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Resolving radiostratigraphy with squinted synthetic aperture radar focusing

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Abstract

Englacial layers are a product of historic accumulation and are reshaped by ice deformation. Hence, radio-echo sounding (RES), which can resolve englacial layering, has been adopted as an observational tool to infer ice age and ice dynamics from ice stratigraphy. However, the commonly applied synthetic aperture radar focusing algorithms, used to improve image resolution, are either i) incoherent or ii) optimized for the ice-bed interface. Dipping specular reflectors, such as englacial layers, are then lost during focusing. Instead, we focus the RES measurements using subapertures, synthetically squinting the radar beam toward orthogonal incidence for every dipping layer. We then either recombine all subapertures or reject those with low signal to generate an image that resolves all englacial targets together. We apply these methods to both along- and across-flow RES images at Academy Glacier, East Antarctica, which has significant englacial layer relief, especially perpendicular to the ice-flow direction. Our method significantly elevates signal power for dipping englacial layers (>15 dB), and quantifiably improves layer continuity compared to other processed data products. This squinted focusing approach enables novel studies of ice deformation (as recorded in englacial layering) in the presence of complex basal topography and heterogeneous substrate properties.

1. Introduction

Radio-echo sounding (RES) is commonly used to survey glaciers and ice sheets (e.g., Schroeder and others, 2020), with the predominant target being the ice-bed interface to provide an estimate of the total ice-sheet volume (e.g., Pritchard and others, 2025). Additional information is preserved within the ice column, where contrasts in conductivity or permittivity, typically associated with changes in the ice impurity content (Gudmandsen, 1975; Eisen and others, 2003) or crystal orientation fabric (Fujita and others, 1999; Gerber and others, 2025), create englacial reflections. Some of these englacial layers are horizontal and smooth relative to the transmitted radar wavelength because they were deposited uniformly as continuous horizons and buried over time, and together the continuous englacial layers form a stratified set of coherent reflections comprising the ‘radiostratigraphy’ (MacGregor and others, 2015). Smooth layers create specular radar reflections, where most energy is reflected at the incident angle. In the case of a highly specular horizontal layer and a nadir-looking radar, all the reflected energy is directed back to the receiver. For this reason, the relatively flat near-surface layers in the accumulation area of an ice sheet are extraordinarily well resolved and can be connected over 100s of km between ice cores (e.g., Cavitte and others, 2021; Bingham and others, 2025).

In other glacier settings, layers are not flat; for example, near the glacier bed, layers can conform to the bed topography, even in high-relief regions (e.g., Hudleston, 2015). In highly dynamic areas, layers may not be flat nor conform to the bed. Layers can be distorted by ice flow (e.g., Jacobel and others, 1993; Holschuh and others, 2017) or mass exchange at the bed (e.g., Bell and others, 2011; Jordan and others, 2018), and they can therefore preserve a history of paleo ice dynamics (e.g., Conway and others, 2002; Siegert and others, 2013). In any case, layer dips can be much steeper compared to the flat ice-sheet surface. Then, a dipping specular layer may be resolvable only by an off-nadir propagating wave, orthogonal to the layer dip. For this reason, received radar power is often diminished for dipping layers (Holschuh and others, 2014), sometimes generating anomalous vertical features within the RES image which have been called ‘tornadoes’ or ‘whirlwinds’ (Karlsson and others, 2009; Winter and others, 2015) (Fig. 1).

RES antennas have a small *real* aperture, meaning that the real beam width is large and some portion of the radar wave is directed off nadir (Heister and Scheiber, 2018). It is therefore



