Raven Snow Science - ICECAPS-MELT 2024

Draft 1: 8 March 2024,

Draft 2: 11 March 2024, updated formatting, science questions, procedures and recommendations for snow science data collection

Draft 3: 15 April 2024, GPR transects, drone-based NIR survey, FLIR images of snowpit face, other tightening of prose.

Draft 4: 16 April 2024, surface height measurements added into executive summary, new TOC, split doc with Lyte Probe manual, revisions to the surface height survey measurement procedure, added SLEIGH foundation depth measurement.

Draft 5: 18 June 2024: Revisions based on the May 2024 Raven installation experience. Snow density measurements, liquid water content measurements, demob ideas, lyte probe recommendations.

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Executive Summary:

Contents: This document contains a summary of science questions, experiments, and field procedures for the snow science aspect of ICECAPS-MELT at Camp Raven during the Summer 2024.

Snow Science Questions: The snow science questions are centered around understanding heat transfer in snow to better predict when the snow in Greenland will melt. The data collection and monitoring are directed towards characterizing the snow stratigraphy to identify melt events and melt layers spatio-temporally. To support our understanding of this, models of heat transfer in snow need snow property data related to thermal conductivity and heat capacity. Some of the best proxies for the information needed for accurate modeling will be in the LWC, mechanical strength, and the density of the snow.

Measurement Plan: The field measurements described here in support of the science questions above include measurements to be made in a series of snow pits at a central location, spatial compression strength/NIR measurements made using the Lyte Probe (a digital ski-pole penetrometer), and high frequency (~5 GHz) snow radar. Recommendations for the execution of the field measurements are made below. Briefly, they are:

1) Snow pits made at the beginning and end of field campaign in a designated 'snow pit' area.

2) Lyte probe measurements made in close proximity to the snow pits.

3) 200-m Lyte probe transects (wind parallel and wind perpendicular) originating from the snow pit area.

4) 200-m high-freq radar transects (wind parallel and wind perpendicular).

5) Relative surface height measurements (drone-based).

6) Characterization of the snow around the SLEIGH during demobilization.

Field Measurement Guidance: Guidance and 'manuals' for the snow science at Camp Raven are listed below.

Section 1: Measurable Science Questions:

The **primary snow science questions** that are potentially directly measurable at Camp Raven in 2024 are:

1. What is the time-varying stratigraphy of the top meter of snow at Camp Raven? How does this vary on a range of time scales (30-min, monthly, across summer season)?

Density, hand hardness, compression strength, NIR reflectivity, shear strength, snow grain size/habit, LWC, dielectric constant (via radar), temperature, snow height.

2. What is the spatial variability of 1-m snow properties at Camp Raven? How does this vary on a range of vertical and horizontal spatial scales (0-10 cm, 0-10 m, 0-200 m)?

Compression strength, NIR reflectivity, dielectric constant

3. What is the relationship between snow properties measured traditionally (i.e., snow pit), the Lyte Probe, and the high freq snow radar?

We might curate data from representative case studies through a series of **opportunistic snow science questions**.

1. How do snow properties evolve in response to atmospheric forcing?

If an interesting event occurs, does it help to monitor snow properties as a function of time through the event (e.g., blowing snow, intense LW event, melting event, hoar frost formation)?

2. Can we identify a few types of representative events to make sure the energy and mass flux measurements are operational and collecting quality data?

e.g. a) *VSBL*: calm periods, into/out of snow pack (depends on context), possibly hoar formation (mass transfer *towards* surface interface (from atmosphere and from deeper in snow)),

b) *Neutral BL/small lapse*: calm, heat leaving snow pack, possibly mass leaving surface

c) *Neutral BL*: windy, rapid heating of the snow, potentially mass leaving the surface through latent heat flux or blowing snow vaporization

Section 2: Field Measurement Guidance

The field measurement guidance here is broken into four categories: 1) Where to make the measurements, 2) What measurements to make in support of science questions, 3) How to make the measurements, 4) How to characterize the measurements themselves (i.e. random uncertainties and biases).

