1. Introduction

Permafrost is ground that remains at or below 0°C for at least two consecutive years. The active layer is the upper layer of soil subject to annual thawing and freezing in areas underlain by permafrost. Active Layer Thickness (ALT) is the thickness of this thawing and freezing soil layer and is typically measured as the maximum depth of thaw at the end of the summer. The International Permafrost Association (IPA) formed the Global Terrestrial Network for Permafrost (GTN-P) to monitor permafrost [*Burgess et al*., 2000] (Figure 1). The GTN-P consists of the Thermal State of Permafrost (TSP) and the Circumpolar Active Layer Monitoring (CALM) networks. TSP measures permafrost temperature and CALM measures ALT, which are essential climate variables to monitor permafrost status [*Brown et al*., 2008]. TSP measures permafrost temperature using thermometers lowered into 860 boreholes that range in depth from 1-500 meters. The CALM network measures ALT at 168 stations using metal probes or buried temperature sensors [*Brown et al*., 2000; *Streletskiy et al*., 2008; *Shiklomanov et al*., 2010]. Despite impressive progress, there are still large gaps in the CALM network.

Figure 1: The Global Terrestrial Network for Permafrost (GTN-P) consists of the Thermal State of Permafrost (TSP) network which measures permafrost temperature and the Circumpolar Active Layer Monitoring (CALM) network which measures ALT. Permafrost temperature and ALT are essential climate variables to monitor the status of permafrost.

Here we describe standard protocols for ALT surveys to leverage data collected by research teams, government work crews, and land management teams independent of the CALM network. While neither continuous in time nor as rigorously surveyed as CALM sites, these data still represent a valuable source of ALT observations.

We focus on ALT survey protocols using a standard probe. An ALT measurement is a single probing of the active layer and a survey is a series of measurements at a single site following a predetermined spatial pattern. We exclude ALT measurements using buried temperature sensors, ground penetrating radar, or other remote sensing techniques.

The protocols apply to any research, but we emphasize calibration and validation of radar products. Pixel size varies between radar systems, but we assume a typical ~10x10 meter pixel. We define standard measurement format and metadata to simplify data collection and integration. We describe four ALT survey techniques of increasing complexity and time so individual teams can select one that meets their scientific needs within the time and manpower constraints of their field operations.

2. Probing Equipment

The standard tool to measure ALT is a metal rod with a handle called a probe (Figure 2). Other common names include 'frost probe,' 'ALT probe,' 'tile probe,' and 'active layer probe.' One should use stainless steel to prevent rusting, since the probe will remain continually wet in the saturated soils found in permafrost areas. We recommend a 1-meter length probe suitable for most situations. Some use probes as long as 1.5 or 2.0 meters for deep active layers. Graduated probes have distances engraved onto the rod to simplify measuring. Breakdown probes use come apart for easy shipping, with the pieces stored in the handle. The simplest probe is sharpened stainless steel rod welded to a stainless steel pipe.

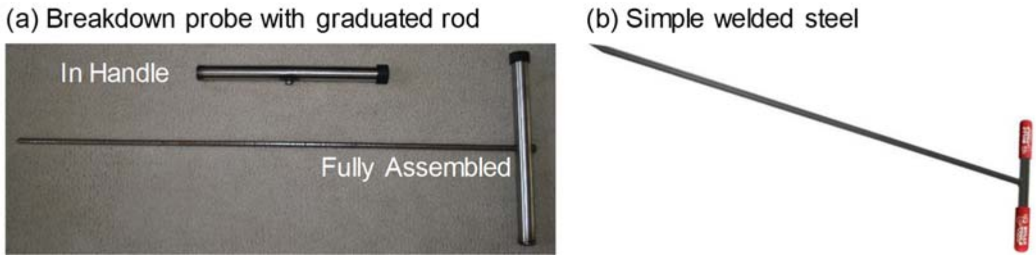

Figure 2: The most sophisticated probe consists of graduated metal rods that screw apart and fit in the handle for shipping (a). The simplest probe consists of a sharpened metal rod welded to a cross bar (b). Most probes are hand made in a machine shop and cost anywhere between \$50 and \$500, but one can buy the simple welded steel model at Home Depot for \$22.

