Institute for Marine and Atmospheric physics Utrecht, Netherlands (IMAU) in Pontresina Switzerland, March 27-30th, 2004 brought together the international AWS community to share practical experience gained since the 1980s when AWS applications really gained momentum. The following text collects major lessons of this group's experience to provide tips for increased success in reliable data acquisition from future AWS operations on glaciers.

Common difficulties facing AWS are:

- Rime and hoar accumulation can interrupt and bias measurements.
- solar radiation shielding of temperature and humidity measurements
- melting and/or accumulation affect instrument height and leveling
- mast stability/leaning and instrument failure due to extreme weather conditions
- limited number of visits owing to remote operation
- High latitude sites have particular power and low temperature challenges.
- Short time-on-site does not allow extensive procedures.

The following discussion offers insight from past efforts to meet these challenges. The report is arranged by topic and is intended as a kind of fact sheet for consideration to boost success in AWS data acquisition.

2. Philosophy of design

In most cases, an AWS deployed on a glacier is costly to install, difficult to visit, and must provide trustworthy data, otherwise the cost and effort seems unjustified. Often a multi year record is required, such as assessing climate variability or developing a climatological baseline, e.g. for an ice core site. Often, data are required real time. This has been facilitated by satellite, radio telemetry and recently by exploitation of proliferating mobile telecommunication networks. In remote applications, aircraft operation can rely on this information. Mean time between failures (MTBF) of more than five times the mean time between visits is a reasonable planning strategy. For many stations this demands MTBF > 5 years! To achieve this level of reliability, the station must be:

- free of design flaws, be they software bugs, electrical wiring errors, or mechanical miscalculations.
- robust, to withstand icing, freeze/thaw, high winds, low temperatures, ice creep, extreme thermal cycling, etc.

Invariably, the pursuit of a robust system has lead investigators to concentrate on *success in simplicity*. Although apparently obvious, simplicity is easily overlooked by engineers keen to make "Can Do" systems, that is, just because modern electronics and software *can* allow clever and complex features, they are not just unnecessary, but can reduce the system reliability. Experience has shown that the number of ways AWSs can fail in an *unexpected* way increases exponentially with complexity. Therefore, it is arguable that it is better to get a smaller high quality data set than a larger set of data with questionable accuracy. Useful considerations include:

- If site visits are planned , is telemetry really needed?
    - Exceptions include if instrument status is needed for planning; near real time capabilities are desirable; and there is a potential of not returning.
- AWS power supplies provide at least 2 x overkill as a rule of thumb, owing to reduced battery performance in the cold. Hence, if 6 months of battery life is needed, success is better ensured by doubling up the batteries to give 12 months, in which case, if annual visits are made, a solar panel and regulator may even be phased out.
- Log raw data, not data with multipliers and calibrations applied in-line. If calibration techniques change, the raw data will need to be available. Furthermore, less calculations reduce power requirements.
- Logging should be as simple as possible, and then tested, tested, tested. Often, it will not be until after years of field deployments that the system runs reliably.

Site Maintenance Considerations

Competing factors exist in terms of success in AWS data acquisition and what is done during site visits.

- The **time on site** if limited may rush a technician and result in forgotten or incomplete maintenance tasks. Competing against sufficient time are a number of factors often not controllable, such as limited aircraft ground stop time, daylight, and weather difficulties. It is therefore clear to maximize and optimize work prior to field deployment to take advantage of the relative comfort of the off glacier environments (e.g. labs, warehouses, or just lower elevations) and once on site, to follow a prioritized maintenance, in light of the lime constraint.

- Time needed to perform maintenance increase with decreasing temperature and as wind speed and altitude increase.
- Often, the logistical cost to visit AWS on glaciers meets or far exceeds the cost of **spare equipment**. Therefore, in cases when no communications with the AWS are available to inform what replacement instruments to bring, it is reasonable to come prepared to replace any AWS component, even AWS platform components. Furthermore, experience has also shown that AWS components may be broken during maintenance and therefore spares are commonly needed.
- Perhaps the most interesting paradox is that maintenance is a source of discontinuities in long term records. Therefore, when on site, exercise extreme caution and change as little as possible.

Consistency

When running more than one AWS, it makes sense to be consistent. Experience has shown that using different instruments at different sites, can lead to data loss given different software to keep track of or more work and uncertainty associated with the need for inter-calibration of changed instruments. Items to be consistent with are:

- Instruments
- Program
- Hardware
- Maintenance protocol

Tips for success

- Change as little as possible. In other words: **"if it ain't broken, don't fix it"**
- If batteries are buried in the snow, include a small backup battery in enclosure or fixed to AWS platform. Thus, if the remote power cable is interrupted, data logging continues.
- Put telemetry power on different batteries, but with shared ground.
- Inexpensive tools and mounting hardware are more likely to fail or simply not do what they are designed for. This also refers to instruments. Usually unless you are lucky or uncommonly clever, **"You get what you pay for"**

Accumulation Zone Issues

Extend accumulation zone sites in autumn so that profile instruments may be near the surface where the gradients (the signal) is largest for the summer when turbulent heat fluxes are often largest. Plan ahead, knowing something about accumulation rate, that the tower will survive abnormally high accumulation.

