



Supplement of

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

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S1: Measurement flowchart

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

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

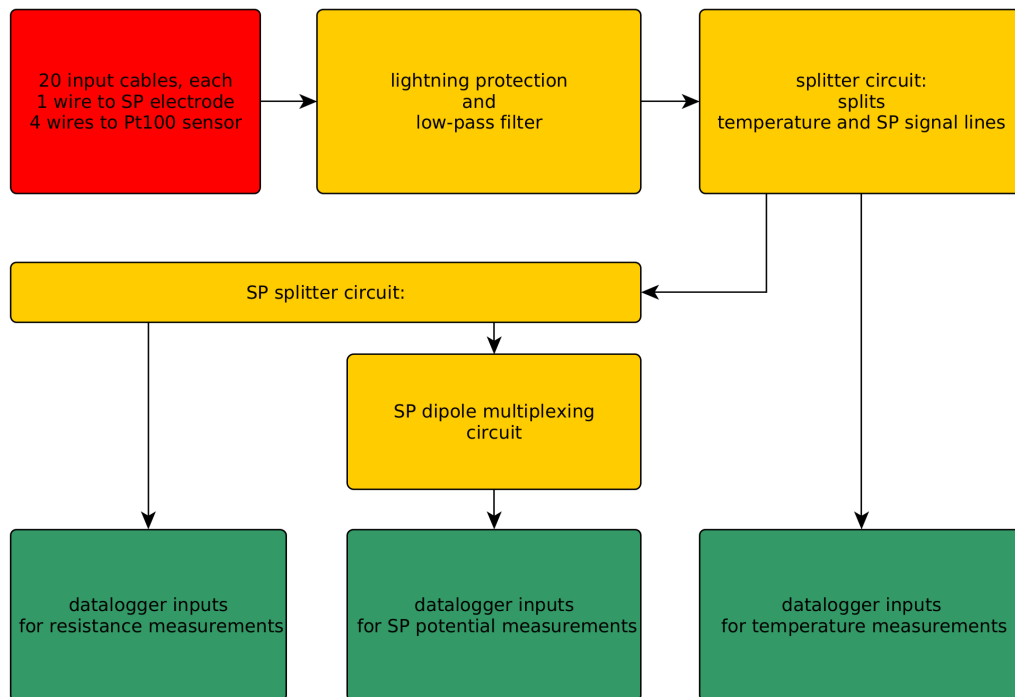


Figure 1: Signal flow in the measurement system. The incoming signal lines (upper left, red) are routed and multiplexed from the incoming cables using custom-made PCB boards, finally connecting to multiple data logger input channels (bottom, green).

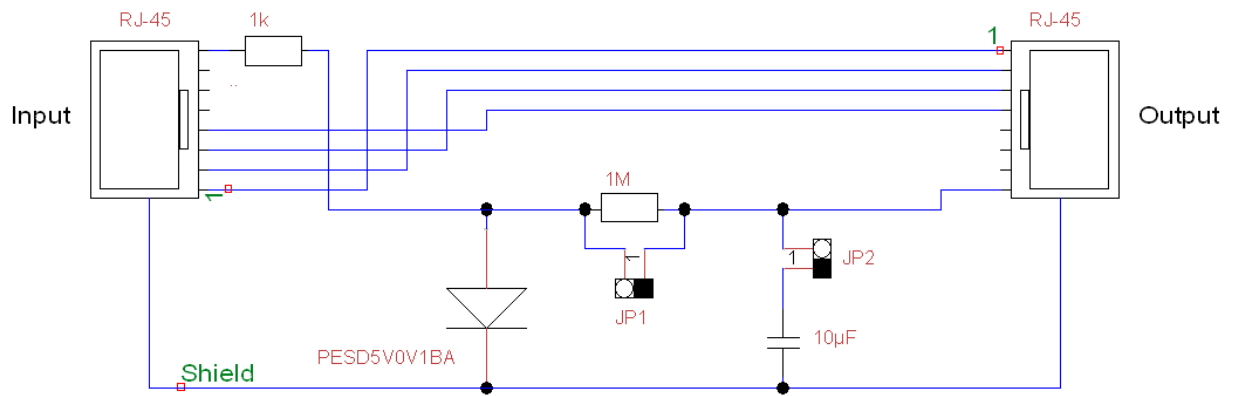


Figure 2: Lightning protection and low-pass circuit, applied to each SP electrode input line (as such this circuit was duplicated 20 times, using 4 pcb boards with 5 circuits each). The electrode and temperature signals arrive into the SP system via ethernet cables (one electrode group per cable), which 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.