ALT surveys also require a measuring tape, a Global Positioning System (GPS) unit, a 100 meter survey line, and a notebook to record data (Figure 3). We want to match the measurements to the correct pixel, so the GPS unit must be WAAS enabled and preferably Differential GPS (DGPS) to obtain accurate enough location information. Note that the GPS available in most cell phones is typically not accurate. The measuring tape is a standard, hand-held model available from any hardware store with metric units and a locking mechanism. We recommend a 100-meter retractable survey line to avoid tangling during use. The survey line itself should be plastic or fiberglass rather than paper, which falls apart after exposure to wet conditions. Hardware stores and online catalogs offer a variety of survey lines.

Figure 3: ALT surveys require a measuring tape with a lock (a), a WAAS enabled GPS unit (b), a 100 meter, retractable survey line (c).

3. Probing Technique

Probing to measure ALT is simple (Figure 4). We assume a typical 2-man team, with the worker making the probe measurements and the scribe writing them down. The worker pushes the probe into the active layer until it reaches permafrost, places the thumb at the surface, and pulls out the probe. The scribe then measures the penetration depth and writes it down. Probes typically cannot penetrate rocky ground and makes a 'ping' or scraping sound when encountering rock, rather than the 'thump' when hitting permafrost. If you encounter a rock, try again in a different spot. If you cannot find a spot without rocks, note this in the data log and move onto a new site.

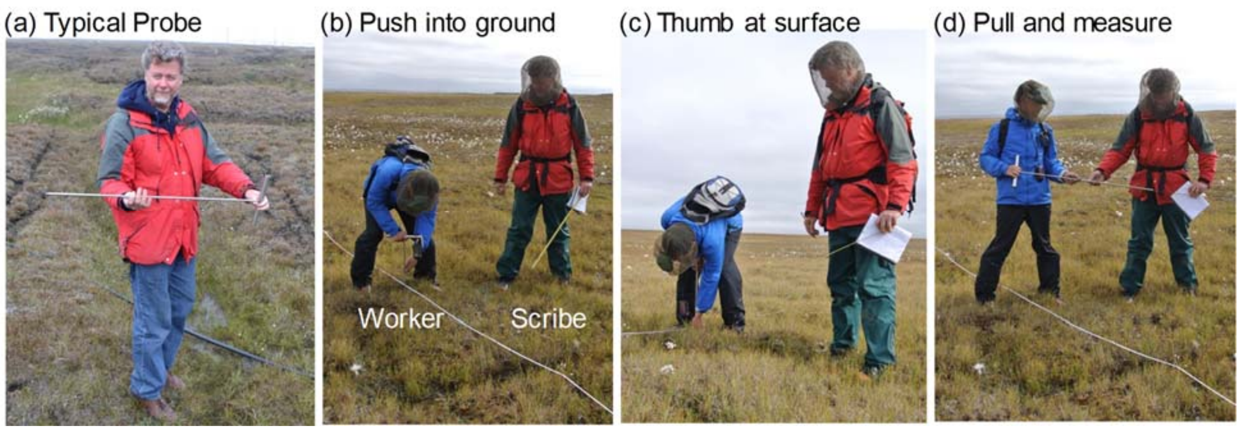

Figure 4: The active layer probe is a metal rod with a handle (a). To measure ALT, the worker pushes the probe into the ground to the permafrost layer (b), places a thumb on the metal rod at the ground surface (c), then pulls out the probe (d). The scribe measures the ALT with a tape measure and writes it down. Here, Lin Liu measures ALT along a survey line at Barrow, Alaska while Kevin Schaefer records the results in a notebook.