2.1 Field Measurement Layout

2.1.1. Camp Raven

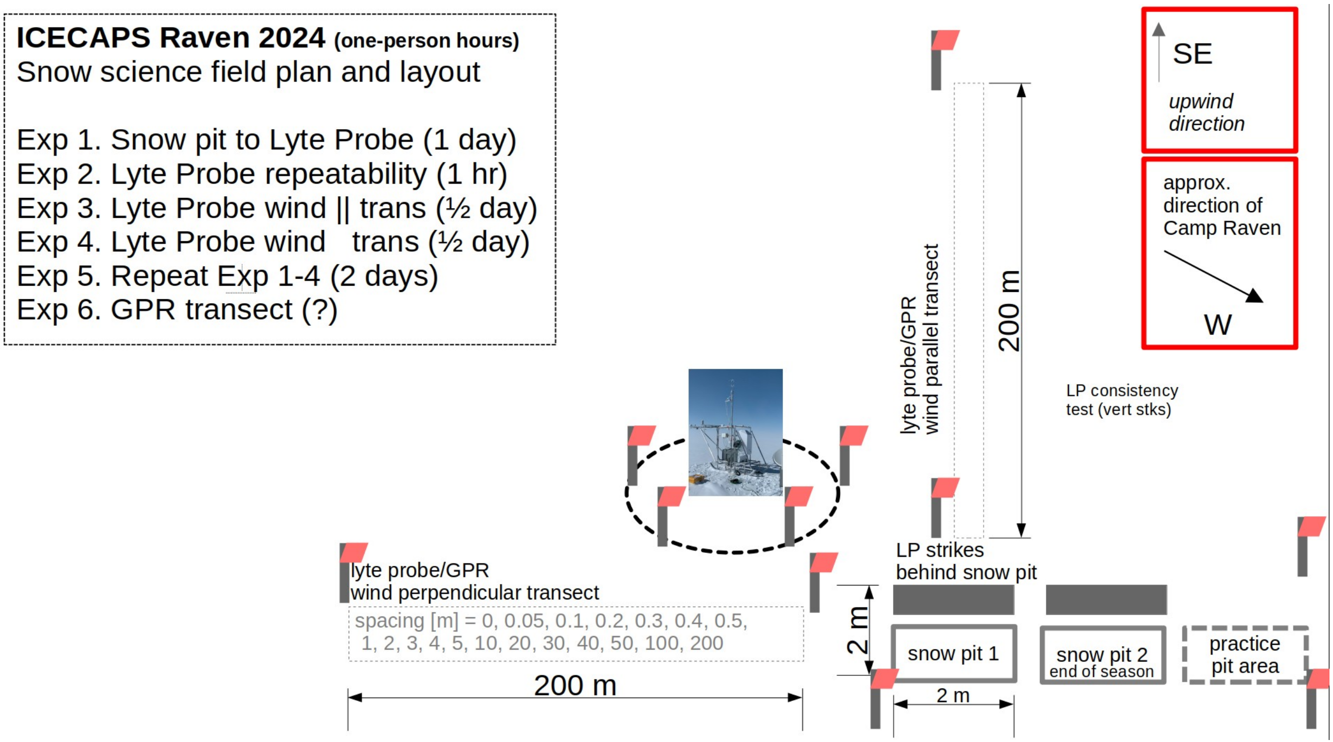

Figure 1. A top view of a potential ICECAPS-MELT field measurement schematic. Included are potential person-hours to complete each suggested measurement suite.

The field measurement schematic shows one concept of the observing platform positioning relative to other field science and the Raven Camp. Some important features and criteria here are:

1) Flag all important areas, or areas that are to be protected for surface science.

2) Keep the SLEIGH on the far side of the field site relative to snow science area, and basically upwind of the snow pits and snow transects.

3) Proximity of the SLEIGH to snow science is not that critical. It primarily matters to minimize the footprint of the experiment and make easier to protect the SLEIGH from interference.

4) **Probe first**! Probe the area with the lyte probe first to make sure that it is possible to characterize the snow coincident with the lyte probe. Take care to first envision where the planned snow pit might be, where the snow will be sampled, then probe the site with the lyte probe (maybe only vertical strikes). Mark these small transects with popsicle sticks.