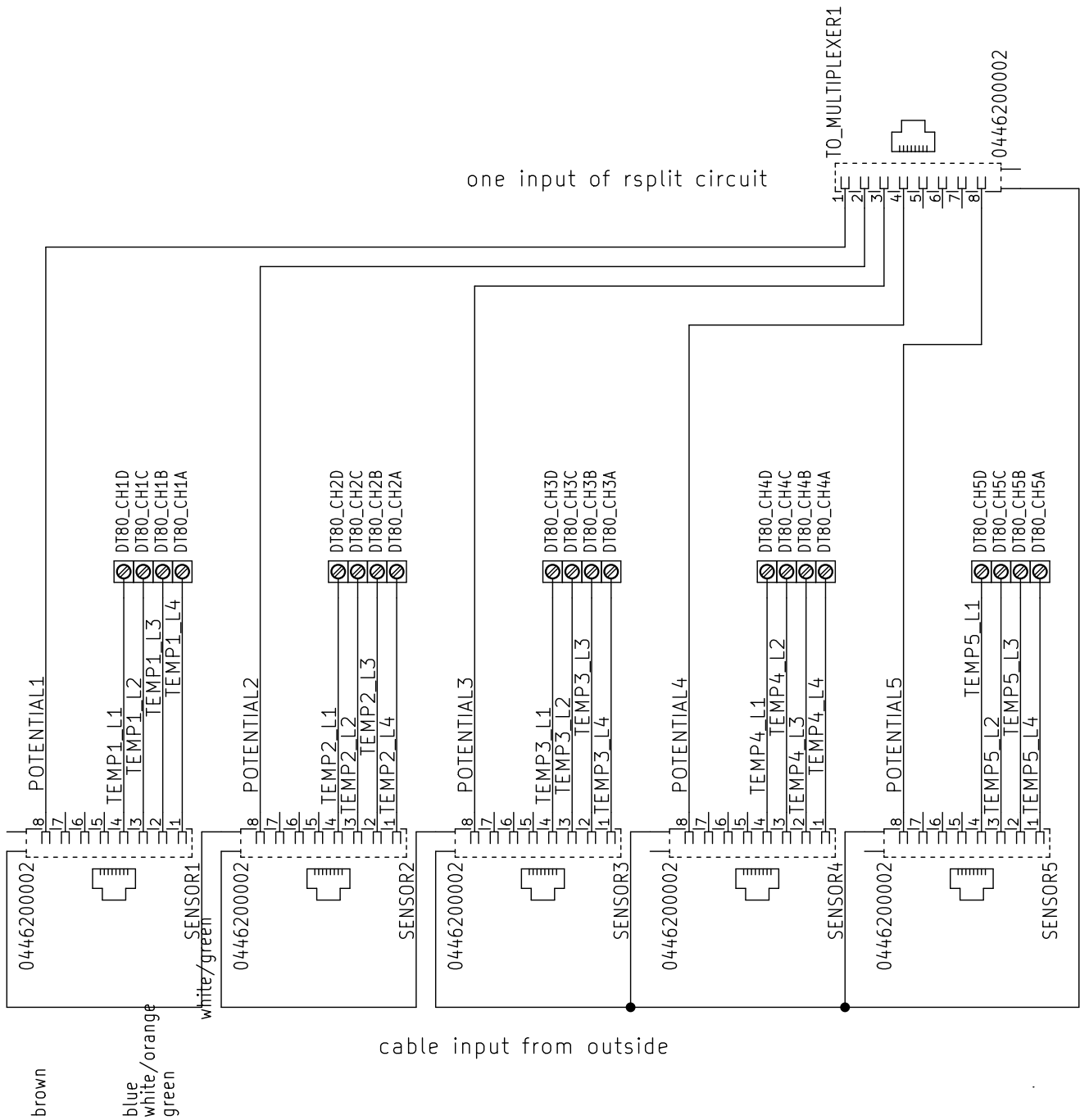


Figure 3: Input splitter diagram, splitting temperature and SP signal lines. Electrode group signals arrive from the lightning protection circuit at the bottom and are then routed either directly to the corresponding logger inputs for temperature measurements (groups of four output in the center), or, 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.