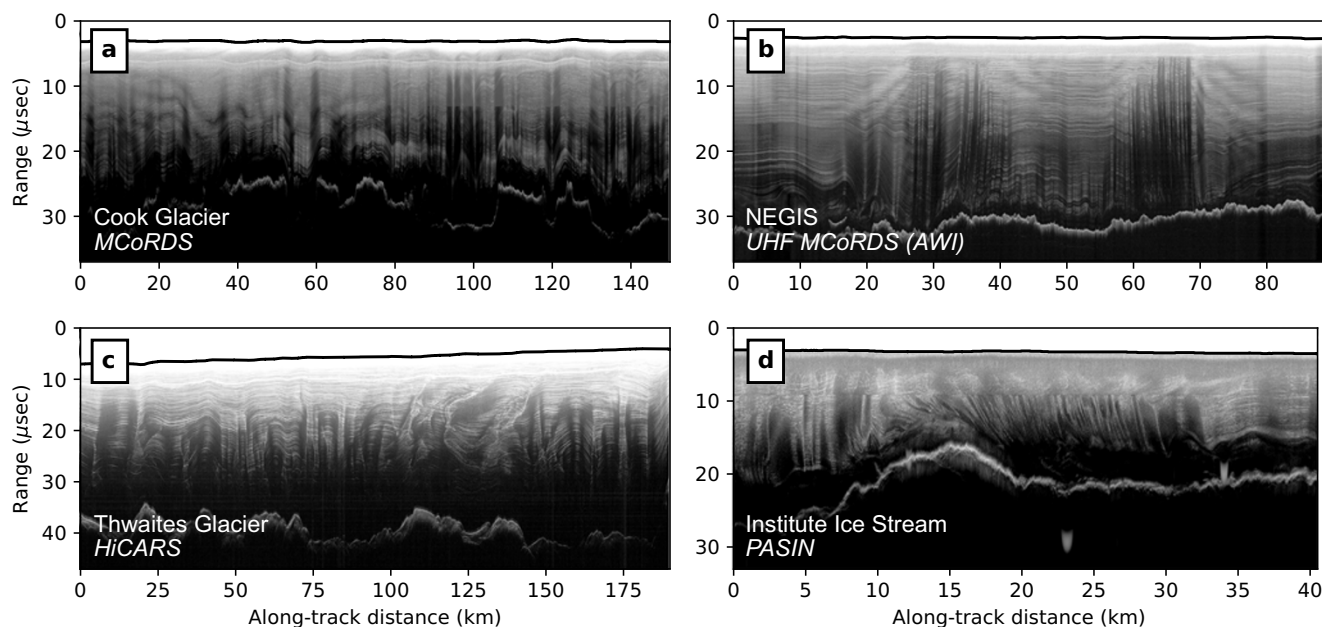


Figure 1. Examples of poorly resolved dipping layers in radar-sounding images: (a) Cook Glacier imaged with the Multi-channel Coherent Radar Depth Sounder (MCoRDS) (Open Polar Radar, 2024); (b) The Northeast Greenland Ice Stream (NEGIS) imaged with an ultra-high frequency version of MCoRDS (Franke and others, 2022); (c) Thwaites Glacier imaged with the High-Capability Airborne Radar Sounder (HiCARS) (Schroeder and others, 2013); (d) Institute Ice Stream imaged with the Polarimetric Airborne Science INstrument (PASIN) (Winter and others, 2015). Vertical or near-vertical dark streaks that interrupt englacial stratigraphy are locations where signals from nadir and off-nadir destructively interfere in standard RES processing frameworks. Profiles are plotted as a measured range in time from the radar instrument, with the ice surface shown as a solid black line.

expected that radar power should be received from dipping specular layers, but that those signals may not be apparent depending on whether they are summed coherently during focusing. In the cross-track direction, multiple antenna elements can be used together in an array to steer the radar beam toward off-nadir targets (Paden and others, 2010), enabling swath mapping of the glacier bed (Holschuh and others, 2020) among other applications. In the along-track direction, signals are coherently averaged within a *synthetic* aperture as the antenna moves between acquisitions (Legarsky and others, 2001; Peters and others, 2005), as is done in spaceborne synthetic aperture radar (SAR) applications (Cumming and Wong, 2005). The SAR algorithms used in RES are generally optimized for targets that are rough at the scale of the radar wavelength (we use the term ‘diffuse’ here), which scatter energy in all directions and are therefore observable from many angles across the synthetic aperture. Then, one can coherently average through a set of look directions around that of the real beam, constructively interfering signals to raise the signal power and narrow the along-track resolution. However, for targets that are both specular and off-nadir, the nadir-looking reference function (used in SAR processing) may not match the shape of the signal return. Incorrectly applying that reference function would diminish, rather than amplify as intended, the output signal, which we are here calling destructive interference (not to be confused with destructive presuming) (Holschuh and others, 2014).

Here, we give context on the SAR algorithms commonly used for glaciological sounding in terms of their ability to resolve dipping englacial layers. Then, we describe two alternative methods that are better suited for considering all types of englacial reflectors together (including dipping specular layers), or a rough ice surface, both using synthetic squint angles to steer the radar beam toward orthogonal incidence with dipping layers. The first method

was previously described by Heister and Scheiber (2018), but has not been commonly used for resolving radiostratigraphy, and the second method we developed here and has never before been implemented to our knowledge. We apply these methods in along- and across-flow radar profiles at Academy Glacier, East Antarctica. The improved result can be used for better interpretations of individual layers of interest and to generate more precise glaciological (e.g., Catania and others, 2006; Sanderson and others, 2023) and paleoclimatological (e.g., Bodart and others, 2021; Lilien and others, 2021) insight.

2. Background

To generate images for interpretation, ‘fast-time’ (range) and ‘slow-time’ (along-track or ‘azimuth’) filtering are performed on radar-sounding data. Fast-time matched filtering (often called pulse compression) localizes energy from a finite-duration pulse to the range bins associated with the scattering target. This type of compression is not the focus of this work, and we use pulse-compressed data as a starting point for our analyses (Fig. 2a). Here, we consider different strategies for along-track compression, which can be thought of both as strategies to focus images and improve their signal-to-noise ratio (SNR). The simplest and least computationally expensive method for along-track compression is with no range correction to signal phase before horizontally summing neighboring traces (called presuming or stacking); this processing strategy can raise the SNR and lower the data volume (generating unfocused imagery, or ‘quicklook’ in Open Polar Radar (OPR) 2024; Fig. 2b). To coherently focus the image (i.e., sum received radar signals after having aligned their phase), one must estimate how the range to target is expected to change through the synthetic aperture and apply the along-track compression with that range/phase