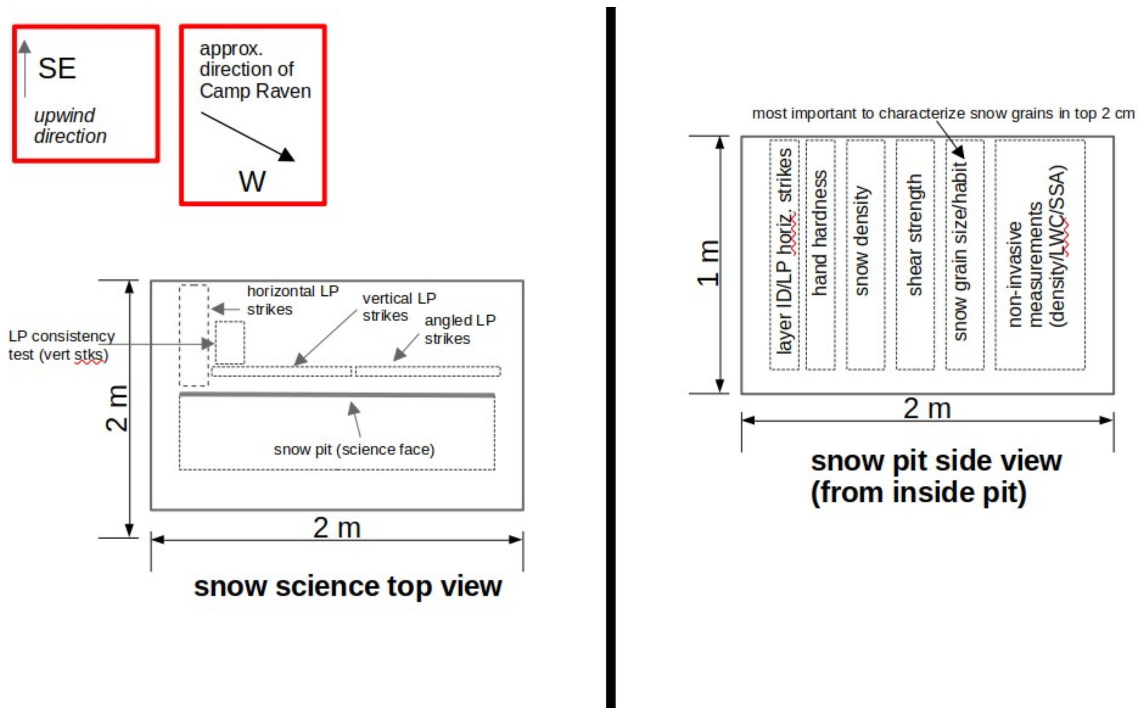

Figure 2. Snow pit diagrams from top view (left) and side view (right). Measurements in this diagram are listed in the next section on Snow Science Measurements. *It is also recommended to take a **NIR photo** of the snow pit face after cleaning and before any measurements.*

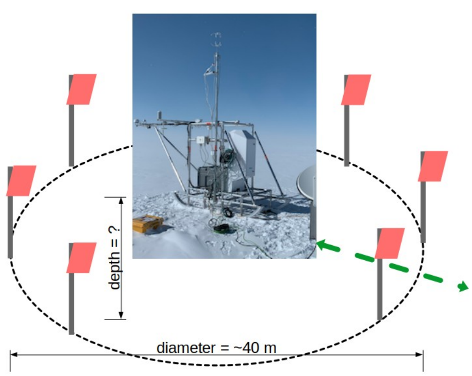

Figure 3. A figure of the SLEIGH deployment with suggested no-impact diameter, approach (**green**), and reminder to measure the depth of anchors and posts for compaction modeling. NOTE: It could be interesting to do a *final survey (snow pit, lyte probe)* at the SLEIGH site after breakdown.

2.1.2 Summit Camp

Heather Guy has obtained permission for doing snow science (pit and lyte probe transect) in a clean air/clean snow region near the ICECAPS measurements. Instructions for this snow pit are the same as for Raven. Less important here is that the site be probed first to identify a pit that can have coincident snow pit science with lyte probe strikes. However, this is still important to confirm.