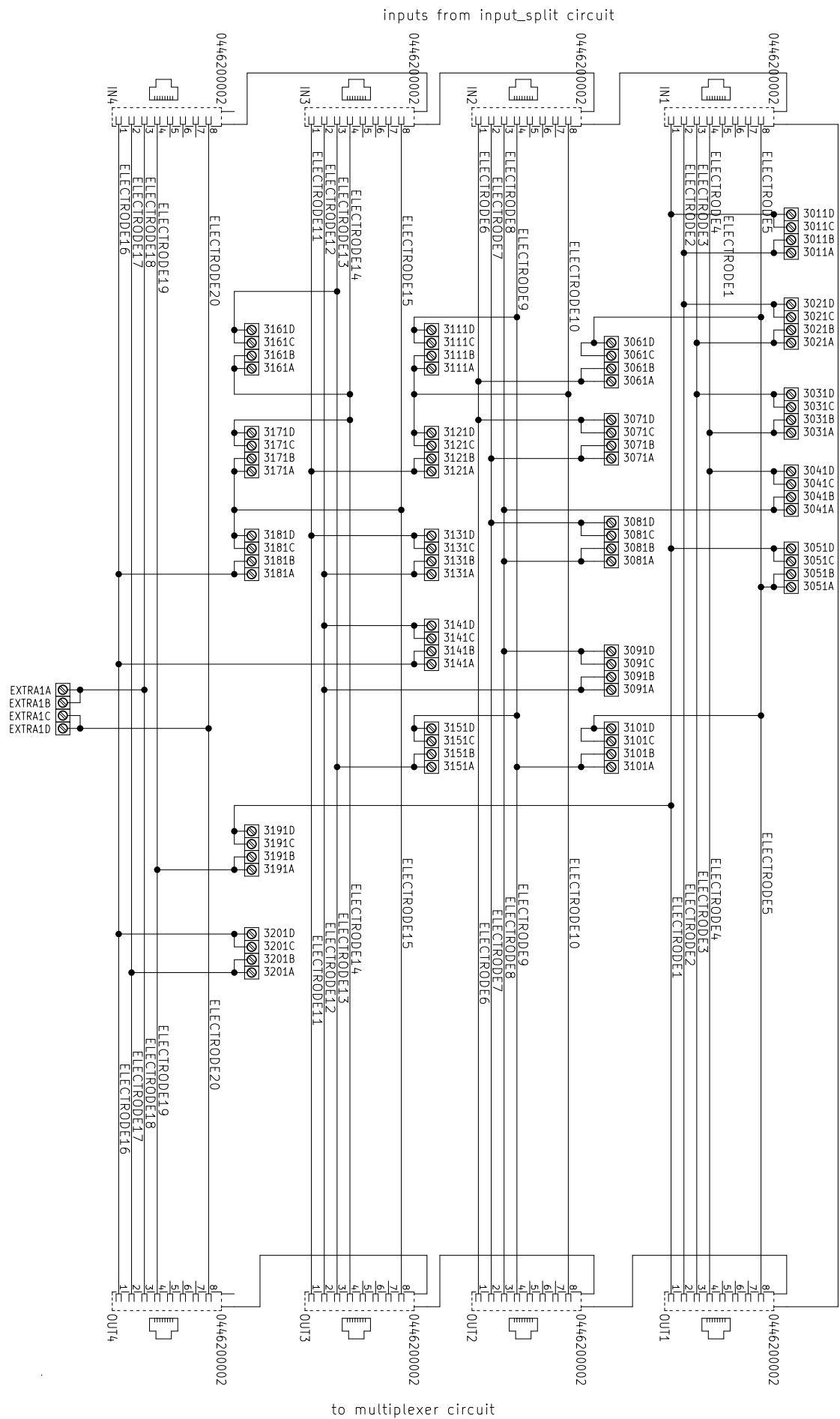
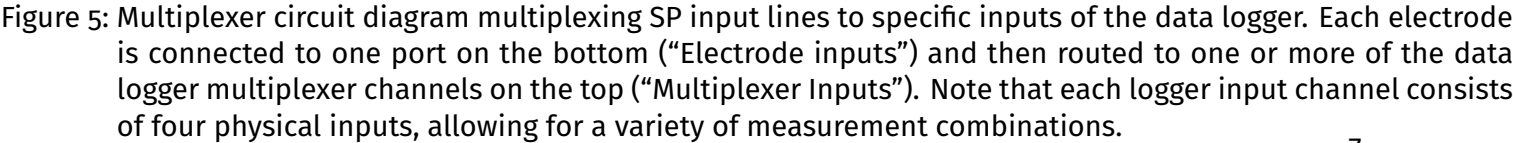