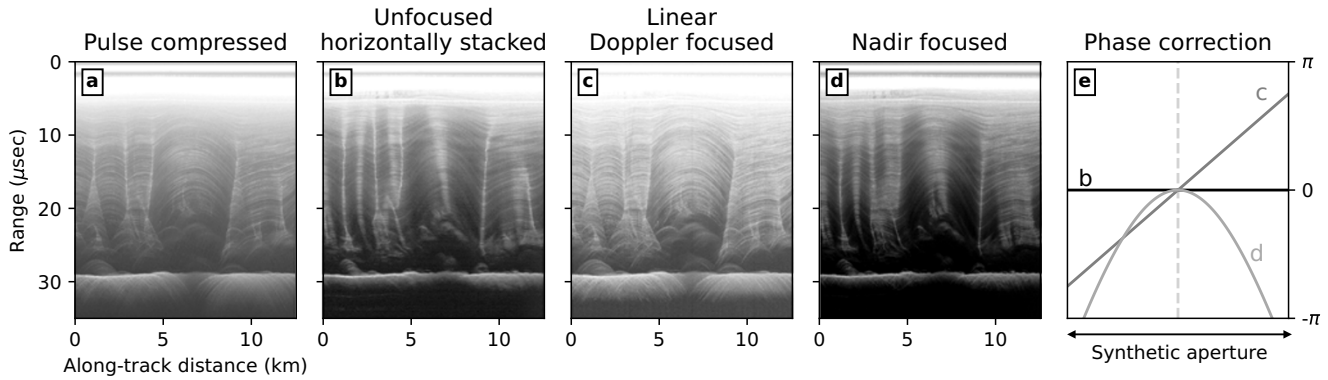


Figure 2. A single radar image processed with four common SAR techniques: (a) pulse compressed; (b) unfocused horizontally stacked ('quicklook'); (c) linear Doppler focused ('LOSAR'); (d) nadir-focused with f - k migration ('standard'). (e) Hypothetical phase corrections within a synthetic aperture for each method (b–d). Data are from and processing is done through Open Polar Radar (2024).

adjustment. In this section, we describe two commonly implemented focusing methods and how they can be used to resolve dipping englacial layers.

2.1. Linear Doppler focusing

The radar-sounding instruments designed for generating radar profiles are on moving platforms, so the range to a target and the associated phase offset between neighboring returns change through the synthetic aperture. The phase, ϕ , gradient in along-track time, η (slow time), is the so-called Doppler frequency, f_D , given as

$$2\pi f_D = \frac{\partial \phi}{\partial \eta}. \quad (1)$$

Measured returns can come across the full Doppler spectrum, even for a single target if it is diffuse, but they are only resolvable within the Doppler bandwidth, B_D

$$B_D = \frac{v}{\Delta x} \quad (2)$$

set by the platform velocity, v , and acquisition spacing, Δx .

Specular targets may only be expressed across some subset of the full Doppler spectrum, centered on the Doppler centroid (the Doppler frequency with greatest power, f_{Dc}), which is (Heister and Scheiber, 2018; Castelletti and others, 2019)

$$f_{Dc} = \frac{2vf_c}{c} \sqrt{\epsilon_r} \sin \theta \quad (3)$$

where f_c is the instrument center frequency, c is the vacuum wave speed, ϵ_r is the relative permittivity of the near-field material ($\epsilon_r = 1$ for airborne platforms) and θ the near-field ray propagation angle ($\theta = 0$ being directly downward, nadir). Then, for normal incidence with an englacial target, it must be dipping at some angle, θ_{ice} , which can be found by rearranging equation 3 and applying Snell's law on refraction from the near-field into the ice,

$$\sin(\theta_{ice}) = \frac{cf_{Dc}}{2vf_c \sqrt{\epsilon_{ice}}} \quad (4)$$

where ϵ_{ice} is the relative permittivity of ice (~ 3.15). Inspecting the Doppler centroids directly can therefore give broad insight into englacial features (Arenas-Pingarrón and others, 2025), which we discuss further in Section 5.

Doppler centroids can also be used for a type of SAR focusing that assumes a linear phase correction through the synthetic aperture (i.e., constant frequency)

$$\Delta \phi = 2\pi f_{Dc} \frac{\Delta x}{v} \quad (5)$$

and can be applied adaptively for each pixel in the image (Fig. 2c). Castelletti and others (2019) implemented this layer-optimized SAR (LOSAR) technique in the time domain. LOSAR images have better-resolved radiostratigraphy compared to prior data products. However, the LOSAR algorithm assumes perfect specularity; that is, it only considers power at a single Doppler frequency (the centroid). It also assumes that targets are linear within the synthetic aperture, which can lead to unrealistic abrupt changes in angles in the processed image if the Doppler centroids are noisy, especially since this method does not include any range migration. Alternatively, if the expected shape of the target is known, can be exhaustively searched for, or can be determined from measured Doppler spectra, an arbitrary reference function could be used to coherently focus over a much larger aperture (Schroeder and others, 2019).

2.2. Conventional nadir focusing

Conventional focusing methods accommodate a range of frequencies across the Doppler spectrum, making diffuse and specular targets differentiable (Fig. 2d). Considering a nadir-looking synthetic aperture, the target comes into view approaching the instrument (positive Doppler frequency), eventually reaches some point of closest approach (zero Doppler), then goes out of view behind (negative Doppler). The frequencies are defined through a function for the expected equivalent range, r , with possible ray bending from the near-field into the ice surface,

$$r = r_{near} + r_{ice} = \sqrt{\epsilon_{near}} \sqrt{h^2 + (x-s)^2} + \sqrt{\epsilon_{ice}} \sqrt{d^2 + s^2} \quad (6)$$

where h is the length scale for the near-field permittivity (for airborne platforms, the height of the aircraft above the ice surface), d is the depth of the target below the ice surface, x is the along-track distance and s is the along-track position for refraction from near-field to ice (the air-ice interface) (Hélière and others, 2007). We refer to r in equation (6) as an 'equivalent' range because it is not a true distance but is convenient for its simple relation to phase by $\phi = 4\pi r f_c / c$ and then to frequency through equation (1).