2.2 Snow Science Measurements

Below are lists of measurements to make broken down by field operation task. Included in each table is a list of measurements for 'calibration' or 'uncertainty' of specific tools/measurements. The lists are in checklist form for use in the field.

*Record all field data in green **Rite in the Rain** notebook.*

Snow pit

Digging the snow pit: In consolidated snow, and especially when an installation will go into the hole, it is **strongly recommended to cut out the snow in blocks** with the **snow saws**. This saves time, energy, and mitigates risk of injury while digging. If you are organized (which is not always possible), you can more or less replace the blocks from where they came. Even if you don't, by using this method, you greatly reduce the compaction and sintering that comes from shoveling snow here then there.

Take pictures/videos: Take pictures of everything if you can. In particular, important to take pictures of context and process. This saves writing, but the pictures must be saved in appropriate places. If important information is contained in a photo/video, that still needs to be noted somewhere.

Measuring depth: Record the reading on the meter stick. **Do not do math in the field.** The dramatic exception to this is measuring LWC with the FPGA instruments. In this case, we need a density measurement before measuring LWC.

Table 1. A list of measurements and calibration tasks for the snow pit. The right-hand side of the table is a field checklist.

Measurement	Priority	Reference	Practice	May 2024	Aug 2024
Pit pictures	1	None			
Layer ID (manual)	1	SWAG CH2			
Hand hardness (manual)	1	SWAG CH2			
Snow density (manual)	1	SWAG CH2			
Shear strength (manual)	1	SWAG CH2			
Snow grain size (manual/photo)	2	SWAG CH2			
Snow grain habit (manual/photo)	2	SWAG CH2			
Liquid water content (manual)	1	Section 2.2			
Density/LWC (FPGA inst., 17)	1	SLF SnowPro User			

		Manual			
Density/LWC (FPGA inst. 4040)	1	SLF SnowPro User Manual			
Isotope sampling	1	Sierra Dabby			
SSA (FPGA inst.)	1	SLF Infrasnow User Manual v2			
Temperature profile (manual)	3	SWAG CH2			
NIR pit-face image (camera)	1	FLIR Camera Manual			

NOTES:

Layer ID - identify summer layers, crusts, and other holistic changes in material properties.

Profile resolution - try to get up to 3-cm resolution in all things. Of course, the layer ID will help you identify when that is appropriate, and when it is unnecessary. Layer ID will have higher precision than anything else (~ 1cm or less).

Profile sampling protocols - try to sample above and below crusts/hoar/and other thin layers with things like HH, snow density, shear strength. Try to sample thin layers separately whenever possible (e.g. snow grain size, snow grain type).

Practice pit - settle on minutae for procedures during the practice pit. Record procedures in notebook (or videos). Upload procedures for review by 'instrument stewards' if possible.

Manual temperature measurements - Lots of considerations here. Assess any solar bias by shading sensors as much as possible (Thomas umbrella or other). Take measurements quickly after exposing snow pit face, or dig deep into pit face, ~30 cm/day the face has been exposed.

Final survey at SLEIGH site? - Could be interesting to do a final, complete survey with Lyte probe and snow pit where the SLEIGH was looking after extraction.Transect Measurements (Lyte Probe, Snow Surface Height, GPR, Demob survey?)

Lyte probe measurement procedure (and important metadata) are described in Lyte probe doc.

Lyte Probe Usage

Most Lyte Probe usage is described in the manual. Some important things to note when using the Lyte Probe in hard snow/ice (now redundant with what is in the manual).

1) When going through hard surfaces, it is better to **use 'constant' pressure** rather than quick, blunt force. *The main thing is to avoid high accelerations* (> 14 gs).

2) When using large amounts of force, **please keep hands and body away from the data cable** connections.

3) **Probe 1 has a high force range** (0-30 N), whereas **Probe 2 has a small force range** (0-15 N). So, you can choose which one to use if you are interested in characterizing hard or soft snow.