Figure 4: Resistance multiplexer diagram, multiplexing electrode lines to separate inputs for resistance measurements. SP signals arrive at the top from the four resistance splitting circuits. Signals are then multiplexed to certain logger inputs for resistance measurements (outputs in the center of 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.



S3: Electrode matching

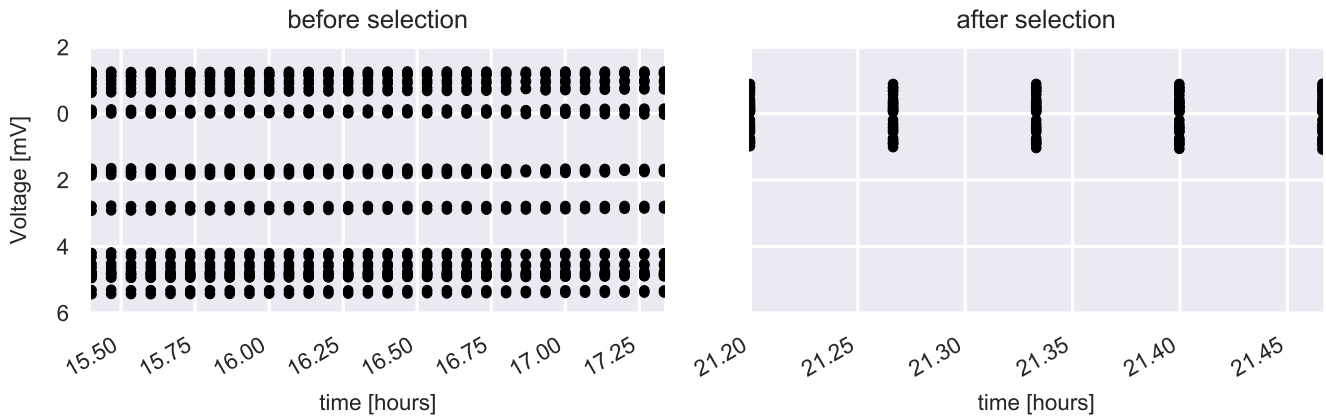


Figure 6: Test measurements of base-line electrical offsets in saline solution. Left: Voltage measurements for 20 randomly selected SP electrodes, right: Voltage measurements for 20 matched SP electrodes

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).