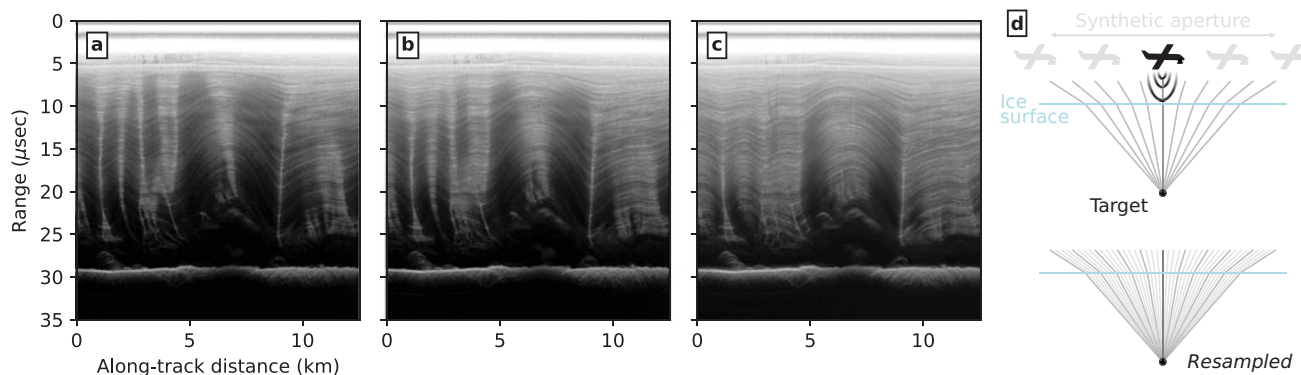


Figure 3. A demonstration of how different sampling intervals in the along-track dimension—(a) 2.5 m spacing, (b) 1.5 m spacing and (c) 1 m spacing—can change the focused result. Finer along-track sampling leads to better SAR coherence for the high Doppler frequency content (i.e., dipping layers). The radar data are from the same segment as in Fig. 2. (d) An illustration of resampling the synthetic aperture.

Thus, a given target has an approximately linear frequency ramp (or hyperbolic phase) through the synthetic aperture (Fig. 2e).

The maximum resolvable Doppler frequency (and hence maximum layer dip through equation (4)) is set by the Doppler bandwidth, equation (2). For steeply dipping reflectors, outside the Doppler bandwidth, the range-matched filter (defined by equation (6)) will lead to destructive interference and decrease the coherent signal power (Holschuh and others, 2014). However, the maximum dip angle from which *individual* radar reflections can be received is instead set by the width of the radar beam and focusing effects of refraction at the ice surface, $\theta_{\text{ice}} = 34^\circ$ (Dowdeswell and Evans, 2004). Since the transmitted waves are relatively low frequency ($\sim 10\text{--}1000$ MHz) and the antenna array is small in the along-track direction, the radar beam is large (Heister and Scheiber, 2018), and some energy should be expected from off-nadir targets. If the raw image is downsampled during processing, as is common due to the computational inefficiency with high data volumes, a larger Δx narrows B_D to where it cannot resolve the steep layers even if those layers are reflecting individual radar returns. To extend the Doppler bandwidth with the goal to resolve more steeply dipping layers, the image can be sampled at higher resolution in the along-track dimension (Fig. 3).

3. Squinted SAR focusing

Resampling in the along-track dimension can expand the Doppler bandwidth, but in some cases, it may not effectively eliminate destructive interference for dipping layers. For instance, the commonly used frequency-wavenumber (f - k) migration (Legarsky and others, 2001) assumes a uniformly horizontal layered geometry. A rough ice surface or short-scale variations in the ice density (and therefore radar-wave velocity) may lead to enough phase variation between acquisitions to prevent constructive interference within the synthetic aperture. Although other migration routines are capable of more complicated geometries and have been implemented for glaciological radar sounding (e.g., time-domain back propagation; Xu and others, 2022), these are substantially more computationally expensive. Instead, we i) divide the full aperture into multiple subapertures and optionally ii) adaptively restrict a single subaperture around the signal, in either case reducing the length scale over which the geometric assumptions are made (Rodríguez and others, 2009), which both resolves dipping layers and allows for spatial variations in the ice surface height and ice density within the firn column.

3.1. Squinted subapertures

Consider multiple subapertures, each assigned a ‘squint’ angle to steer the radar beam in the along-track direction and toward orthogonal incidence with dipping englacial layers (Fig. 4) (Rodríguez and others, 2009; Ferro, 2019). The radar instrument may be physically or electrically squinted forward or backward to illuminate targets in front of or behind the instrument, respectively. Here, the radar antennas have zero physical squint (pointed at nadir), but since the real beam is large, we can use synthetic squint angles to distinguish subapertures within the beam. Since, in this case, the migration routine (f - k) is in Doppler space, the subapertures represent portions of the Doppler spectrum, with the forward squinted subaperture illuminating the highest Doppler frequencies.

