Supplement of

A monitoring system for spatiotemporal electrical self-potential measurements in cryospheric environments

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**S1: Measurement flowchart**

<table>
<thead>
<tr>
<th>schedule</th>
<th>measured parameter</th>
<th>action</th>
</tr>
</thead>
<tbody>
<tr>
<td>daily</td>
<td>contact resistances</td>
<td>measure</td>
</tr>
<tr>
<td>hourly for $V_{bat} &gt; 12.3 \text{ V}$ or 6-hourly for $V_{bat} &lt; 12.2 \text{ V}$</td>
<td>electrode temperatures</td>
<td>measure</td>
</tr>
<tr>
<td><strong>5 am - 8 pm</strong></td>
<td>SP-voltages</td>
<td></td>
</tr>
<tr>
<td>10 min, if $V_{bat} &gt; 12.6 \text{ V}$ hourly, if $V_{bat} &gt; 12.3 \text{ V}; &lt; 12.5 \text{ V}$ hourly, if $V_{bat} &lt; 12.2 \text{ V}$</td>
<td>battery voltage</td>
<td></td>
</tr>
<tr>
<td></td>
<td>air-temperature</td>
<td></td>
</tr>
<tr>
<td></td>
<td>solar voltage</td>
<td></td>
</tr>
<tr>
<td><strong>8 am - 5 pm</strong></td>
<td>SP-voltages</td>
<td></td>
</tr>
<tr>
<td>30 min, if $V_{bat} &gt; 12.6 \text{ V}$ hourly, if $V_{bat} &gt; 12.3 \text{ V}; &lt; 12.5 \text{ V}$ hourly, if $V_{bat} &lt; 12.2 \text{ V}$</td>
<td>battery voltage</td>
<td></td>
</tr>
<tr>
<td></td>
<td>air-temperature</td>
<td></td>
</tr>
<tr>
<td></td>
<td>solar voltage</td>
<td></td>
</tr>
<tr>
<td>6-hourly daily</td>
<td>send data by email</td>
<td></td>
</tr>
<tr>
<td></td>
<td>update logger time to UTC using ntp</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Measurement schedule of the measurement system. Note that data upload and ntp schedules have been varied over time to reduce power consumption and increase system reliability.
S2: Internal signal flow

Figure 1: Signal flow in the measurement system. The incoming signal lines (upper left, red) are routed and multiplexed from the incoming cables using custom-made PCB boards, finally connecting to multiple data logger input channels (bottom, green).
Figure 2: Lightning protection and low-pass circuit, applied to each SP electrode input line (as such this circuit was duplicated 20 times, using 4 pcb boards with 5 circuits each). The electrode and temperature signals arrive into the SP system via ethernet cables (one electrode group per cable), which are then connected to an ethernet panel (see Fig. 5 of manuscript, lower right corner). From here on each electrode group is routed using a short ethernet cable to the lightning protection circuit.
Figure 3: Input splitter diagram, splitting temperature and SP signal lines. Electrode group signals arrive from the lightning protection circuit at the bottom and are then routed either directly to the corresponding logger inputs for temperature measurements (groups of four output in the center), or, in groups of 5 SP signals, are routed to the resistance split circuit (ethernet output at the top). This circuit was duplicated four time to accommodate the 20 electrode groups.
Figure 4: Resistance multiplexer diagram, multiplexing electrode lines to separate inputs for resistance measurements. SP signals arrive at the top from the four resistance splitting circuits. Signals are then multiplexed to certain logger inputs for resistance measurements (outputs in the center of the circuit, note that two outputs are always short circuited). The SP signals are directly routed to the outputs at the bottom for further multiplexing in the multiplexing circuit.
Figure 5: Multiplexer circuit diagram multiplexing SP input lines to specific inputs of the data logger. Each electrode is connected to one port on the bottom ("Electrode inputs") and then routed to one or more of the data logger multiplexer channels on the top ("Multiplexer Inputs"). Note that each logger input channel consists of four physical inputs, allowing for a variety of measurement combinations.
**S3: Electrode matching**

Figure 6: Test measurements of base-line electrical offsets in saline solution. Left: Voltage measurements for 20 randomly selected SP electrodes, right: Voltage measurements for 20 matched SP electrodes

