PERMAFROST REQUIREMENTS
Outline

- What is permafrost?
- How is it measured? Networks, projects ...
- Regions of interest
- Parameters of interest with respect to satellite data
- Requirements
- Suggestions regarding SAR
- Requirements summary with respect to current missions
Permafrost is an Essential Climate Variable
About 25% of the land surface is underlain by permafrost
Defined by temperature (at least two years with <0°C)

Permafrost extent
Soil temperature profiles
Active layer thickness

Further related properties of interest are:
- thickness of permafrost
- spatial patchiness of permafrost
- ground ice content
Changing permafrost

- Ground thermal regime changes due to
  - Changes in air temperature and/or precipitation
  - Surface disturbances
    - Clearing of vegetation
    - Removal of insulating organic layer
    - Forest fires
    - River channel migration
    - Shoreline erosion

- Response to climate change depends on variations in local seasonal factors
  - Snow cover
  - Vegetation
  - Surficial material
  - Moisture content
  - Drainage
Current WMO OSCAR data base requirements specifications

Requirements defined for Permafrost (2)

This table shows all related requirements. For more operations/filtering, please consult the full list of Requirements.

Note: In reading the values, goal is marked blue, breakthrough, yellow, and threshold orange.

<table>
<thead>
<tr>
<th>Id</th>
<th>Variable</th>
<th>Layer</th>
<th>App Area</th>
<th>Uncertainty</th>
<th>Stability / decade</th>
<th>Hor Res</th>
<th>Ver Res</th>
<th>Obs Cyc</th>
<th>Timeliness</th>
<th>Coverage</th>
<th>Conf Level</th>
<th>Val Date</th>
<th>Source</th>
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</thead>
<tbody>
<tr>
<td>401</td>
<td>Permafrost</td>
<td>Land surface</td>
<td>Hydrology</td>
<td>6.5</td>
<td>25</td>
<td>0.1 km</td>
<td>1 km</td>
<td>6 h</td>
<td>6 h</td>
<td>6 h</td>
<td>Global land</td>
<td>2003-10-20</td>
<td>ODRRGS</td>
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<tr>
<td>472</td>
<td>Permafrost</td>
<td>Land surface</td>
<td>Climate-TOPOC</td>
<td>6.7.10</td>
<td>10</td>
<td>0.25 km</td>
<td>0.35 km</td>
<td>24 h</td>
<td>24 h</td>
<td>24 h</td>
<td>Global land</td>
<td>firm</td>
<td>2007-07-19</td>
</tr>
</tbody>
</table>

- Too coarse for hazards
- Timeliness?
Active layer monitoring

CALM Sites
- Grids
- Thaw Tubes
- Ground Temperature

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In-situ measurements

- GTN-P / CALM (IPA – International Permafrost Association)
- Global Cryosphere Watch
Projects I

ESA DUE Permafrost
GTNP-DUE-PAGE21 connection

Remote sensing product validation within service setup time frame

Arctic Portal
Time series for selected GTN-P monitoring sites - LST, Soil moisture and surface status

Artic Portal/GTN-P/PAGE21 sites borehole management system

DUE Permafrost data (LST, SSM) as metadata
Projects II

- NASA Above (Alaska, Canada)
- ADAPT (Canada)
- DEFROST (Skandinavien)
- Plus national interests
- Definition of cold spots, general and reduced requirements
- General observation requirements:
- Reduced [extent] observation requirements:
- Science mission requirements:
- All regions underlain by permafrost
- Transects across permafrost zones as well as arctic coasts
- acquisitions with higher resolution modes over long term *in situ* monitoring sites (‘cold’ spots).
Southern/northern PSTG extent?

Coastal change rate (source AWI)
- stable or aggrading
- 0.1 - 1 m
- 1 - 2 m
- 2 - 10 m

Permafrost extent (source NSIDC)
- C
- D
- I
- L
- S

Available as:
- KML, KMZ
- Meta information as excel-sheet
Meta-Information for 48 Cold spots

- Coordinates (extent)
- Monitoring activities (projects, permafrost features, GTN-P & CALM IDs)
- Terrain and vegetation

FAQ

- Why only small areas and not e.g. entire Lena Delta?
- Southern limit of PSTG?
- Swath aligned polygons?
Complementing in-situ measurements?
Filling gaps?