In our implementation of squinted subaperture processing, we offset squint angles by one-half the subaperture width so that each overlaps with its neighbor (Fig. 4a–e), then convolved with a Hanning window in Doppler space so that the total power is conserved. Finally, the subapertures are incoherently averaged (multilooked) to create the mosaic in which both specular and diffuse targets can be resolved across the Doppler spectrum (Fig. 4f). Note that specular targets may exhibit a drop in SNR relative to the original nadir-focused image since we are now averaging over more measurements through the full Doppler spectrum, most of which are noise in the case of a specular target. This is true of both the multi-squinted algorithm and simple resampling, as can be seen in Fig. 3, where the targets that are resolved in Fig. 3a have a slight power reduction with resampling in Fig. 3b and c.

3.2. Adaptive squinting and spectral filtering

Next, consider an adaptive subaperture, one that is restricted to the portion of the Doppler spectrum with signal above the noise floor (Fig. 5). Here, we increase the number of squinted subapertures, enough that Doppler space can be treated as its own dimension (with the many small subapertures as Doppler bins) to be analyzed and filtered. We then iterate through each pixel in the image, applying a Tukey filter in Doppler space to suppress noise at high Doppler frequencies and again identifying the Doppler centroid as the bin with the greatest SNR. From the centroid, we progressively step outward, including bins until they fall below a prescribed SNR threshold (in this case, within 10 dB of the system noise floor, which is defined by range bins well below the deepest targets, or

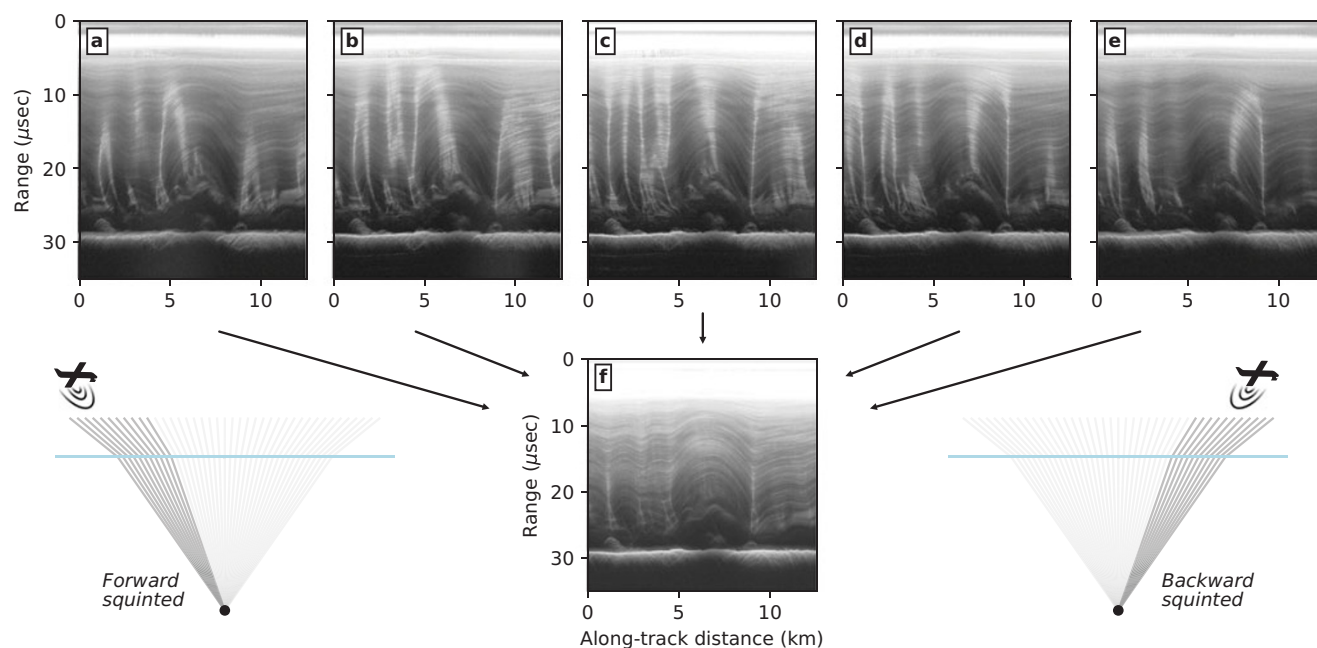


Figure 4. Results from multi-squinting, again using the same data segment as in Figs. 2 and 3. Individual images processed with one squinted subaperture, with (a, b) forward, (c) nadir, and (d, e) backward look angles. The nadir-squinted subaperture is the same nadir-focused image as in Fig. 3a. (f) The mosaic image, which is an incoherent average of all squinted subapertures in panels (a–e) and six additional subapertures at higher Doppler frequencies not shown here, for a total of 11 distinct squint angles. Illustrations on either side of the final mosaic image show cartoon examples of the forward- and backward-squinted subaperture geometries.

any possible clutter, $\sim 40 \mu\text{sec}$). To maintain a continuous aperture and to restrictively limit its extent, we do not include any additional bins after the first is rejected (i.e., the lowest frequency bin that falls below the threshold is the aperture extent). In the limit where the adaptive aperture is confined to a single frequency at the Doppler centroid, our adaptive approach reduces to the linear-Doppler focusing method described above (Castelletti and others, 2019).

Since this adaptive focusing method removes the Doppler bins with low signal, which were averaged into previous results, the overall SNR is elevated, especially for specular reflectors that have a narrow response in Doppler space (Fig. 5b and c). However, the method is computationally expensive compared to those approaches with a fixed number of (sub)aperture(s). A similar and faster approach would be to apply spectral filtering (Heister and Scheiber, 2018) on an image that has already been focused with one of the methods above, but in that case, the focused image may have already destructively interfered signals, and therefore have diminished SNR for dipping layers. In those cases, layers will be more recoverable with a low-level adaptive aperture as we describe here compared to higher-level filtering.