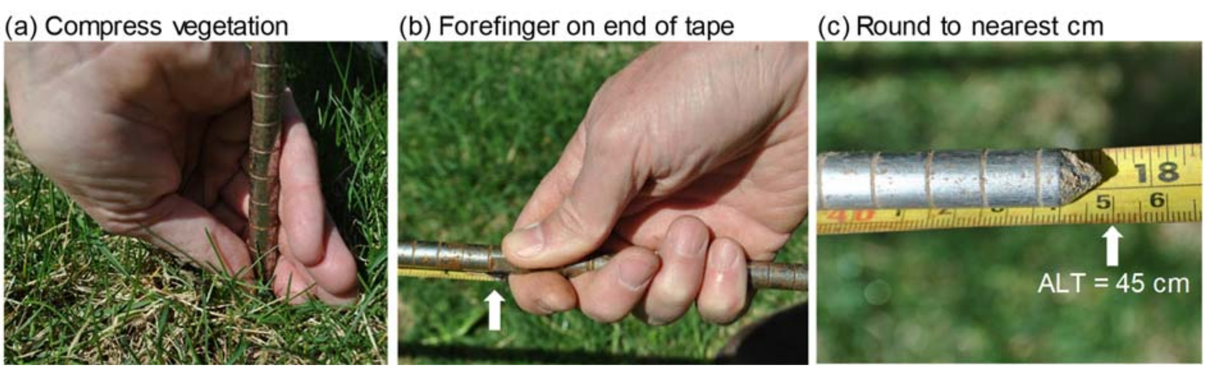

Figure 5: Grasp the rod and compress the vegetation with your thumb and forefinger to ensure you reach the soil surface (a). Lay the probe right on the measuring tape with your forefinger on the end (b). Round the ALT to the nearest whole centimeter value relative to the probe tip, 45 cm in this case (c).

You should compress the vegetation down to the soil surface with your thumb and forefinger (Figure 5). When probing in grass or woody shrubs, push the thumb down until you reach the soil surface. When probing in moss or lichen where dividing line between vegetation and soil becomes vague, push the thumb down you meet some resistance. When probing in standing water, a common occurrence in permafrost regions, place the thumb at the water surface. After pulling out the probe, place the rod onto the tape measure held by the scribe and read off the ALT, rounding to the nearest centimeter.

We estimate a single probe measurement has an accuracy of ±3 cm [*Schaefer et al*., 2014]. Some uncertainty results from the thickness of the transition layer at the permafrost table, which contains a mixture of ice and water. Rounding off to the nearest centimeter introduces an uncertainty of about ±0.5 cm. However, the bulk of the uncertainty results from errors in thumb placement. For example, vegetation like lichen will have spatially varying levels of compression during thumb placement, or the thumb may penetrate the surface of the standing water.

4. Site Selection and Survey Strategy

The ideal performance target of any remote sensing product is to match observations within uncertainty. Each pixel represents an area average value while a field observation represents a value at a single point. ALT varies widely in space, so ideally one should make many field measurements and use the statistical average to compare to the pixel value. The size of an individual pixel depends on the instrument and altitude, but we assume each pixel is 10x10 m^2. Based on statistical analysis of previous probe surveys, 20-30 probe measurements will give a robust, statistically significant average ALT to compare with a pixel [*Schaefer et al*., 2015].

The best strategy to evaluate radar data is to cover as many pixels as possible with field data. However, the time required to make 20-30 ALT measurements per pixel means the field team can cover only a certain number of pixels per day. The survey strategy then becomes a tradeoff between time and coverage. Sparsely placed measurements mean you can cover more pixels in a day, but the measurements are less representative of the area average of each pixel. Spatially dense measurements better represent the area average, but result in fewer pixels covered per day. Each of the techniques below include an estimate of the number of pixels per survey.

Please choose survey locations representative of local terrain and vegetation. Our field measurements will cover only a small fraction of the hundreds of thousands of pixels in each radar swath. A representative sample will provide better validation and calibration for the area-average measured in a typical remote sensing pixel. For example, the center of a polygon is more representative than the surrounding ice wedge. Try to avoid locations influenced by human infrastructure, within 100 meters of a road or building, for example, because these areas are not representative of the broader area covered by remote sensing data. We recognize team science objectives and other considerations may dictate the survey location.

5. Required Data and Metadata

Table 1 lists the data and metadata for all ALT surveys. This metadata ensures sufficient standardization to integrate data from multiple sites into a single dataset to evaluate radar data. We need to match the data to the appropriate pixel, which requires meter-level location accuracy, which means six significant digits for latitude and longitude. The number of ALT measurements and locations will vary depending on the survey technique. Knowing the survey technique allows us to assign uncertainty to the measurements. The worker and scribe names allows us to trace the measurement to an individual who could answer questions.