3. Measurements

3.1 Overview

A discussion of problems encountered for the most frequently required variables in glaciometerology follows. The variables include:

- air and surface temperature
- wind speed and direction
- snow/ice accumulation and ablation
- humidity
- snow/ice conductive heat flux
- shortwave and terrestrial radiation fluxes

3.2 Temperature

Under ideal circumstances, air temperature measurements may be obtained with errors corresponding to accuracy specified by the instrument manufacturer, e.g. ±0.1 K RMS error. However, over glaciated surfaces, the accuracy of temperature measurements are often degraded owing to the following factors:

- solar and infrared radiation
  - shields and instruments heat up from solar radiation absorption and emit excessive infrared radiation. These factors contribute to overheating errors that can exceed 10 K.
  - upward (reflected) shortwave radiation from the high albedo surface contributes to excessive shield absorption and also shortwave diffuse radiation absorption by the instrument if exposed in line of sight from below
  - There is some debate as to what single factor is most important. Suspects include direct-beam visible radiation, surface albedo, and actinic flux.
- Power limitations commonly preclude continual forced aspiration.
- If continual forced aspiration is made, sublimation of ice formed or sucked in the shield can significantly depress the observed temperature, giving an ice-bulb or wet-bulb effect. The opposite effect of heating is feasible in conditions of condensation or hoar/rime growth on sensors.
- Ice accumulation can insulate the sensor from expected normal air flow
- Self ventilating shields - Although radiation shields are now available with their own solar powered ventilation, it may be impossible to be certain of the ventilation rate without monitoring ventilation speed (motor voltage), considering that the ventilator motor can degrade, i.e. slow down, and fail at an otherwise unknown time.

3.2.1. Insolation

Invariably, "naturally" aspirated radiation shields are used, as power for active aspiration has commonly been unavailable. Most radiation shields are designed to protect the sensor from down-welling shortwave radiation, and assume that the ground has a low albedo. However, snow can reflect more than 90% of this radiation, and when viewed from below, to restate, some sensors within the shields are actually visible from below.

Incident shortwave radiation can affect the sensor reading in two ways. Firstly by reflecting into the shield and hitting the sensor directly. Secondly, by being absorbed inside the shield, and heating the air *inside the shield* and the shield itself. As yet, there are no models of shield response to both these effects, although D. Scherer (see report in this issue) makes a good attempt to correct overheating using an instrument independent physically based model. Some shields have black inner faces, which will eliminate direct sensor heating, but will exacerbate "shield heating”. It is also clear that a shield made of perfect white material will actually have *no* shielding effect if exposed to perfectly isotropic diffuse shortwave radiation, because the diffuse shortwave will eventually reach the sensor! This argues for sensors colored as white as possible. A second counterintuitive effect is that diffuse shortwave radiation has a higher *actinic* flux (photons per cubic meter) than the equivalent direct radiation (as measured by the magnitude of the downward flux). This is due to the photons cris-crossing the same volume, an effect well documented in the air chemistry literature where the actinic flux dominates atmospheric photochemistry, not the more familiar "meteorological" directional radiation fluxes, i.e. Watts passing though a horizontal unit area. It is the local *actinic* flux that governs the sensor heating. This must be born in mind over snow, as shortwave radiation reflected from snow is highly diffuse, and hence snow cover would more than double the actinic flux acting on an unshielded sensor.

It is plain that no matter how the shield is designed, the *sensor* should be white. We suggest even sensors within aspirated shields (e.g. the standard Vaisala HMP45 inside the Young aspirated "umbrella" shield (not the plated shield)) should be painted to reduce reflected insolation errors. However, a robust paint must be used, to withstand brittle effects at low temperatures, UV radiation, and adhering to a smooth plastic. Paint does not adhere well, for example, to Teflon, a common thermocouple cable shielding material.

3.2.3. Dual Function Shields

A secondary solution to insolation error is to add solar powered aspiration to a naturally ventilated shield (or have two shields, one aspirated, but solar powered). Given that insolation errors are worst when the sun is shining, solar power is available when aspiration is most needed. Such shields are under comparison at Halley (a standard Young natural ventilation shield with added aspiration) and the commercial Davos system IMAU and BAS have independently developed a computer-fan aspirated shield Actively aspirated shields offer an obvious solution, but for confidence in results, need to be evaluated under true over snow conditions, in which case, persistent overheating errors may be of little surprise.

3.2.4 Remotely sensed temperature: The Future?

Moderately thick fine wire thermocouples (0.003”) are superior in measuring air temperature (passively, i.e. no aspiration power and fan problems) than any kind of ‘naturally’ or ‘actively’ aspirated shield. Finewires have been observed to break from impact of snowflakes and blowing snow and from snow-creep and freeze thaw. Another alternative to the shield albatross is sonic or otherwise remotely sensed temperature, e.g. CSAT3D sonic temperature, IR thermometers. This technique requires more validation.

Apart from surface temperature derived radiometrically, one will always need to measure air temperature at least at one level.

3.2.5 A Shield Standard?

Given that shield designs change, there is no apparent standard and it is best not to recommend a specific design, but to recommend that each investigator be sure to assess the limitations of whatever shield selected based on an experiment made in the glacier environment with reliable ventilated shields, fine wire thermocouples, or perhaps even sonic temperature.