4. Application at Academy Glacier

We apply the above methodology to selected segments of an Operation IceBridge airborne radar survey flown by the Center for Remote Sensing and Integrated Systems (CRSIS) in October and November of 2018 (Fig. 6). For this survey, the Multi-channel Coherent Radar Depth Sounder 3 (MCoRDS3) (Rodríguez-Morales and others, 2013), with a six-element antenna-array, was mounted in the cross-track direction under a DC8 airframe and operated across a 165–215 MHz frequency band. The surveyed area included both along- and across-flow (flux-gate) profiles for

glaciers in the Filchner Ice Shelf drainage basin, East Antarctica. Here, we emphasize two profiles in particular from Academy Glacier.

Academy Glacier is a part of the broader Foundation-Patuxent-Academy ice-stream system (Ross and others, 2025), being closely coupled to neighboring Foundation and Support Force ice streams. The upstream accumulation area, in the vicinity of the South Pole, overlies the large Pensacola-Pole bedrock basin (Paxman and others, 2019), and accumulated ice from that basin is funneled through the Pensacola Mountains by Academy Glacier. Cross-glacier convergence creates folding in the englacial stratigraphy (Bons and others, 2016), which causes destructive interference within radar images of dipping layers (Fig. 7a) for the reasons discussed above. Those dipping layers are effectively reconstructed with squinted SAR processing (Fig. 7b), indicating that the dominant dip angle is in line with the flight track (perpendicular to the flow direction). After layer reconstruction, alternative mechanisms of radar power reduction become more apparent; for example, there is a birefringent beat signature (Young and others, 2021; Hills and others, 2025) at 55 km and 150 km along-track distances, near the lateral extent of streaming flow. In the along-flow direction, Academy Glacier has a retrograde bedslope (Jeofry and others, 2018) before it drops into Foundation Trough. The along-flow radiostratigraphy is relatively uniform and flat overlying the retrograde bed, but some artifacts are present in the radar image (Fig. 7c). Since those features are not suppressed by squinted focusing (Fig. 7d), we assume they are cross-track layer folds (see Section 5.2), consistent with what is observed in the cross-flow profile.

Even for features which are well resolved with standard focusing (e.g., the ice-bed interface), the resulting SNR changes substantially between focusing methods (Fig. 8). Methods with a large Doppler bandwidth tend to average in more noise and increase the noise floor, but they do so while resolving specular reflectors from all dip angles equally (as opposed to fading in and out of the nadir

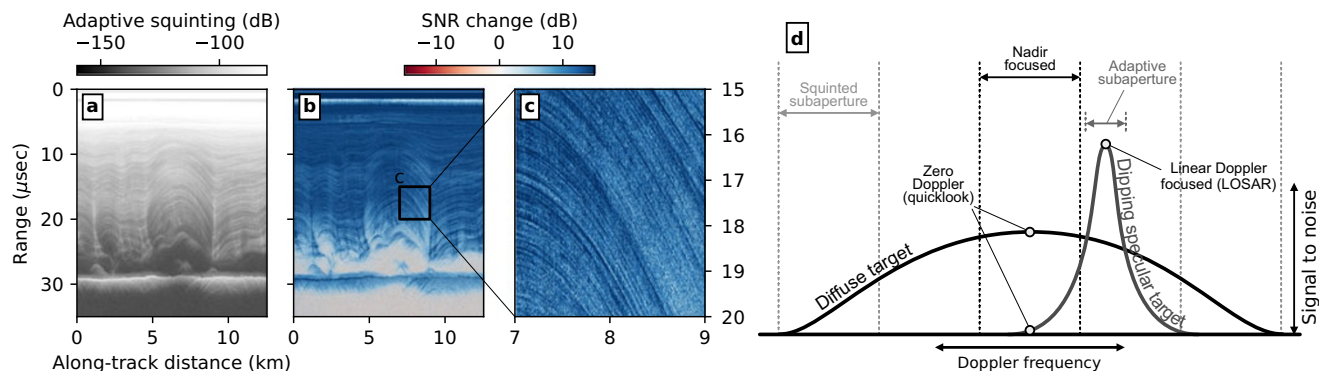


Figure 5. A signal-to-noise ratio (SNR) improvement through adaptive squinting. (a) The resulting image from adaptive squinting, (b) the SNR difference of adaptive squinting compared to multi-squinting across the full Doppler bandwidth (i.e., Fig. 4f) and (c) an inset of the difference to better highlight the SNR improvement for specular, dipping englacial layers. (d) Conceptual diagram of englacial targets (diffuse and specular) as they are represented in Doppler space and how they are sampled through different processing types or (sub)apertures.