The absolute potentials of SP electrodes changes with age, chemical environment, and usage history. As such, it is commonly advised to check the baseline potential difference between electrodes before measurements commence (e.g., Corwin, 1989), in order to not confuse the offsets with process-based signals. Out of the pool of available SP electrodes, we initially selected 20 random electrodes. This yielded voltages with respect to electrodes 1 and 16 of down to -5.4 mV (Fig. 6, left). Following this, electrodes were selected out of the available pool to minimize this offset voltage, resulting in a maximum voltage difference of ±1 mV (Fig. 6, right).
Captured SP data presented in this study exhibits quite large noise levels (e.g., Fig. 7a). This is caused by aliasing artifacts, as well as anthropogenic noise due to the operation of the cable-car to the summit and corresponding touristic operations. As such data was processed as follows: First, data was resampled to 30 minute intervals, using linear interpolation and averaging. The effect of this operation is exemplarily shown in Fig. 7b. Depending on the specific application, in the following various rolling mean filters are applied.
applied to the data, serving as simple, yet crude, low-pass filters. The effects of various window sizes is presented in Fig. 7c.

We fully acknowledge that the use of rolling average filters is not necessarily optimal for frequency-domain filtering. In addition, other filters, such as the rolling median or the alpha-trimmed-mean filter (Gersztenkorn and Scales, 1988), are known to better preserve transient spikes. Yet, in the present study we only aimed at presenting certain characteristics or concepts, which allowed us to use the robust and simple rolling average filter.
S5: Wavelet analysis of noise data

In order to gain more information on spatio-temporal spectral content, a wavelet-based analysis (e.g., Grinsted et al., 2004) was conducted on the noise measurements conducted in 2019. The analysis shows strong 30 minute components during the day, a section of a few hours with 60 minute components just before night, and no significant spectral components during night-time hours (Fig. 8).

The analysis was conducted using the waipy software package (originally from https://github.com/mabelcalim/waipy, fork used here: https://github.com/m-weigand/waipy).
1 Data Logger programming

' DT80M program Schilthorn SP system 2017

' reset the logger
session stop
session clear
cvlog
cerrlog
deld_job+= archive=y
deljob *

' restore settings to default
factorydefaults

' some debug infos
profile parameters P56=-1

' we operate on UTC
profile locale time_zone=+0H

' sim:
profile modem service=gsm_preferred
profile modem MIN_SIGNAL_FOR_DATA_DBM=-110

' coop mobile CH internet settings
profile modem pix=XXXX
profile modem apm=click
profile modem apm_account=""
profile modem apm_password=""
profile modem_session smtp_server=XXXX
profile modem_session smtp_account=XXXX
profile modem_session smtp_password=XXXX

PROFILE UNLOAD FTP_RETRIES=10

' mains frequency [Hz]
profile parameters p11=20

' sleep while on power, but not if USB is connected
profile parameters p15=1

' 5V power output while the measurement system is on
PWR5V=1

' should prevent some debug messages
profile http_server enable_wdg=no

' reduce power by disabling ethernet
profile ethernet enable=no
profile ethernet ip_address=192.168.21.10
profile ethernet subnet_mask=255.255.255.0

' define functions for the yellow button
profile function f1_label = "mail data"
profile function f1_command = "copyd start=new \n    dest=mailto:XXXX.XX@XX.XX?&subject=sch17_01&priority=high\n    interface=modem \n    format=dbd merge=N"

profile function f2_label = "PWR5V"
profile function f2_command = "PWR5V=1"
profile function f3_label = "session signal"
profile function f3_command = "session signal"

profile function f4_label = "download all"
profile function f4_command = "COPYD job=* dest=a: merge=N format=dbd; \
    servicedata a:\servicedata.txt; removemedia"

profile function f5_label = "servicedata to usb"
profile function f5_command = "SERVICEDATA a:\servicedata.txt"

profile modem_session start_CRON=0:5:10:*:*:*
profile modem_session stop_CRON=0:20:10:*:*:*
profile modem_session timing_control=cron

' [ seconds : minutes : hours : day : month : weekday ]

BEGIN "sch7_01"