3.3. Wind Speed and Direction

Power constraints for remote AWS have meant that winds are invariably measured with cup anemometers + wind vanes, or the combined propeller and vane (propvane). Other methods (acoustic, pitot) present problematic power requirements. The most significant problem with measuring winds at glacier AWS sites, in low power systems, is **rime ice** accumulation, which acts to reduce the measured wind speed, and prevent the vane from turning. Scale is an issue, in that 1 cm of rime will obviously affect a small cup set more than a large cup set. Similarly, a large vane with a large turning moment will remain free to rotate, or break free of the rime sooner than a small vane. Therefore, bigger appears to be better, apart from the disadvantage of increased over-speeding error with bigger cups. The propeller vane is also better able to cope with rime accumulation than the cup. The propeller itself is nearly frictionless and cuts a near perfect helix through the air as it turns. Only the leading edge of the propeller is passing through the air, and hence there is only a small area that is being impacted by any cloud/fog droplets (and hence accumulating rime). The cup anemometer is a much less desirable design, as it is constantly turning with the back of the cup in opposition to the wind, and the front of the cup (through the drag on the other cups) traveling slower than the wind. In this design, rime accumulates more rapidly than on a propeller. In heavy riming both propvane/cup+vane will eventually stall.

3.4. Snow Depth

Acoustic surface height indicators are susceptible to the following problems.

- Instrument failure from freeze-thaw delamination of the acoustic membrane
- membrane obstruction by snow/rime.
- erroneous height from reflection from a dense drifting snow layer
- Raw data should be collected and speed of sound correction applied in post processing. Reason: temperature measure can foul surface height data.
- Snow drift tower wakes and moats can be problematic. Therefore, instruments should be oriented upwind.
- H. Gubler has installed a cone on the SR-50 to protect the aperture from snow packing in.
- Membrane failure rate has been observed to increase with age. Therefore, regular replacement of the acoustic membrane should be considered each year.
- It has been noted that the proximity of open sea significantly reduces membrane lifetime. On Iceland, where the sea is never far away and the air carries a lot of

salt, membranes last as short as 1 year; in Antarctica, lifetimes as long as 5 years have been recorded without a single problem

3.5. Humidity

Vapor pressure, dew point, mixing ratio etc. are commonly derived from capacitive (occasionally resistive) humidity sensors when deployed on AWS. Other sensors, notably the cooled mirror hygrometer are more accurate but require human interaction (occasional cleaning of ice lenses on mirror) and much more power.

The sensor itself has many of the problems associated with the measurement of temperature, especially as the sensor itself must be in both hygrometric *and thermal* equilibrium with the ambient air. Most sensor packages include a temperature sensor adjacent to the active capacitive humidity sensor. In the HMP45, the 100 ohm PRT air temperature sensor is completely electrically isolated from the humidity electronics. There is usually a secondary, cruder temperature sensor within the instrument housing, used to add correction to the humidity value. A number of points should be noted to understand the problems with common humidity instruments.

- The capacitive *and* resistive (and hair!) active components respond to a first approximation to RH with respect to water (RH_{water}). This is before any correction is added by the instrument.
- The Goff-Gratch equations (Sargent 1980) or approximations thereof are needed to calculate actual RH relative to saturation over ice (RH_{ice}), see Anderson (1994)
- The linearity of the active sensor is poor above 98% RH_{ice}
- When the ambient air is saturated or super saturated, the porous sensors become clogged, and takes minutes or hours to recover given drier air. This is even after the apparent surface ice which may be coating the sensor has sublimated.

Many commercial sensors have a slight residual non-linearity at low temperatures, temperatures below the manufacturers specifications, but the instruments often still work well, and this non-linearity can be corrected following Anderson (1994). There is some uncertainty as to whether only a simple gain correction is needed, and not a gain plus offset. This requires some further study, and comparisons with chilled mirror devices.

The main difficulty with using the hydroactive sensor is the inability to measure super-saturation, and the long recovery time following clogging. See Anderson (1995) for a description of this effect. Data quality can be judged visually from RH time series, especially in drainage or katabatic regions: the reading will remain clipped and constant at 100% RH_{ice} and then suddenly dip to more believable drier values.

We suggest that where possible, the RH sensor should also be painted white, but this is not directly feasible as the paint would prevent vapor transport into the hydroactive material. Most RH instruments included a protective cap and the cap at least should be painted white. Within the protective cap there is often a permeable membrane: obviously this should *not* be painted!

3.6. Snow/Ice Conductive Heat Flux

Unlike soil heat flux, where a standard flux plate will give a suitably accurate reading, snow and ice heat flux suffers from the ever changing level of the surface and solar radiation absorption. Accumulation buries any sensor, ablation exposes it again, melt water advects heat vertically and horizontally, whilst the latent heat of melting itself acts as an additional flux with its own difficulties in autonomous measurement. Solar radiation absorption is mitigated using thin wire thermocouples or extrapolating deeper temperatures to shallower layers and comparing the estimated surface temperature with accurate IR thermometry (Van den Broeke et al. 2004).

3.6.1 Dry snow heat flux

In polar regions where the snow remains dry (but may still ablate), the situation is somewhat easier than described above. The conductive heat flux may be estimated from thermal gradients at the surface, and estimates (from occasional measurements) of snow density. The thermal gradient themselves are either estimated from temperature probe arrays, or derived from the time series of the snow surface temperature (see below). Snow temperature probe arrays come in three varieties

- Robust steel sheathed temperature sensors on a rigid pole, i.e., 'Magic Sticks'
- Temperature sensors along a cable bundle
- Non-rigid sensors which move with the snow compaction.

All suffer from the requirement for sensors to be near the surface at all phases of the accumulation/ablation processes, with a small separation (*c.* 10 cm). The cost and complexity of logging can be formidable for accumulation/ablation regimes > 2m. The bonus is that the snow level itself can be estimated from variance differences, or inversion techniques, which may augment or check on the snow depth gauge readings. Also, the presence of liquid water is readily detected by measured values constant heat 0° C.