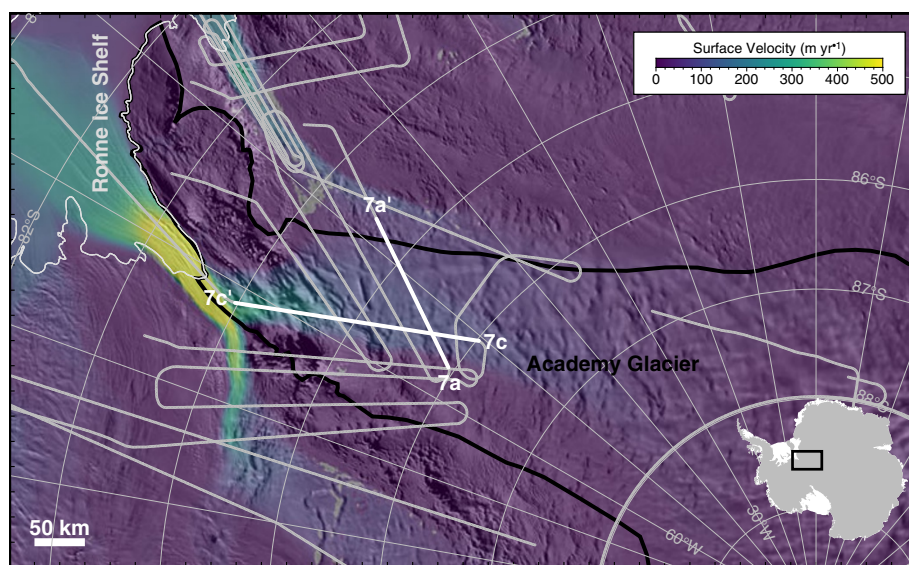


Figure 6. A map of the airborne radar survey flown by CReSIS in 2018, overlain on the observed surface velocities (Mouginot and others, 2019) and MODIS imagery Scambos and others (2007). The Academy Glacier drainage basin is outlined in black (Rignot and others, 2011) and the grounding line in white (Depoorter and others, 2013).

image). The adaptive aperture minimizes this additional noise to the point where SNR for flat layers is at least equal to nadir focusing (or greater for large nadir apertures) and SNR for dipping layers is elevated to match those that are flat (Fig. 8a and c). The trailing tail beneath a bed echo and clutter from surface crevassing can be intensified relative to the nadir image since this energy is associated with diffuse reflections from off-nadir topography (as opposed to the initial bed- or surface-echo impulse associated with scattering at nadir). Compared to the linear-Doppler image (Fig. 8b and d), adaptive-squinting has lower SNR for some targets, especially those that are highly specular, but now with more ability to accommodate changes in layer shape through range migration and non-linear focusing.

5. Discussion

Englacial stratigraphy has commonly been used to infer ice flow and ice-sheet history, including in past studies at Academy Glacier (e.g., Bingham and others, 2007; Sanderson and others, 2024). In cases where layer folds and/or disruptions are spatially consistent with the measured velocities at the ice-sheet surface, ice flow has been interpreted to be in a steady state (e.g., Martín and others,

2014). Alternatively, in cases where the two measures are inconsistent, historical changes to ice flow have been interpreted (e.g., Conway and others, 2002; Karlsson and others, 2009), and in some cases an approximate timing has been assigned to the change (e.g., Beem and others, 2017; Hoffman and others, 2025). As we have shown, the degree to which layers appear disrupted also depends on the processing methodology. In this section, we discuss how the different SAR processing methods may or may not affect interpretations of the stratigraphy and how additional analyses may be possible with our new data product(s).

5.1. Layer continuity

Radiostratigraphy can be analyzed by discrete interpretation of individual layers (MacGregor and others, 2015); however, depending on the goal, it can be simpler and faster to quantify abnormalities on a trace-by-trace basis, for instance, with an A-scope continuity index (Karlsson and others, 2012)