S4: SP data filtering

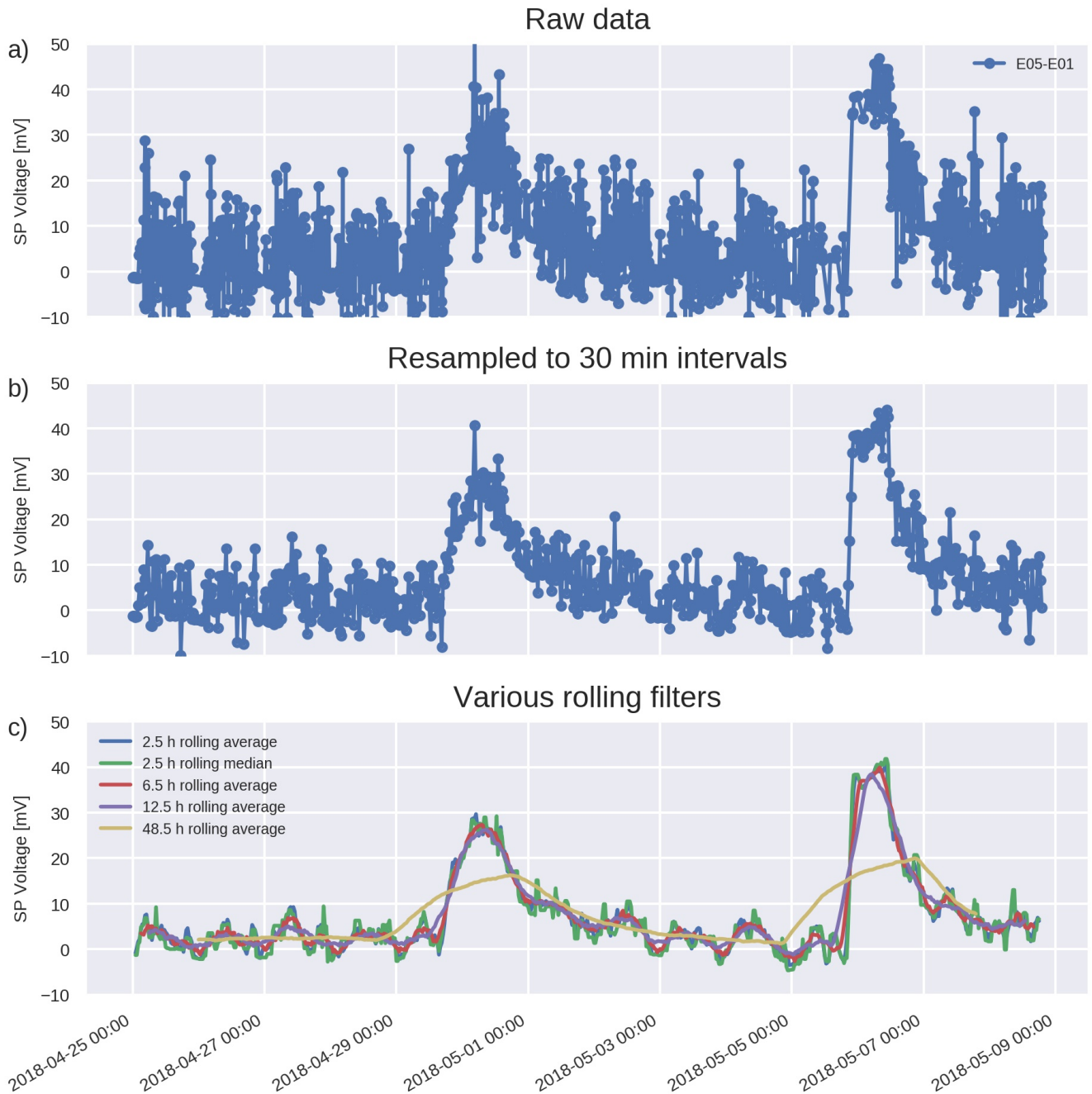


Figure 7: Data processing steps applied to SP data presented in this study, shown for the dipole E5-E1.

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 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