Table 1: Required data and metadata for each survey

Parameter	Type	Units	Comments
ALT	Required	cm	All probe measurements as specified by the survey technique
Average ALT	Optional	cm	The calculated average of the individual probing measurements
Distance	Required	m	Distance (Currently required only for the survey line technique)
Latitude	Required	Degree North	Decimal degree with 6 significant digits for all locations specified by the survey technique
Longitude	Required	Degree East	Decimal degree with 6 significant digits for all locations specified by the survey technique
Survey Name	Required	Text	A unique name or code number for each survey
Point Name	Required	Text	A unique code for each point in the survey of the form RRRR_YYMMDD_NN, where RRRR is the survey name, YY is year, MM is month, DD is day, and NN is the point number.
Survey Technique	Required	Text	The name of the survey technique used
Vegetation	Optional	Text	General vegetation category (moss, lichen, sedge, etc.)
Date	Required	MM/DD/YYY	Date the measurement was taken
Time	Required	HH:MM	Local time of day that the measurement was taken using military 24-hour clock
Team Name	Required	Text	Name of team or project making the measurement
Worker Name(s)	Required	Text	Full name(s) of all workers making probe measurements
Scribe Name	Required	Text	Full name of the individual recording the data
Scribe Email	Required	Text	Email address of the individual recording the data

6. Survey Techniques

Table 1 lists ALT survey techniques we selected in order of increasing time required to do them. The time estimates assume a 2-man team, a worker to make the probe measurement and a scribe to write them down. The descriptions include variants and the estimated impact on time, such as a 3-man team with two workers simultaneously making probe measurements. The time estimates do not include travel to and from the selected survey location.

Table 1: summary of ALT surveys

Survey	Time	Description	Equipment
Single Point	10 min	Single location in research site	Probe, GPS, tape measure
Multi-Point Transect	90 min km^{-1}	Multiple locations along a path	Probe, GPS, tape measure, 10-meter rope
Survey Line	60 min	Every meter on a straight line for a 100 meters	Probe, GPS, tape measure, survey line
Square Random Walk	60 min	30 measurements in a 10x10 meter square	Probe, GPS, tape measure, survey line

We based the protocols on widely-used techniques to survey ALT, but make no attempt to include all techniques in the published literature. For example, the Survey Line came from previous efforts to evaluate radar remote sensing products and we adapted the Square Random Walk from the existing CALM protocol. However, we exclude the CALM 1 km grid survey because it takes eight hours to execute, making it impractical for most field teams. We want a limited number of standard survey techniques that any field team could quickly and easily use.

The best time to measure ALT is near the end of the thaw season so that the probe depth approximates the maximum thaw depth, typically late August or early September. We have a forward model of thaw as a function of time, so any measurements of thaw depth is useful. Thaw depth as a function of time for a single season or ALT for multiple seasons is especially useful. If you plan to return to make multiple measurements over time at the same location, we recommend marking the spot with a metal flag with a bright plastic flag attached.

5.1 Single Point

Description: measure ALT at a single location in research site. One should use this technique when you have little time available.

Time: 5 minutes

Number of Pixels: 1

Number of people: 2, a worker to probe, a scribe to measure and record

Equipment: Probe, GPS, tape measure

Procedure:

1) Choose the location.
2) Record the required metadata (survey name, location, date, etc., as specified in Table 1).
3) Make 3-5, randomly-placed probe measurements within a 0.5 meter radius circle around the GPS measurement. The official measurement of ALT at this point is the average of these individual measurements.

Options:

Single Person (add 5 minutes). One person can do the survey if the rest of the team is occupied. A graduated probe with engraved distances makes this easy, but if one does not have a graduated probe, lay the measuring tape on the ground first and then make the probe measurement.

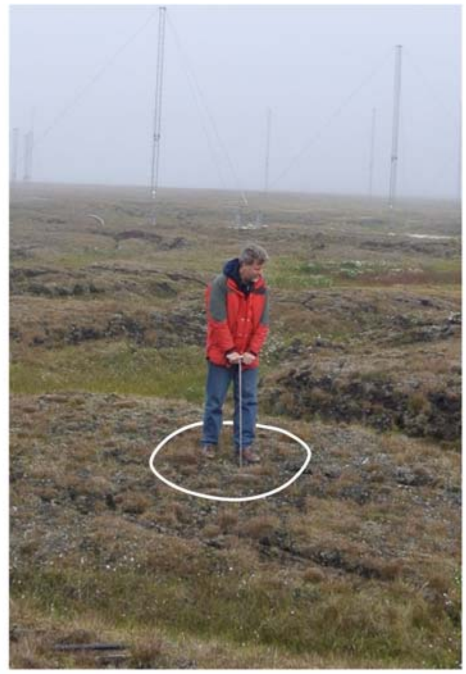

Figure 5: For a Single Point Survey, make 3-5 probe measurements within a radius of 0.5 meters around the GPS location (Barrow, 2013).