Robust steel sheathed sensors give accurate temperatures, and do not appear to suffer from conductive losses down the pole given a pole of light wood, and that the whole apparatus is painted white. Near surface heating and cavitation (air gaps around the probe) are occasionally problematic in summer.

The cabled sensor is most often used for snow chemistry work. Compression of the cable is unknown, and the accuracy of the data has not been tested as comprehensively as the solid pole array.

Laying sensors unsupported within the snow is suitable for ablation sites, but suffers from the inability to cope with accumulation: in order to be at the correct separation once snow has covered the sensors, they need some level of support whilst in the air awaiting burial. In addition, the uncertainty in probe separation as the snow compacts causes errors in the calculation of the heat flux.

Given these difficulties, an alternative to measuring the snow temperature profile directly is by Fourier, Laplace or Crank-Nicholson schemes. The snow is assumed to be a pure 1D semi-infinite thermally diffusive medium. This approximation is good for non-melting snow. In this situation, the snow profile is governed solely by the history of the surface temperature and the thermal diffusivity of the firn. This latter can be measured by one extra sub-surface probe, or estimated from previous measurements. For a diurnal cycle in the snow surface temperature, the Fourier transform of the heat equation is most suitable (i.e. the polar summer), whereas where synoptic / katabatic events dominate (where there is no dominate mode in the frequency), the Laplace transform is appropriate. The technique is well documented in many engineering texts.

The snow temperature profile may also be modeled directly, using the Crank-Nicholson scheme for the 1D diffusion equation. This is somewhat more computationally demanding but this may prove of small consequence given the power of modern PCs.

3.7 Shortwave and longwave radiation fluxes (adapted from Van den Broeke, 2004)

For a long time, radiation measurements from polar AWS have been regarded as of little use due to problems of a poor cosine response under high zenith angles, low temperature malfunction and/or riming of the sensor windows. This has changed with the advent of low cost, robust sensors like the Kipp and Zonen CNR1 that incorporate four individual sensors for the upward and downward shortwave and longwave radiation fluxes. These sensors have been operated for about 8 years now on glacier AWS in the Alps, Norway, Iceland, Greenland and Antarctica. They seem to perform well when compared on-site to higher-standard sensors. The big advantage of this sensor is that it measures all components individually, so that corrections may be applied to individual radiation fluxes. Linearity seems to become poorer below -45 °C but this has to be investigated closer. Although the sensors include a heating option (several Watts), this is probably not feasible for low power AWS, nor is ventilation.

3.7.1Shortwave radiation fluxes

A shortwave sensor with a single dome is advantageous because it is much less susceptible to riming; when the sun shines, the black sensor plate heats up considerably and therewith also the glass dome, which prevents rime formation. A single domed shortwave sensor thus should always be the first choice, even though this will allow some convection. Note that the downward facing shortwave sensor is much less prone to measurement error. It thermally equilibrates with the relatively warm surface (warm compared to the clear atmosphere) so that riming is less likely to occur on down-looking pyranometers. Down-looking pyranometers also receives isotropic radiation, making them much less susceptible to errors associated with a poor cosine response and sensor tilt. When one uses 24-h running integrated values of both sensors to calculate albedo (therewith minimizing cosine response errors) in combination with the instantaneous signal of the downward facing sensor, much better estimates of instantaneous net shortwave radiation are obtained compared to simply subtracting the reflected from the incoming signal, especially over highly reflective surfaces when both fluxes are of similar magnitude. Another advantage of this method is that spuriously high/low albedo values may indicate icing problems and assures an easy quality check. A disadvantage of this method is that the daily albedo cycle is eliminated. This can be partly remedied by adding a theoretical daily cycle.

3.7.2 Longwave radiation fluxes

The measurement of longwave radiation fluxes is important, as longwave radiation play a major role in the energy balance of the polar regions, where most of the shortwave radiation is reflected at the surface. It is therefore desirable to measure the longwave fluxes directly rather then obtaining them from measurement of allwave radiation from which the shortwave fluxes is subtracted. Because net radiation is usually small in the over ice, this procedure leads to large errors. Another advantage of the direct measurement of upwelling longwave radiation is that one has a reasonable estimate of surface temperature (assuming unit surface emissivity). Having a value for surface temperature is advantageous to calculate temperature gradients in the air and the snow pack, facilitating heat flux calculations. It also provides a good estimate of surface moisture concentration (assuming the snow/ice surface to be saturated), an important parameter for sublimation calculations.

Longwave radiation measurements suffer from a window-heating offset caused by absorption of solar radiation by the wavelength selective filter. This error is hard to detect but can be minimized by ventilation, if power allows. Over highly reflective surfaces, window heating will tend to offset in the calculation of net longwave radiation when both longwave fluxes are used. Another major problem is icing of the sensor windows. Rime completely obstructs the passage of longwave radiation. If sensor design is a thermopile, i.e. to measure the temperature difference between the sensor body and the object it looks at, the signal will go to zero. As such, this error is easy to detect, but hard to solve in postprocessing. One may try to design a parameterization of net longwave radiation with temperature as predicting variable, based on data collected from non-riming episodes. Experience from Antarctica has learned that sensors operated in katabatic wind zones are much less prone to icing than those operated o the flat coastal ice shelves or in the interior; a probable explanation is that the adiabatically heated air is always sub-saturated, which maintains a constant sublimation even in mid-winter.