GTN-P
- Permafrost temperature
- Active layer depth

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Changing permafrost

- Ground thermal regime changes due to
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![Diagram of database and numerical model of heat transfer](image)
Observable surface parameters

- Land Surface Temperature, status (frozen/unfrozen)
- Landcover (classes?) & Disturbances
- Snow properties
- Soil moisture (near surface)
- Terrain
Surface expressions and terrain changes

Source: C. Duguay, ESA DUE
Permafrost Tutorial 2010
Observable indicators
Subsidence - active layer properties

North Slope (Alaska), TerraSAR-X

Summer 2010
/reference point on floodplain

GAMMA REMOTE SENSING
Observable indicators
Subsidence – active layer properties

North Slope (Alaska), TerraSAR-X

Summer 2011
reference point on floodplain

GAMMA REMOTE SENSING

-3 cm +3
Requirement documents after IGOS 2007

- 2009 workshop and survey
- 2014 national workshop report (NRC)

**BOX 2.1**

**Important Permafrost and Related Ecological Variables to Measure with Remote Sensing**

- Active layer thickness
- Ground ice (volume and morphology)
- Snow characteristics (extent, water equivalent, depth, density, conductivity)
- Surface topography (static, macro-, and micro-)
- Longer-term surface subsidence
- Thermokarst distribution
- Surface water bodies (including dynamics, redistribution)
- Surficial geology-terrain units (including lithology, bedrock)
- Soil organic layer (thickness, moisture, conductivity)
- Land cover (including spectral vegetation indices)
- Vegetation structure and composition
- Methane (flux or concentration)
- Water vapor flux
- Carbon dioxide (flux or concentration)
- Land surface (skin) temperature
- Subsurface soil temperature
- Seasonal heave/subsidence
- Soil moisture
- Biomass (above ground)
White paper

- Observational requirements and recommendations for landsurface changes including geohazards assessment
  - Subsidence and thermokarst
  - Rock glacier and landslides
  - Coastal erosion
  - Thaw lakes and wetlands
- Comments on models (various spheres): forcing, constraining
  - Land surface modelling
  - Permafrost modelling
  - Consistency of the satellite-derived and simulated variables
- Comments on assessments of ecosystems, carbon pools and fluxes in permafrost regions
- Metadata for GTN-P
- WMO PSTG SAR group – specific recommendations and comments
- Preliminary requirements summary with respect to current missions
Satellite data should be utilized to

- identify **hot spots** of surface change and thus advice on extension of *in-situ* monitoring networks;
- support modelling of sub-surface conditions;
- provide higher resolution (spatial and temporal) measurements in the proximity of long-term in-situ monitoring sites; and
- place the *in-situ* measurements into a wider spatial and temporal context.
Observational requirements and recommendations for landsurface changes including geohazards assessment

- Subsidence and thermokarst
  - InSAR for long-term surface subsidence due to permafrost thaw, annual frost heave/thaw settlement of the active layer, or rapid mass wasting due to thermoerosion (gullies) and thermo-abrasion (coasts, streams).

Requirements summary: high-resolution (10-20 m), single (HH or VV) or dual polarization SAR data; less than two weeks intervals for seasonal subsidence analyses in case of X- and C-Band; interannual analyses possible with L-band (but constrained by ionospheric effects); DEM for removal of topographic phase and geocoding (30 m posting, 2 m relative height accuracy for flat terrain). Very high resolution (< 10 m) SAR (C-band and L-band) and DEM data (5 m posting, 0.5 m relative height accuracy for rough terrain) for thermokarst deformation.
Observational requirements and recommendations for landsurface changes including geohazards assessment

- Coastal erosion
  - displacement of the land/water boundary, on an intermediate level thaw slumps occur locally.
  - Along large parts of the arctic coasts erosion rates range between 1 - 10 m per year

Requirements summary: Annual coverage during ice-free period of all active arctic coastal areas and selected lake-rich areas with high (1m) to medium resolution (10-20m) satellite optical data and single-polarization, very-high resolution SAR data (HH (or VV)). For highly active areas, coverage is required at a less than two weeks interval with optical and SAR data. Exposition of slopes and looking direction need to be taken into consideration.
Observational requirements and recommendations for landsurface changes including geohazards assessment

- Rock glacier and landslides
  - time series of interferograms with seasonal, annual or pluriannual repeat rates could reveal changes in movement rates, which can be related to climatic changes (e.g. through changes in ground ice temperature or water percolation), and reveal slower rates of movements (on the order of magnitude of mm/year).