5.2 Multi-Point Transect

Description: measure ALT at multiple points along a path with a spacing of ~10 meters. The 10-meter spacing ensures each point lies in a separate pixel. Each point follows the procedures described above for a single point. This survey is very flexible because it requires minimal setup and one can adjust the number of points to fit within the time available. *This is the recommended survey for any team that wants to provide validation data for ABoVE radar products*.

Time: 2 minutes per point; ~30 points per hour.

Number of Pixels: variable depending on time, but ~30 pixels per hour, assuming 10 meters between points.

Number of people: 2, a worker to probe, a scribe to measure and record

Equipment: Probe, GPS, tape measure

Procedure:

1) Choose the location.
2) Record the required metadata. To save time, only record metadata that changes between points: point ID, latitude, and longitude. If you have a GPS unit that records location, only write the GPS point number.
3) Make 3-5, randomly-placed probe measurements within a one-meter circle of the GPS measurement. The official measurement of ALT is the average of these measurements.
4) Go to the next location.

Figure 6: For a Multi-Point Survey, make repeat single point measurements along a path with a spacing of about 10 meters (Toolik Lake, 2015). The path should be a straight line or a loop crossing as many different land units as possible. We do not recommend a grid pattern because it takes so long to set up with minimal benefit for validating radar data. Every point counts. Even a short transect of only 2-3 points can provide valuable validation data.

5.3 Survey Line

Description: probe every meter in a straight line for 100 meters. Use this technique when you want to evaluate spatial variability across multiple landscape units, across multiple polygons, for example. This technique is especially useful in evaluating remote sensing data, since the line will cross at least 10 pixels.

Time: 60 minutes, 15 minutes to set up the survey line and 45 minutes to make the probe measurements.

Number of Pixels: 10

Number of people: 2, a worker to probe, a scribe to measure and record

Equipment: Probe, GPS, tape measure, survey line

Procedure:

1) Lay out the survey line. Make the line as straight as possible so that we can interpolate the distances to get latitude and longitude. If you plan to return, mark the ends and the middle with a metal stake and flag.
2) Record the required metadata. Record the latitude and longitude of both ends and the middle. Errors in the GPS coordinates sometimes results in a ‘curvy’ line that may not result in 100 meters when projected onto the globe, even though we know with absolute certainty the line is 100 meters long. The three points provide a correction capability.
3) Make one probe measurement every meter and record the distance and value. Include both the zero and 100 meter marks for a total of 101 points. A single probe measurement per meter represents a random statistical sampling of ALT along the survey line sufficient to capture the spatial mean and variability.

Options:

Two workers probing (subtract 15 minutes). Two workers probing and one scribe recording speeds things up considerably.

Record vegetation (add 15-20 minutes). The exact time required depends on the technique you choose. Record vegetation every meter, coincident with the probing data. Also record the start and end of major features, such as the location of ice wedges.

Probe every 50 cm or less (add 20 minutes for every 100 probes). Sometimes one needs higher resolution.

5.4 Square Random Walk

Description: make 30 randomly-placed probe measurements in a 10x10 meter square. Statistical analysis of previous measurements indicate 30 probe measurements can accurately capture the area mean and variability. Use this when you want a statistical sampling of spatial variability, but the exact location of each probe measurement is not important. This technique represents 1-4 pixels, depending on the overlap.

Time: 60 minutes, 15 minutes to set up the survey line and 45 minutes to make the probe measurements.

Number of Pixels: 1-4, depending on overlap

Equipment: Probe, GPS, tape measure, survey line

Procedure:

1) Lay out the survey line in a 10-meter square. Pull out the survey line for 10 meters. Then have someone stand on the 10-meter mark to keep it stationary and turn 90 degrees to the right and walk another 10 meters. Then have someone stand on the 20-meter mark and turn to the right another 90 degrees. Once you practice this, it takes about 15 minutes to set up. If you plan to return to the location, mark the corners with metal stakes with flags. For our purposes, the square does not have to be perfect, but if you want an exact square, use a compass to align the sides.
2) Record the required metadata. Record only the latitude and longitude of all four corners and the rough center rather than every probe location. Use only one site name.
3) Randomly walk within the square and record 30 probe measurements. Try to make the probe measurements evenly spaced around the square.

Options:

Two or three workers probing (subtract 15 minutes). Multiple workers probing and one recording can speed things up considerably.