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Seasonal and annual dynamics of frozen ground at a mountain permafrost site in the Italian Alps detected by spectral induced polarization

Theresa Maierhofer[1,2], Jonas K. Limbrock[4], Timea Katona[1], Elisabetta Drigo[3], Christin Hilbich[2], Umberto Morra Di Cella[3], Andreas Kemna[4], Christian Hauck[2], and Adrian Flores-Orozco[1]
[1]Department of Geodesy and Geoinformation, TU-Wien, Austria (theresa.maierhofer@tuwien.ac.at)
[2]Department of Geosciences, University of Fribourg, Switzerland
[3]ARPA (Agenzia Regionale per la Protezione dell'Ambiente), Aosta valley, Italy
[4]Institute of Geosciences, Geophysics Section, University of Bonn, Germany

Warming of permafrost regions with an associated increase in subsurface temperatures has been reported worldwide. Thus, long-term monitoring of the thermal state of permafrost and the associated ground ice contents has become an essential task also for the European Alps. Geophysical methods have proven to be well-suited to support and interconnect spatially sparse borehole data and investigate the distribution and temporal evolution of permafrost. In particular, electrical resistivity tomography (ERT) is a widely applied technique for permafrost characterization, commonly associated with a significant increase in the electrical resistivity upon freezing. However, air is also characterized by high electrical resistivity values complicating the interpretation of ERT results. Recent studies have revealed that the spectral induced polarization (SIP) response of frozen rocks is affected by the temperature-dependent polarization behaviour of ice at higher frequencies. Thus, the SIP or complex resistivity method offers potential for an improved characterization of permafrost sites.

We here present SIP imaging results conducted over a broad range of frequencies (0.1-225 Hz) at an operational long-term permafrost monitoring site covering a period of one and a half years. The selected study area Cervinia Cime Bianche (Italian Alps) is situated at an elevation of ~3100m and provides comprehensive geophysical, borehole temperature and water content data for validation. Shielded cables and an adequate measuring protocol were deployed to minimize the electromagnetic coupling in the SIP data. Data were collected as normal and reciprocal pairs for the quantification of data error, and we developed an analysis scheme for data quality that considers changes in time and in the frequency to remove spatial and temporal outliers and erroneous measurements. To understand the temperature dependence of the polarization response, we compare our field results with SIP laboratory measurements on water-saturated rock samples, collected in close proximity to the monitoring profile, in a frequency range of 10 mHz to 45 kHz during controlled freeze-thaw cycles (+20°C to -40°C).

Our field results show clear seasonal changes in the complex resistivity images. Resistivity

magnitude shows an increase in winter and decrease in summer throughout the image plane, with most prominent changes at shallow depths, where also resistivity phase shows distinctly increased (absolute) values in winter for frequencies above 10 Hz. This region coincides with the active layer as monitored by borehole temperature logging, suggesting that especially the polarization response is indicative of the seasonal freezing and thawing of the ground. This interpretation is confirmed by the laboratory measurements on the rock samples from the site, which upon freezing and thawing exhibit an absolute phase increase with decreasing temperature at higher frequencies (above 10 Hz for temperatures down to -10°C), with the general spectral behaviour being consistent with the known polarization properties of ice. We conclude that with appropriate measurement and processing procedures, the characteristic dependence of the SIP response of frozen rocks on temperature, and thus ice content, can be utilized in field surveys for an improved assessment of thermal state and ice content at permafrost sites.