4. Platforms and Power Systems

4.1 Masts

A variety of instrument platforms have been used successfully. The main instrument platform remains erect using structures including (for lack of better terms):

- monopods (e.g. GC-Net)
- tripods (e.g. GLACIOCLIM)
- quadopods (e.g. IMAU)
- light weight simple guyed pole masts (BAS upAWS, BAS LPM)
- lattice masts (e.g. US Antarctic AWS)

Monpods – ablation zone experience in Greenland (i.e. GC-Net) has shown that to minimize tower leaning, monopods must be inserted to a depth at least double the anticipated ablation, otherwise, one may expect thermal conduction down the mast to cause tower leaning even if as much as 2 m of the mast remains in ice. It may be that a thermal conduction insulator, such as from carbon fiber, may reduce thermal induced leaning, however, this has not been proven to be of sufficient strength to attempt operationally. To minimize maintenance, deeper insertions can prepare the monopod to survive multiple years.

Tripods – tripods are perhaps the most common AWS platform, as they are commercially available from such vendors as Campbell Scientific. Steel tripods, though strong, are often not desired for remote applications owing to their excessive weight. Aluminum versions are commonly used.

Quadropods – IMAU have been successful using broad base (2.5 m?) 4-leg platforms, with the aim that the AWS instruments remain parallel with the slope, for example on valley glaciers with up to 9 m of annual ablation, it is advantageous to have instruments parallel to the sloping surface rather than horizontally level, to obtain data to drive one dimensional energy transfer models with coordinate system oriented along the slope. In this sense, also the wind speed appears to be to be parallel to the surface. It was not really the aim to keep the AWS parallel to the slope, but IMAU colleagues found that this is the most stable construction to operate in rough terrain (such as the margin of the Greenland ice sheet) and/or in high ablation areas. As such this design does not differ fundamentally from a tripod, it just reduces even further the risk of tipping over.

In any platform configuration, if tilting is possible, logging data from tilt sensors have eliminated uncertainties of tower level.

Guyed pole masts - For low accumulation zone sites with less than 2m annual snow accumulation, a very simple and inexpensive guyed pole is suitable. Guys reduce wind induced vibration and maintain the mast vertical. The settling of snow will increase the tension in the guy lines very significantly, so 5 mm wire rope and equivalent mountings are needed to prevent mechanical failure. The footprint spacing of the cables must be equitable to avoid unbalanced tension causing tower leaning.

Note that problems with snow settling can be avoided by attaching the guying cables to the end of the legs instead of using anchors. This makes the structure stiff both in accumulation episodes as well as during strong ablation. Usually it is then also necessary to connect all four legs about halfway with a single cable to avoid bending the legs upward if the guying cables are tightened.

4.2 Power Systems

In polar latitudes, the restrictions of power availability is a major obstacle in achieving high quality data. Further, power systems in cold climates have a number of non-obvious aspects that have been re-discovered time and again by glaciologists and meteorologists. We include some of these discoveries below...

4.2.1. Very low power: battery only

Most traditional AWS or similar remote systems with low power (< 1W) use a battery and solar panel. The battery needs to store power for dark periods, the solar panel to re-charge the battery and run the system during light periods. However, for polar use, where darkness may last months, the battery capacity needs to be relatively very large, unless AWS power requirements can be minimized within power storage requirements. Further, if battery capacity is required for 6 months, then doubling this capacity may be a simpler option than adding a solar panel and regulator, which can fail and drain the batteries. IMAU has operated all its AWS with lithium batteries. They have the advantage that they have good temperature characteristics and may last for many years. The obvious disadvantage is that they are relatively expensive, that transport regulations for these batteries are strict and they are not rechargeable.

4.2.2. Solar power + battery

For non-polar regions, AWS operated over moderate temperature glaciers (> -10^{o}C) can use off the shelf panels and regulators. For polar regions of moderate power, the panel allows "intelligent operation", where active instruments (e.g. Sodars) are operated or faster logging achieved, during all but the winter months.

Panels will yield up to double the expected power output when operating over snow, due to the additional reflected power from the high albedo surface. In addition, panels work better at colder temperatures.

For polar operation, the solar panel is recommended to be mounted vertically and pointing in the direction of the equator. The power is most needed on the day the sun returns following winter, and it will appear just above the horizon. Each day following, the panel will be reducing battery drain, and finally start charging the system. Usually, the system is near fully powered by start of summer. i.e., do not put a tilt on the panel. The vertical mounting is also more robust (in general) and is best for shedding of ice/snow.

The battery / panel unit will require regulation, to prevent over charging. Most batteries take a maximum charge current that is a function of temperature, and for a given power (from panel or other source) there is a trade between just heating the battery and actually charging the battery. Get this wrong, and your system will fail in spring through overcharging the batteries when they are cold.

4.3 Logger housing, mountings and wiring

4.3.1 Blizzard Static

When dry particles of snow impact a target, the target may acquire an electrostatic charge. Wet snow does not appear to generate "blizz static", and the worst affected locations appear to be in strong katabatic zones.

Blizzard static affects electronics in two ways, destruction and interference. Destruction occurs quite simply when one part of a system charges up differentially from a second. If the two parts are electrically isolated but in proximity (< 10 cm, possibly more) the charge can equalize by arcing. Often this sparking is from a mast structure (exposed to the blizzard) to the isolated electronics. The solution is to ensure that every part of the system is electrically common, such that as the metal structure charges, so does the electrical system. This is most easily achieved by designating the zero volts point (often the "negative" of the battery) as an "earth". It is not a true earth, the whole system may be charged to a few thousand volts absolute (with small amperage). But if everything is bonded to "earth" the system will work and no sparking will occur. The above considerations will *not* protect the system from lightning!