**Requirements summary**: Very high-resolution (3-10 m), single polarization (HH or VV) SAR data; repeat X-, C-, or L-band data with temporal baseline of a few weeks in maximum during summer and autumn; repeat of acquisition pattern on an annual base; good quality DEM for removal of topographic phase (<5 m posting, 0.5 m relative height accuracy for rough terrain).
Observational requirements and recommendations for landsurface changes including geohazards assessment

- **Thaw lakes and wetlands**
  - Current global land cover datasets cannot capture tundra lakes since a significant proportion of lakes and ponds in tundra regions have an extent below 200 m, many even below 30m.
  - Lake ice may freeze to the bottom of such lakes and prevent the formation of thawed zones under lakes, whereas lakes that do not freeze to the bottom will develop perennially thawed zones.
  - Thermokarst lake ice has been demonstrated to capture methane ebullition from thawing permafrost under lakes.
  - Sediment influx and redistribution: water colour, measurements of lateral erosion along thermokarst lake shores.
  - Open water and emerging vegetation.

**Requirements summary:** SAR data (HH and combination of H and V) with better than 30m resolution and weekly intervals. High-spatial resolution multispectral satellite data (min. 5 (for thermokarst lakes) - 20 m; optimum 1 m, weekly resolution) are needed to monitor turbidity events and changes in lake colour. High spatial resolution imagery (panchromatic) (<1m) in annual intervals to quantify thermokarst lake expansion.
Comments on models (various spheres): forcing, constraining and evaluation

- The required parameter accuracy of the temperature product is high around the freezing point: ~0.1°C, and 1°C when far from the freezing point.
- Parameter accuracy for ‘soil moisture’ should be 5 to 10% of the volumetric water content.
- Land cover (differentiation between mosses, shrubs, sedges and cryptogam crusts), topography and snow coverage provide the boundary conditions.
- Permafrost modelling Requirements summary: weekly to monthly averages of land surface temperature and snow water equivalent (resolution see TOPC requirements). Better than weekly surface status from SAR (C or L-band) at similar spatial resolution like thermal data (ca. 1km). Snow parameters - separate white paper.
Consistency of the satellite-derived and simulated variables

- The satellite-derived albedo products, normalized to mid-day clear-sky, are not consistent with the simulated model albedo at a respective time node that is calculated throughout the whole spatial domain with all sky conditions.
- Meta data on the number of feasible acquisitions / pixel are lacking in the available satellite products for LST and albedo to correctly simulate clear-sky LST and clear-sky albedo in the models.
- Also a rigorous assessment of the random and systematic errors of satellite products is needed for high-latitude permafrost landscapes.
- At the high latitudes north of 70°N, the spatial grid nodes are not consistent for satellite products in sinusoidal projection formats: the gridding processing for the sinusoidal projection that is inherent to all MODIS-derived products (e.g., albedo, LST, vegetation products and many more) causes a minimum of 10 % percent data loss.
- Even if there is < 15 % vascular plant cover, there is 100 % moss cover underneath/ not 75 % open soil as currently defined in global landcover datasets.
## WMO PSTG SAR group – specific recommendations and comments

<table>
<thead>
<tr>
<th>Mission</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sentinel-1</td>
<td>Coastal regions which are covered due to the objective of sea ice monitoring are mostly located within continuous permafrost. It is however crucial to have discontinuous permafrost zones covered as well. Modes will be IW and EW, where IW would be preferred for permafrost applications. The foreseen HH-HV or HH polarization for the monitoring of polar environments would be also applicable for land surface hydrology monitoring over permafrost.</td>
</tr>
<tr>
<td>ALOS-2 Palsar</td>
<td>ALOS-2 PALSAR acquisitions are foreseen over two of the reduced observation requirement transects (Alaska, Western Siberia) where permafrost changes are reported. The defined areas cover all permafrost zones.</td>
</tr>
<tr>
<td>TerraSAR-X</td>
<td>Continuous acquisitions are available for selected ground monitoring sites (cold spots – science missions requirements) since 2013. The TanDEM-X lake mask which is produced as side product would be of value for regional analyses of permafrost regions, but does however not include repeated surveys. Polar region DEMs are mostly based on winter acquisitions, which introduces elevation offsets due to snow cover.</td>
</tr>
<tr>
<td>Radarsat-2</td>
<td>Continuous acquisitions are available for selected ground monitoring sites, mainly in Canada. Coastal regions which are covered due to the objective of sea ice monitoring are mostly located within continuous permafrost, but acquisitions are at lower spatial resolution.</td>
</tr>
</tbody>
</table>
### WMO PSTG SAR group – specific recommendations and comments