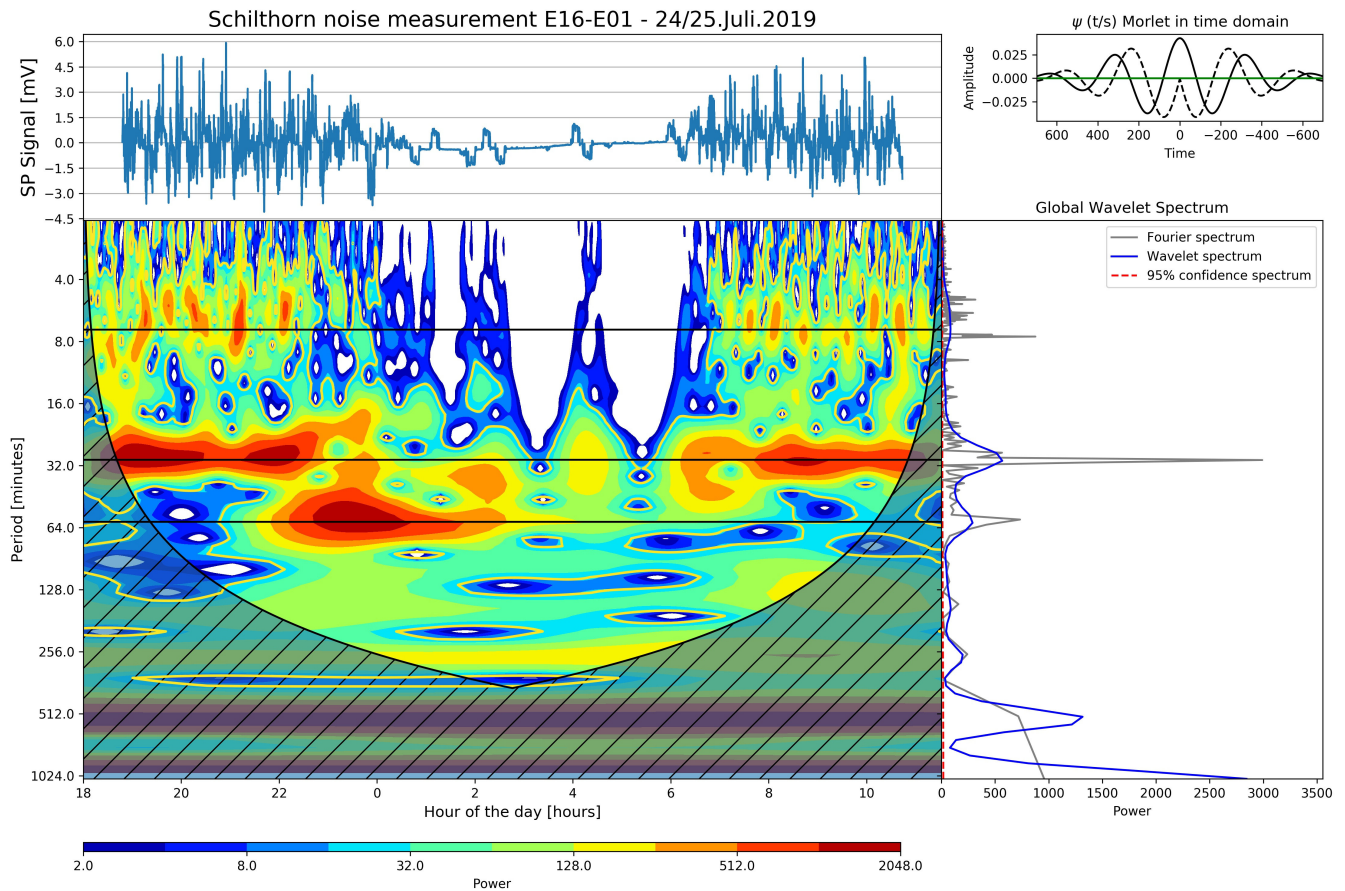


Figure 8: Wavelet analysis of the noise measurements 2019

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
cevtlog
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 pin=XXXX
profile modem apn=click
profile modem apn_account=""
profile modem apn_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 \
    dest=mailto:XX@XX.XX?&subject=sch17_01&priority=high&interface=modem \
    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 "sch17_01"

' measure voltages
RA"SPV"("B:",data:ov:370D)10M
    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("E19-E01",ES10)
    106+V("E20-E01",ES10)
    107*V("E02-E16",ES10)
    107+V("E03-E16",ES10)
    107-V("E04-E16",ES10)
    108*V("E05-E16",ES10)
    108+V("E06-E16",ES10)
    108-V("E07-E16",ES10)
    109*V("E08-E16",ES10)
    109+V("E09-E16",ES10)
    109-V("E10-E16",ES10)
    110*V("E11-E16",ES10)
    110+V("E12-E16",ES10)
    110-V("E13-E16",ES10)
    111*V("E14-E16",ES10)
    111+V("E15-E16",ES10)
    111-V("E17-E16",ES10)
    112*V("E18-E16",ES10)
    113*V("E18-E20",ES10)
    113+V("E19-E20",ES10)
    114*V("E17-E19",ES10)
    115*HV("Battery")
    116PT385("TempOutside",4W)
    117*HV("RH_INSIDE")
    118*HV("RH_OUTSIDE")
    119*HV("RAIN")
    120*HV("SOLAR")

```

VEXT

' measure temperatures

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

' Resistances

```
RC"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

```
D0{copyd start=new2 dest=mailto:XXX@XXX.XX?&\
    subject=schl7_01&priority=high&interface=modem format=dbd merge=N}
```

```

' Alarm section
RH2H
    ALARM1(115*HV>12.6)"Battery larger than 12.6 V"{RA10M RB1H}
    ALARM2(115*HV><12.3,12.5)"Battery below 12.5, but above 12.3 V"{RA1H RB1H}
    ALARM3(115*HV<12.2)"Battery below 12.2 V"{RA6H RB6H}
    DO{PWR5V=1}

' update clock
RX[0:10:11:*:*:*] do{ntp}

LOGON

END

[ ] disable debug
profile parameters P56=0