A related effect is blizzard induced electrical *noise*, occurring when the outside plastic shielding of a signal cable acquires a surface charge, which arcs through to the cable shielding. Without shielding, the spark will can burn out the sensor or logger input channel. With insufficient shielding, these sparks generate a small current pulse in the shield. With thousands of such sparks occurring every second, the result is noise on the *signal cable* similar to radio frequency interference. The solution is to use complete shielding (foil) and twisted pair signal cable with differential inputs. This design should also be used for digital signals: hence use RS422 or RS485 where possible, not single line RS232. Most manufacturers will supply the alternative version.

The worst level above the snow for picking up blizzard static is below 10 cm in the saltation zone. A cable hanging in the saltation zone will be much more prone to noise than at 1m above the surface.

Care must be taken when a complex system is deployed or a system is upgraded, such as adding telemetry. Either the separate systems must be earth grounded, or communications must be ‘optical’ with a long optic cable. Again, independent circuit grounds are best shared than isolated. In the absence of a true ground, invariably the case when deploying over snow, the "earth" is taken as the zero volts level and referenced to the battery pack.

4.3.2 UV damage

Sunlight degrades most plastics, and this is especially true over snow with the added insolation from the very high UV albedo surface. The use of some plastic in the AWS is inevitable, either due to the instruments purchased, the cable used, or the choice of tie-wraps (cable ties). Be prepared to replace some plastic parts each year, and test tie wraps each year for brittleness.

4.3.3 Snow compaction

Densification is the process by which the snow compacts under its own weight. Guy lines will tend to be carried along with the compaction. Guy lines therefore need to be over engineered, and 5 mm wire rope or better is needed, with corresponding strong rigging. One benefit of the strength of the firn is that anchors can be surprisingly small. A 10cm square steel plate (0.01 m^2 area) has been found to take > 5 tonnes tension when buried at 1 m depth. Snow anchors made of blocks of wood are cheap, light and they work! Guy attachment points at the mast or the anchor will be the weakest point of a guy, especially if bent steel hooks or small shackles are used: these are often supplied with the mast kit and should be replaced. Exchange for chain (round the anchor) or welded eyes on the mast. If the mast is tubular, go for KeyKlamp-type fittings that encircle the whole mast.

4.3.4 Temperature effects on equipment and people

The air temperatures over snow often vary over a wide range, and this may be exacerbated by radiative cooling of the equipment on clear nights. This temperature cycling can loosen screw threads, bolts and nuts. "Nyloc" nuts, with an internal plastic shim work well down to -20 C, but these can be replaced with a pair of normal nuts and lock washers.

One obvious effect of temperature is that the user will be wearing gloves, or will have cold fingers. Either way, working with the AWS will be clumsy. Think about how this can be assisted by using large handles, minimal nuts and washers, simple connectors. Clumsiness also damages equipment. Use over-engineered connectors, such as the "Amphenol" or "Mil. Spec" range. When talking to the logger for a data down-load or calibration, can the user and Laptop (or equivalent) sit in a tent some distance away?

Mast mounts are often supplied as plates with U-bolts. Booms and even instruments can be mounted with scaffold clamps such as Nu-Rail or KeyKlamp. A single (studloc'd) grub screw tightens the clamp using a hex key, all possible using even the thickest gloves. Nu-rail Connectors are favored over KeyKlamp because they fix to the tower with twice the mounting, are lighter, and do not rust.

5: Maintenance

5.1 Calibration

The importance of relative and absolute calibration of instruments cannot be overstated, especially when dealing with more than one instrument or AWS. The following considerations related to instrument calibration should be considered.

- If temperature, humidity, and wind speed measurements are made at more than one level, both the uncertainty of vertical profiles may be assessed and potentially reduced through calibration correction schemes by collecting data from the multiple instruments at the same level over as wide a range as possible in environmental conditions. For practical purposes, commonly at least half a diurnal cycle provides a useful data set for relative accuracy assessment between instruments. Such calibrations are recommended at the installation time, during site visits, and just before the station is removed. Stay on top of these and follow up thoroughly in post processing.
- As, relative accuracy may also be expected to drift over time, periodic relative and/or absolute calibration experiments should be planned. The calibration exercise provides a means to demonstrate measurement uncertainty (observational error) and in favorable cases, to boost the confidence one has in the data collected.
- Most instruments are obtained from manufacturers with some specified absolute accuracy which may change over time and may be assessed by comparison with other instruments with known absolute accuracy. Therefore, it can be valuable to bring an instrument along, to each site, to compare will all instruments, and thus develop an inter-calibration of sites. If this is a very accurate instrument, inter-site absolute calibration may be considered.
- Humidity capacitance chips degrade with exposure to extremely low temperatures and therefore require regular calibration. One should also refer to the correction scheme of Anderson (1994) to understand one method of auto calibration of humidity instruments at low temperatures at the upper limit of their sensitivity.

5.2 Microclimate Drift

Moving AWS confronts one with a troubling issue: is the AWS constantly moving through different microclimates? The extent to which this is important depends on the complexity of the topography and local shading. The example of experience in Greenland, where flow rates exceed 100 m per year, has shown that it became necessary to move the AWS to avoid it flowing into a crevasse region. At the new site, there was evidently a different microclimate, as prevailing wind direction had shifted. Pressure also would drift if the glacier is steep and fast. The extent to which microclimate drift is important is unclear, however, is something to be aware of and to include in site selection.