4) When making **horizontal probe strikes**, you may encounter an **error** to do with surface detection (**type 0**). **Don't worry**, data has still been collected. If you encounter a *'comms' error*, then the *data cable has become unseated*.

5) If something funny comes up, **take a screenshot of the error on tablet screen**.

Lyte Probe Adjacent to Snow Pits

Table 2. Lyte probe measurements that ought to be made adjacent to the snow pits shown in Figure 2 are list below. Check list here in case it is helpful in the field.

Measurement	**Priority**	**Reference**	**Practice**	**May 2024**	**Aug 2024**
vertical strikes along pit face	1	Lyte Probe Manual for ICECAPS 2024			
consistency test	1	Lyte Probe Manual for ICECAPS 2024			
angled strikes along pit face	1	Lyte Probe Manual for ICECAPS 2024			
horizontal strikes into pit face	2	Lyte Probe Manual for ICECAPS 2024			

NOTE:
When to measure - Try to make these LP measurements within a day or two of digging the snow pit. Ideally you are probing the area first to make sure that an intercomparison with snow pit data is even viable. Try to make the LP measurements on the upwind side of the snow pit after the pits have been sampled.

Consistency test - In this box, keep strikes around 5 cm apart. Suggest to record the pattern (if possible) after completion (a small circle or square). Be careful to make strikes vertical. Use clineometer to check angle of attack *in situ* to self-calibrate on angle of attack. An angle of 3 deg should correspond to about 5 cm deviation from vertical over 1 m.

Transects (Lyte Probe, Snow Surface Height, GPR)

We ask for at least four (4) transects during the field season. Two in May and two in August. They ought to be wind-parallel and wind-perpendicular, approximately 200 m in length at variable resolution including a transects of surface height, Lyte probe strikes, and GPR measurements.

Table 3. Lyte probe measurements along transects.

Measurement	**Priority**	**Reference**	**May 2024**	**Aug 2024**
vertical strikes along wind parallel transect	1	Lyte Probe Manual for ICECAPS 2024		
angled strikes along wind parallel transect	2	Lyte Probe Manual for ICECAPS 2024		

vertical strikes along wind perpendicular transect	1	Lyte Probe Manual for ICECAPS 2024		
angled strikes along wind perpendicular transect	2	Lyte Probe Manual for ICECAPS 2024		
Survey of surface height (cm resolution)	2	Gallagher		
GPR Survey (200 m)	1	Gallagher		

NOTES:
LP Strike locations -

1. These transects can be measured with 100 m tape, and marked out initially using the popsicle sticks or other temporary marking. The transect lines should be marked at each end with flagged bamboo poles.
2. Strike locations should be at a progressively coarse resolution so that fine resolution measurements are made, but not overburdening the field crew.
3. Probe strikes in a line parallel/perpendicular to prevailing wind (and surface structure axes). Use variable spacing, out to 100-200 m.
4. Variable spacing should match expected surface structure changes (e.g. dunes/sastrugi, small hills, megadunes, etc...).
5. Transects begin at central snow pit.
6. Make multiple strikes at each of the coarse distance locations to assure data fidelity. This is not necessary for closely-spaced strikes.

Surface Height Survey

Gallagher will take a NIR drone survey of the surface and get relative surface height from the stereographic images. This is all that is needed at the beginning and end of the field season as long as the transects are in survey.

If drone survey does not happen for some reason: use the laser level/range finder to collect surface height changes along transects (wind parallel and wind perpendicular). Make a target with a bamboo post and a 'lambertian' reflective face. Put the laser level/rangefinder on a tripod at one end of the transect. Walk out the transect with target. Gently set target pole on snow surface and hit target center with range finder. Record distance and angle. Mark location with popsicle stick for subsequent Lyte probe survey.

Alternative procedure (or proc at Summit Station). Level the range finder on the tripod and aim along a transect. Make a big target on a bamboo pole. Walk one meter from the tripod and mark the location of the laser location on the target. This is your 'zero' point. As you move down the transect, measure the relative height change of the laser light on target for each location along the transect. This procedure will require less fidgeting with the tripod, but a larger target.