```

Listing 1: Programming of the DataTaker DT8oM – Series 4 logger

S6: Laboratory Experiment

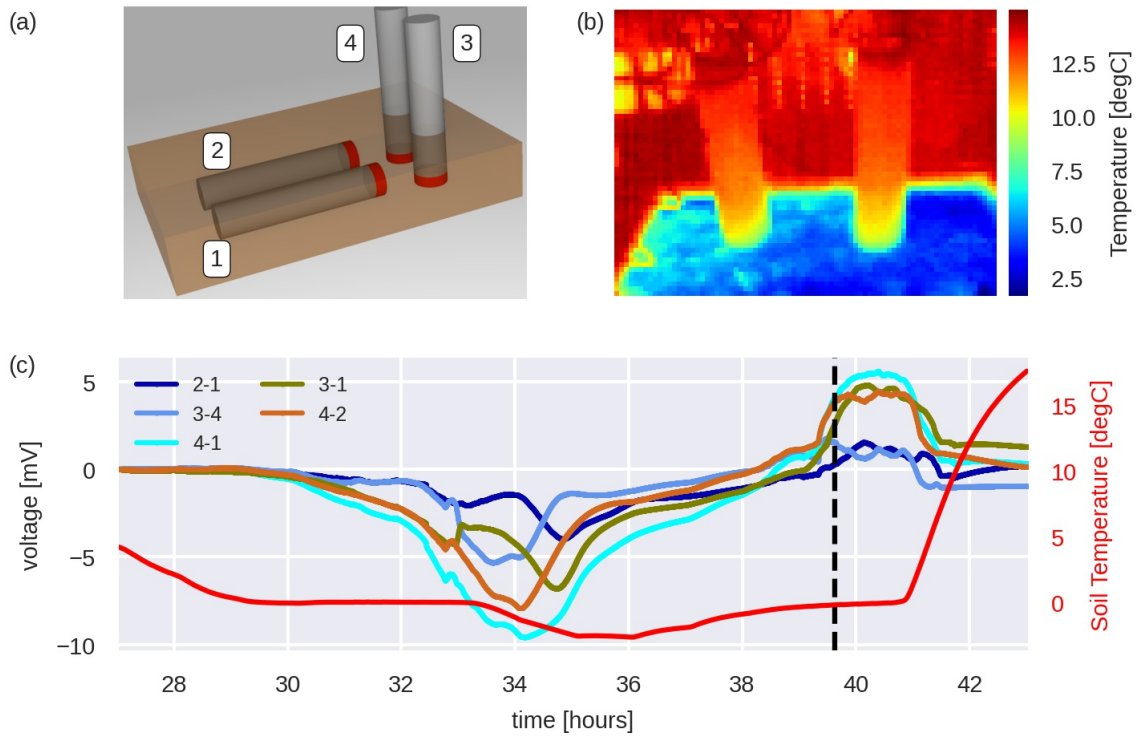


Figure 9: Laboratory experiment investigating electrode effects during freezing and thawing. a) Sketch of experimental setup. The container is 30 cm in length, 20 cm in depth, and 5 cm high. Electrodes are shown in gray, with the wood membranes in contact with the surrounding highlighted in red and assigned 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

- Corwin, R.: Data quality for engineering self-potential surveys, in: Detection of Subsurface Flow Phenomena, edited by Merkler, G.-P., Militzer, H., Hötzl, H., Armbruster, H., and Brauns, J., pp. 49–72, Springer Berlin Heidelberg, Berlin, Heidelberg, <https://doi.org/10.1007/BFb0011630>, 1989.
- Gersztenkorn, A. and Scales, J. A.: Smoothing seismic tomograms with alpha-trimmed means, *Geophysical Journal International*, 92, 67–72, <https://doi.org/10.1111/j.1365-246X.1988.tb01121.x>, 1988.
- Grinsted, A., Moore, J., and Jevrejeva, S.: Application of the cross wavelet transform and wavelet coherence to geophysical time series, *Nonlinear processes in geophysics*, 11, 561–566, <https://doi.org/10.5194/npg-11-561-2004>, 2004.