' measure voltages
RA"SPV"("B:",data:ov:370010M
101*V("E02-E01",ES10)
101+V("E03-E01",ES10)
101-V("E04-E01",ES10)
102*V("E05-E01",ES10)
102+V("E06-E01",ES10)
102-V("E07-E01",ES10)
103*V("E08-E01",ES10)
103+V("E09-E01",ES10)
103-V("E10-E01",ES10)
104*V("E11-E01",ES10)
104+V("E12-E01",ES10)
104-V("E13-E01",ES10)
105*V("E14-E01",ES10)
105+V("E15-E01",ES10)
105-V("E16-E01",ES10)
106*V("E17-E01",ES10)
106+V("E18-E01",ES10)
106-V("E19-E01",ES10)
107*V("E20-E01",ES10)
107+V("E21-E01",ES10)
107-V("E22-E01",ES10)
108*V("E23-E01",ES10)
108+V("E24-E01",ES10)
108-V("E25-E01",ES10)
109*V("E26-E01",ES10)
109+V("E27-E01",ES10)
109-V("E28-E01",ES10)
110*V("E29-E01",ES10)
110+V("E30-E01",ES10)
110-V("E31-E01",ES10)
111*V("E32-E01",ES10)
111+V("E33-E01",ES10)
111-V("E34-E01",ES10)
112*V("E35-E01",ES10)
112+V("E36-E01",ES10)
112-V("E37-E01",ES10)
113*V("E38-E01",ES10)
113+V("E39-E01",ES10)
113-V("E40-E01",ES10)
114*V("E41-E01",ES10)
115*HV("Battery")
116PT385("TempOutside",4W)
117*HV("RH_INSIDE")
118*HV("RH_OUTSIDE")
119*HV("RAIN")
120*HV("SOLAR")
measure temperatures

R8:TEMPS("B: .data:ov:370D:1H
201V("T1Voltage") 201PT385("Temp01",4V)
202V("T2Voltage") 202PT385("Temp02",4V)
203V("T3Voltage") 203PT385("Temp03",4V)
204V("T4Voltage") 204PT385("Temp04",4V)
205V("T5Voltage") 205PT385("Temp05",4V)
206V("T6Voltage") 206PT385("Temp06",4V)
207V("T7Voltage") 207PT385("Temp07",4V)
208V("T8Voltage") 208PT385("Temp08",4V)
209V("T9Voltage") 209PT385("Temp09",4V)
210V("T10Voltage") 210PT385("Temp10",4V)
211V("T11Voltage") 211PT385("Temp11",4V)
212V("T12Voltage") 212PT385("Temp12",4V)
213V("T13Voltage") 213PT385("Temp13",4V)
214V("T14Voltage") 214PT385("Temp14",4V)
215V("T15Voltage") 215PT385("Temp15",4V)
216V("T16Voltage") 216PT385("Temp16",4V)
217V("T17Voltage") 217PT385("Temp17",4V)
218V("T18Voltage") 218PT385("Temp18",4V)
219V("T19Voltage") 219PT385("Temp19",4V)
220V("T20Voltage") 220PT385("Temp20",4V)
RPT IREFT 2REFET 3REFET

**Resistances**

R8:RES("B: .data:ov:1MB:0:5:6)
301R("R01-02",III) 301*V("V01-02")
302R("R02-03",III) 302*V("V02-03")
303R("R03-04",III) 303*V("V03-04")
304R("R04-08",III) 304*V("V04-08")
305R("R01-05",III) 305*V("V01-05")
306R("R05-06",III) 306*V("V05-06")
307R("R06-07",III) 307*V("V06-07")
308R("R07-08",III) 308*V("V07-08")
309R("R08-12",III) 309*V("V08-12")
310R("R05-09",III) 310*V("V05-09")
311R("R09-10",III) 311*V("V09-10")
312R("R10-11",III) 312*V("V10-11")
313R("R11-12",III) 313*V("V11-12")
314R("R12-16",III) 314*V("V12-16")
315R("R09-13",III) 315*V("V09-13")
316R("R13-14",III) 316*V("V13-14")
317R("R14-15",III) 317*V("V14-15")
318R("R15-16",III) 318*V("V15-16")
319R("R01-19",III) 319*V("V01-19")
320R("R16-17",III) 320*V("V16-17")

VLITH
R100
VREF
VZERO

at night we increase measurement intervals

RD(0:5:20) IF(115*HV>12.6) (RA30M)
RE(0:5:4) IF(115*HV>12.6) (RA10M)

RF6H

DO(copystart-new2 dest=mailto:XXX@XXX.XX?&subject=sch17_01&priority=high&interface=modem format=dbd merge=3)
Listing 1: Programming of the DataTaker DT80M – Series 4 logger
Figure 9: Laboratory experiment investigating electrode effects during freezing and thawing. a) Sketch of experimental setup. The container is 30 cm in length, 20 cm in depth, and 5 cm high. Electrodes are shown in gray, with the wood membranes in contact with the surrounding highlighted in red and assigned electrode numbers in white boxes. b) Thermal image (surface temperatures) during thawing c) Electrical voltages and soil temperatures; vertical black line indicates time of thermal image in b).
References