*Demob instructions:*Photo document the drifting around the instruments.

GPR Survey

We will want a GPR survey next to (or over) the transects where the Lyte Probe strikes have been performed. Reminders of details for data collection.

1. **Timing**: The field team will have to decide whether it is better to perform the Lyte Probe strikes first or the GPR survey. Mark the location after the first survey has been taken. *Decide where subsequent surveys will be taken before taking the first survey, and mark these out also!*

2. **Location**: It will be important to have enough information to co-locate the GPR with any other survey information like Lyte Probe strikes or surface height information. Ideally, co-location of measurements does not result in measuring disturbed snow in a way that would bias the measurement.

3. **Invasive/noninvasive**: Ideally the GPR will be on a system that does not disturb the snow. This will rely on the ingenuity of the field team to build a rig that safely and easily transports the GPR across the snow, without disturbing the snow surface too much. At a minimum, the GPR can be transported to a location and set on the snow surface (blocks or simply lightly on the snow surface).

4. **Melt water and heterogeneity**: Could be that there is a lot of melt in August. Could be also that the melt is heterogeneous. The GPR won't see past the first melt layer, but is there pooling lower down? If the surface is melting, we won't see it. One idea will be to do a GPR transect early in the morning when the surface has had a chance to refreeze (if it is indeed melting). Maybe try this?

Snow density measurements

FPGA density - Can only be made in dry snow! Otherwise, these tools measure snow LWC.

FPGA dens17 - Read manual for general use instructions. This instrument can be held against the vertical surface of the snow pit. Scrape the surface flat with a snow card or other appropriate implement. Use the clamp provided to hold the instrument in place.

FPGA dens4040 - Read manual for general use instructions. Insert this *vertically* into the snow. Use the 'dry wall saw' (pointy, short saw) to clear an appropriate slot. This measurement should be made with a different resolution than the FPGA-dens17.

Manual density - A few things to keep in mind.

1) keep the scale level. You can use the clineometer to make sure it is level.

2) For very hard snow, consolidated snow: cut out and measure a 'cube' volume, put in a whirlpak bag and weight this. Of course, you need to weigh the bag first.

3) Follow the SWAG instructions for everything else.

Liquid Water Content - combine with Density meas.

The *FPGA* instruments will measure LWC when present (and cannot accurately measure density when LWC is present). The LWC measurement requires a snow density estimate to start. Published methods for this include either done by getting a snow density when it is cold, using tools we don't have access to, or simply squeezing the snow with gloved hands and seeing what comes out (see SWAG for details). The first ignores mass loss due to percolation, the second we can't do, the third characterizes current snowpack but without real quantities.

Melt water content will be important for our project. So, combining some of these methods is what we will have to do.

Proc:

1) **Mass** a *dry*, *empty* whirlpak **bag**, **record**.
2) **Cut out** volume of **snow**, and put into **bag**.
3) **Mass** the **bag+snow**, **record**.
4) **Squeeze** out all **liquid water** possible **from bag** without warming the snow in bag.
5) **Mass** the **bag+snow** again, **record**.
6) **Compute snow density** with a phone-based field calculator, **record**.

This procedure will give an accurate lower limit to the LWC in the snow, as well as give us accurate snow/water density, and upper limit of 'dry snow' density.

After the snow (dry plus wet) density has been calculated, then you can use the FPGA instruments to determine LWC.

Isotope Sampling

To measure isotope content of snow in conjunction with the ICECAPS-MELT snowpit science work, follow this procedure.

1) **Mass** a *dry*, *empty* whirlpak **bag**, **record**. (I like to have the bags labeled ahead of time. Label with an ID number, rather than location/depth. This may change in the snow pit).
2) **Cut out** volume of **snow**, and put into **bag**. Seal the bag.
3) **Mass** the **bag+snow**, **record**.

Summit Station will predominantly be a dry snow situation. This procedure gets slightly more tricky if liquid water needs to be accounted for. Basically, don't lose any water in the procedure, but collect any water that gets squeezed out into another bag. Record what happened.