5.3 Clock Drift

Clock drift causes an erroneous time stamp and can lead to transmitter synchronization loss. The extent of clock drift has been identified in a variety of ways, i.e., using theoretical solar radiation calculations (though be careful not to mix up with leveling errors) and nearby station pressure records. Telemetered data may include an independent time stamp with which can be compared with the station clock data. The clock drift problem has been solved with integrated GPS circuitry.

6: Metadata

6.1 Introduction

Metadata (data about data) are increasingly recognized as important for AWS programs. Table 1 lists commonly desired information concerning AWS data. We recommend these data be entered into digital files to accompany disseminated data.

List of recommended metadata for AWS data

1. position, i.e. latitude, longitude, elevation, and date when sampled
2. instrument types and manufacturers and serial numbers
3. sampling rate
4. data logger type and serial number
5. date
    a. installation
    b. visit times
    c. calibrations to which instruments and calibration remarks including weather conditions
6. what method used to determine true north, if made by compass, what magnetic declination was used?
7. persons present at installation and in each subsequent visit
8. UTC time coordinates used? (UTC should always be used)
9. What other site survey information exists, e.g.:
    a. what direction does site slope?
    b. Is surface homogeneous?
    c. What is the fetch distance to any major wind obstructions?
10. condition of instruments and cables
11. details on radiation shield for temperature sensors, including ventilation remarks and if shield damaged yellowed
12. instrument azimuths
13. instrument height and date when measured
14. what problems encountered on revisit
15. what problems anticipated for subsequent visits
16. how much is rime frost a problem?
17. Note if and how much clock drift.
18. Any other site or tower-specific idiosyncrasies should be noted.
19. Photos are recommended from different directions and catalogued for each site visit and should accompany data in dissemination.

6.2 Geographic Coordinates Precise and accurate AWS positions, including elevation to within a few m at least, are needed for the following reasons and are typically obtained only reliably using differential GPS.

- Atmospheric model pressure and temperature validation exercises commonly require height adjustments to eliminate height offset errors owing to model topography biases. Therefore, the position, particularly elevation must be known to within a few meters absolute.

- The position of AWS on glaciers changes with glacier velocity. The year to year and multi year site displacement may be so large, that the station position needs to be logged regularly. For example, accurate AWS positions are vital to locate an AWS for remote sensing applications, for aircraft over flights, for future planning in the case that the site may flow into a hazardous part of the glacier, and for the obvious yet not always trivial site search for maintenance.

6.3 Miscellaneous Considerations

- ***Sensor cable length*** - excessive cable lengths need to be coiled somewhere. Usually, there is insufficient space inside the data logger enclosure. Therefore, this coil would remain outside, where it is exposed to the degrading effects of UV radiation and acts as a rime frost collector. Cable length should therefore be optimized for the application but beware that spare cable length is valuable if instrument distance to logger would someday change. Note also that cable length may affect instrument response/calibration.
- ***radiometer domes*** – There are shortwave and longwave radiometers available with horizontally shaped detectors, i.e. no domes. These do not collect as much rime. However, this instrument type may also be of lesser accuracy. Therefore, a decision must be made here.
- ***meltwater flow down cables*** – a spurious meltwater percolation signal may occur if liquid water (from rain or melt) percolates down the temperature string bundle. A dip in the buried cable avoids this problem.
- ***guy wires*** – Guy wires are attractive to use to stabilize and level the AWS. Steel 'wire rope' is the common material with diameters ranging from 2-5 mm. Experience has proven that often, the guy wires can cause more problems than they solve. In regions of net snow accumulation, guy wires become increasingly tight because the AWS tower tends to be set at a greater depth than the guy wires. Since snow compacts most near the surface, there is a net tightening effect. The force can become so great as to cause tower level-drift and eventually failure of one or more of the wires causing a more severe leveling problem. Broken or melted out guy wires can interfere with measurements, e.g. propeller-vane anemometer, acoustic surface height sensors, radiometers, etc.. Perhaps if a strain relief mechanism such as a spring is installed, guy wire troubles could be mitigated.

7: Quality Control Software

Quality Control (QC) and associated software indicates to the end user some criterion for confidence in the data generated by the instruments and logger system. Once the data are 'in hand', *post hoc* analysis can then filter out obvious errors and malfunction. This is the common understanding of quality control, but we wish to stress that QC software should be developed in conjunction with the system built, to allow greatest confidence in data which passes the QC criteria, with minimal rejection of actually good data.

7.1 System design and Instrument Choice: help your QC software.

What makes any measurement more trustworthy? One obvious way is to take multiple measurements, either repeatedly with the same instrument or preferably with two separate sensors. Taking this to its logical conclusion, with AWS being relatively cheap, and logistics relatively expensive, deploy two completely separate AWS.

Notwithstanding, once the decision has been made to only put out one system, a number of design criteria should be held in mind. Choose non-analogue instruments that either work or they don't. Compare the cup anemometer, which gradually under-reads with increased rime accumulation to the sonic anemometer, which in general works well and then fails abruptly.

Record not just mean but sigma (standard deviation) of a set of readings. Sudden high sigma for a 10 second mean of say temperature, indicates the likelihood of radio or static noise.

Know what causes reading error and know its climatology: icing is a gradual phenomenon, although "unsticking" tends to be sudden. Blizzard static occurs in high winds, and affects low signal instruments (e.g. pyranometers) more than low resistance ones (e.g. PRTs). Clocks drift at very low temperatures. Measure the causes if possible, or design methods for detecting it.