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Spatial res.</th>
<th>Temporal res.</th>
<th>Band</th>
<th>Polarization</th>
<th>Comment</th>
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<tr>
<td>Subsidence</td>
<td>10-20 m</td>
<td>Bi-weekly during snow free season</td>
<td>L, C, X</td>
<td>Single (HH or VV)</td>
<td>InSAR</td>
</tr>
<tr>
<td>Rock glaciers</td>
<td>3-10 m</td>
<td>Bi-weekly during snow free season</td>
<td>L, C, X</td>
<td>Single (HH or VV)</td>
<td>InSAR</td>
</tr>
<tr>
<td>Surface status</td>
<td>&lt; 30 m</td>
<td>Better than weekly, shoulder seasons</td>
<td>L, C, X</td>
<td>any</td>
<td></td>
</tr>
<tr>
<td>Wetlands and lakes</td>
<td>&lt; 30 m</td>
<td>Weekly, shoulder and snow free seasons</td>
<td>L, C, X</td>
<td>HH plus HV/VH, HH/VV or quad</td>
<td></td>
</tr>
<tr>
<td>Coastal erosion</td>
<td>1 m</td>
<td>Annually during the ice and snow free season</td>
<td>L, C, X</td>
<td>Single (HH or VV)</td>
<td>Be-weekly for highly active areas (figure 3)</td>
</tr>
<tr>
<td>Lake depth and thawed zone characteristics</td>
<td>1-30 m</td>
<td>Weekly during winter</td>
<td>C, X</td>
<td>Single (HH or VV)</td>
<td>Detecting whether lakes have grounded or floating ice; indication of thermokarst activity under lakes</td>
</tr>
<tr>
<td>Methane emissions from lakes</td>
<td>1-20 m</td>
<td>Weekly during should seasons (freeze-up, ice-out)</td>
<td>L, C</td>
<td>Single (HH or VV), HH/VV, quadpol</td>
<td>Quantification of methane ebullition bubbles</td>
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**requirements summary with respect to current missions**

<table>
<thead>
<tr>
<th>Level</th>
<th>Specifications</th>
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<tbody>
<tr>
<td><strong>Science</strong></td>
<td>○ bi-weekly SAR acquisitions of all 'cold spots' for InSAR applications</td>
</tr>
<tr>
<td></td>
<td>○ annual high resolution optical (&lt;1m) acquisitions of all 'cold spots' (July-August)</td>
</tr>
<tr>
<td><strong>Reduced to General</strong></td>
<td>○ bi-annual (early and late summer) high (&lt;1m pan, &lt;5m ms) to medium resolution (&lt;30m ms) optical and SAR of all monitoring transects for landcover applications</td>
</tr>
<tr>
<td></td>
<td>○ once per year high resolution SAR and optical acquisitions of arctic coastline (high activity areas) in consistent polarization and frequency, and orbit (with differentiation between actual exposition of slope)</td>
</tr>
<tr>
<td></td>
<td>○ annual coverage of all rock glacier-characterized regions with high-resolution optical (1 good image) and SAR (2-3 cycles for interferometry) for general inventory and hot spot identification</td>
</tr>
<tr>
<td></td>
<td>○ annual circumpolar lake inventory (&lt;30m) in thermokarst dominated lowland regions (with time stamp for each pixel in case of higher level product, consistent frequency and resolution)</td>
</tr>
<tr>
<td></td>
<td>○ annual lake ice status for monitoring transects (grounded versus floating ice)</td>
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</table>