SLEIGH Installation Characterization

Three ideas for the SLEIGH installation characterization:
1. *Critical!* **Please measure the depth of the footers for the SLEIGH**. This is critical for estimating compaction between the base of the SLEIGH and the surface. If the measurement of surface height begins right after the footers and jack stands are in place, then we only need two of the measurements in **black** (bottom of postholes to surface **(2.)** , sensor measurement of height (**1.**). If the surface height measurements start after (> 1-2 days) the footers are set, please measure the **blue** heights (**3.**, **4.**). Then, when the surface height is being measured by the SLEIGH, please measure SLEIGH-to-surface (**5.**).

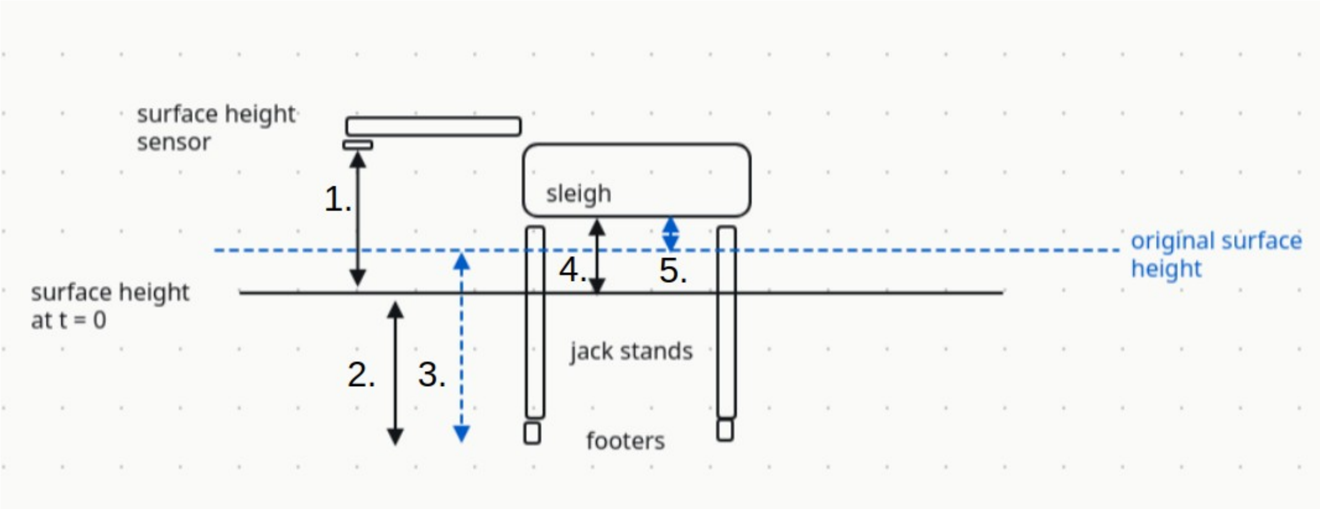

Figure 4. Illustration of measurements necessary for estimating the surface height change due to compaction between the footer of the height measurements and the surface.

The ultimate goal of all of this is to always know the depth of the bottom of the footers (measurements **2. or 3.** as a function of time). If this can be known in some other way continuously (e.g. GPR), then so much the better.

2. **Shade the area** to assess **solar bias** of **SIMBA temperatures**. This can happen at beginning or end of field season. I suggest during demob.

Suggestion: Shade the area several times, increasing the area each time so that we can estimate the time at which there would be zero heating by side-scattered light. Record the time of day when this happens. Please do it when the Solar downward flux sensor is operating.

SLEIGH Demob Characterization

1) Characterize the SLEIGH positioning (e.g., measure heights 1. and 4.).
2) **Shade the area** to assess **solar bias** of **SIMBA temperatures**. Suggestion: Shade the area several times, increasing the area each time so that we can estimate the time at which there would be zero heating by side-scattered light. Record the time of day when this happens. Please do it when the Solar downward flux sensor is operating.
3) **Final snow pit, lyte probe, and mobile GPR survey** of **area around** the **SLEIGH** after the SLEIGH is demobilized. If possible, set the SIMBA measurement frequency to every 1-2 min.