Given the well designed system, the QC software will have something to get to grips with.

7.2 Supervised Q. C. – Whilst the system is running, both in pre-deployment trials and during operation, the most vital level of QC is the (skilled) human operator, coupled to *good* visualization software (*ViS*). Lessons learnt at this stage will add to previous experience gained. The emphasis however is on suitable visualization of the data. As discussed above, data logging and the *ViS* data presentation should be kept separate, with data being sent to a file which can then be read back (as read only) by the *ViS*. The *ViS* should have a number of easy to access screens which show time series and statistical output, the main purpose to detect anomalies in the data set. This is especially important during the supervised operational stage in order to identify the effect known factors (such as riming) on the measurements. The *ViS* should be the on-hand microscope to view what the system is recording.

Useful *ViS* displays are

- Time series of any channel, with zoom and pan

- Histograms
- Wind rose with variable number of arms and ability to ignore calms.
- Running mean time series with 3rd standard deviation limits overlaid.
- Channel by Channel scatter plots (e.g. RH against T).

Labview is ideal for writing *ViS* software, for whatever AWS system, and makes user selected channel display easy to implement. With a little work and a Nat Inst A/D/ card, it can also turn the laptop into a simple digital storage scope for those difficult in-field fault tracing.

Once the QC criteria are agreed, following experience gleaned at testing and known limits to the measurements, these can be combined into a confidence estimate for less knowledgeable users. Whatever the QC chosen, however, the AWS system should still record every record. This should be stressed: *it is not the logger that manages QC, and rejects data. It is the post processing software*. Invariably some aspect of the QC criteria will be wrong; everyone makes mistakes. If the logger has rejected data on the basis of erroneous QC, those data are lost forever. Hence, we may make the general comment that the non-knowledgeable, who requires all the data they get to be trusted, should never have access to the logger data, but it must pass through some level of QC software filtering before dissemination.

7.3 Generic QC Criteria – Each individual AWS will have its own idiosyncrasies, some of which will be captured by during testing, other will appear after (or during) the field phase. Some general criteria exist which will help to generate a robust automatic QC filter for hands-off generation of data for the non-knowledgeable user. Always be aware that the strange, peculiar and dramatic real events will most likely be filtered by such procedures: use the QC software to filter for other users, but also to bring the unusual your own attention.

7.3.1 Limits – Typical temperatures, wind speeds, radiation levels and so forth should be known for the area. Flag data well beyond these limits. Well beyond meaning "impossible to occur", not "unlikely to occur". Erroneous data may be binned into:

- < 5 % Error. Generally impossible to capture but does not matter anyway*
- 5% > 100%. Serious error and difficult to capture
- > 100% error. Obvious to capture.

* with the caveat of, say, air temperature difference, where small errors are significant. But then no one said it would be easy. For instance, in polar region, limit air temperature to -100^{o}C up to + 20ºC. Limits get rid of gross instrument failures, but are poor indicators of riming or blizzard noise effects.

Remember to look at the difference between successive time stamps: these should be constant and known.

7.3.2 Statistical Filtering – Over the course of a certain time period, statistical values of the readings can be made. Variance (or standard deviation) is the most useful, to test whether a signal is noisy. Ensure that what may be noise is not actually wave effects (pressure, winds and temperature) or shadow passing (radiometrics). Statistical filtering also identifies errors of stationarity, where a reading is unusually constant. Iced up wind vanes, or open circuit channels often exhibit zero variance. Statistical filtering can eliminate some of the middle error (5% - 100%) records.

7.3.3 Consistency – The most fail safe method for detecting middle range measurement error is inter-comparison/consistency. Inter-comparison is simply the method of comparing two separate sensors which should measure the same thing. Consistency is deriving a compound measurement via two different data sets, e.g. measuring outgoing longwave radiation by radiometer and by snow surface temperature, or wind speed by propeller vane and by sonic anemometer. Non-agreement will highlight error, but agreement does not *necessarily* imply reliable data. Judicious use of comparison data, however, may allow the detection of known effects, that is, choosing two instrument sets where the resulting error will be expected to diverge.

7.6 Quality Control Identifier (QCI) data

Along with the development of GC-Net QC software, a code to track data modification was developed. Therefore, a QCI data set can accompany the post-QC data. In the GC-Net case, the QCI data set has one or more columns of QCI values for each data point. For example, non synthetic data may be given a QCI value of 1, interpolated values a QCI value of 2, air temperature data thought to contain significant solar radiation overheating error a QCI value of 3, and so on, depending on the variable. Then in the data application or reduction phase, the QCI values may be parsed depending on the data quality requirements of the given data application. For example, for computing annual means, some interpolated values can be used with reasonable confidence, whereas for input into aerodynamic profile calculations, synthetic values can give crazy results. Therefore, QCI data can be an important by-product of the raw data and can give data users more insight into possible data limitations.

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9. Glossary

AWS: Automatic Weather Station
BAS: British Antarctic Survey
GC-Net: Greenland Climate Network
GLACIOCLIM: C. Vincent and P. Wagnon, Laboratoire de Glaciologie et Géophysique de l'Environnement (LGGE), Grenoble, France.

IMAU Institute for Marine and Atmospheric physics Utrecht, Netherlands

LMP Low Power Magnetometer: single battery, non-solar unit designed to last one year (or more) of operation with polar winter operation.

upAWS micropower **AWS:** single battery, non-solar unit designed to last one year (or more) of operation with polar winter operation.

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