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Three methods for observing firn densification velocities with phase-sensitive radar

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Firn densification operates at the boundary between the atmosphere and ice sheets, impacting estimates of ice thickness change, paleoclimate reconstructions, and near-surface hydrology. Direct measurements of firn densification are scarce and firn densification models, which rely mostly on point measurements of density, disagree on the impact of environmental factors like surface temperature and accumulation rate. Phase-sensitive radar systems (pRES) can observe the movement of isochronal layers in firn and ice by tracking the relative two-way travel times (T) of radio waves. In this work, we demonstrate three methods for extracting measurements of densification velocities from pRES data. Method one uses independently measured firn densities to derive compaction velocities. Method two derives vertical velocities in the firn from an inversion that assumes a steady state and exponential density profile. Method three models changes in T using a semi-physical densification model and compares these changes to the pRES observations. We apply each method to radar data from three ice rises in the Weddell Sea Sector of West Antarctica. Results demonstrate how pRES can be used to explore the accumulation dependence of steady-state densification rates. Average accumulation rate is estimated from pRES measurements in areas that are approximately in steady state. Accumulation gradients can be seen across divides (Korff Ice Rise) and densification-rate differences are observed between relatively high (Fletcher Promontory) and low (Skytrain Ice Rise) accumulation environments. With minimal logistic requirements, new pRES systems like autonomous pRES could be inexpensively deployed to monitor firn densification. Furthermore, existing data may contain densification information even in cases when its deployment primarily targeted other processes.