$$\Psi = \frac{1}{2\Delta zN} \sum_{i=n_1}^{n_N} |P_{i+1} - P_{i-1}| \quad (7)$$

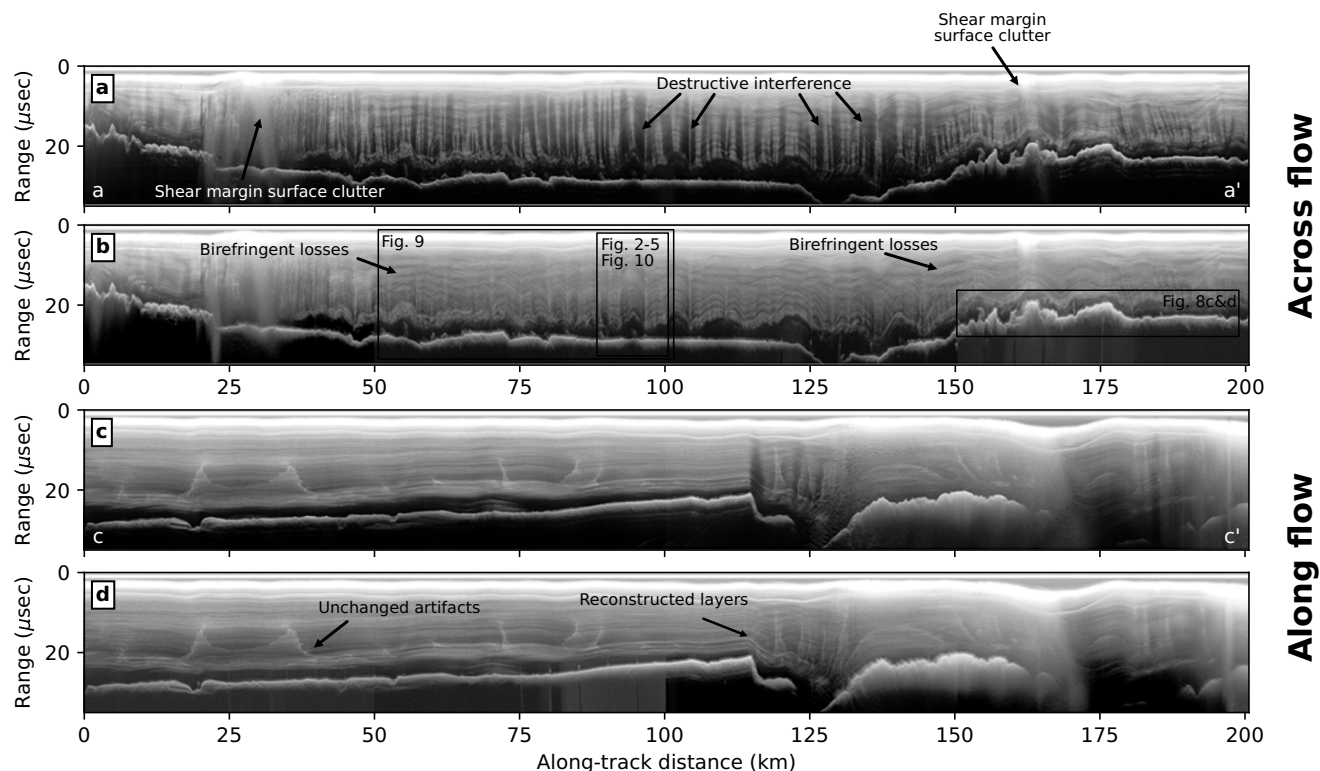


Figure 7. Radar profiles from the 2018 Operation IceBridge survey of Academy Glacier aligned (a, b) across and (c, d) along ice flow using (a, c) conventional nadir-focused and (b, d) our adaptively squinted processing, each with color scales in dB relative to their noise floor. The cross-flow profile is aligned such that ice is flowing into the page. Most of the destructive interference in the cross-flow profile, which is from dipping englacial layers in panel (a), can be recovered, as shown in panel (b). The along-flow profile is aligned such that ice is flowing left to right. Constructively interfered vertical artifacts in the first 100 km of the along-flow profile are unchanged in the squinted image, indicating that they are associated with cross-track layer dips. Some Doppler-filtering artifacts arise in the squinted processing (e.g., panel (d) within 75–100 km and below the bed interface), which could be mitigated appropriately with adjustments to the applied Tukey window. Steeply dipping layers from 115 km to 125 km are successfully reconstructed with our squinted subaperture processing.

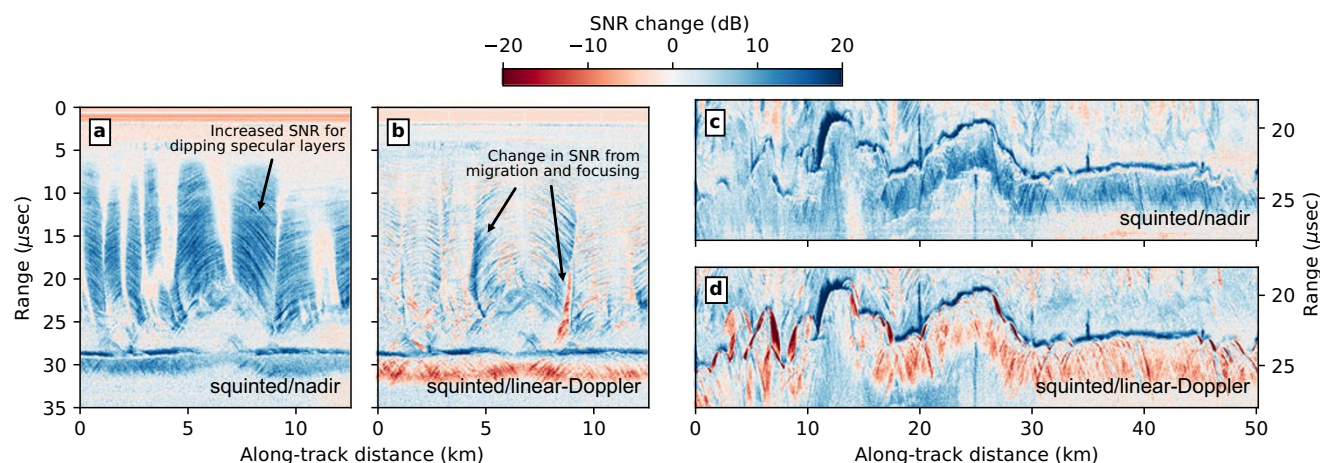


Figure 8. SNR difference between focusing methods for (a, b) the same cross-flow profile segment shown in Figs. 2–5 with specular englacial layers, and (c, d) a different segment of the same cross-flow profile with diffuse bed echoes (location shown in Fig. 7b). (a, c) Difference between adaptive squinting and nadir-focused images. (b, d) Difference between adaptive squinting and linear-Doppler processed images.

where Δz is the vertical distance, in meters, between range bins, N is the number of range bins included in the sum (generally restricted to some subset of the total ice thickness) and P is the radar power (or SNR) at a given range bin, i . We calculated the continuity index for layers within the same radar image from the cross-flow segment of Academy Glacier (Fig. 9a; location in

Fig. 7b) processed five ways: unfocused, linear-Doppler focused, nadir focused, multi-squint focused and adaptive-squint focused (Fig. 9b). In the three more commonly applied data products, destructive interference in dipping layers is associated with a drop in the continuity index, whereas the adaptively squinted image has relatively continuous layers throughout. The multi-squinted image

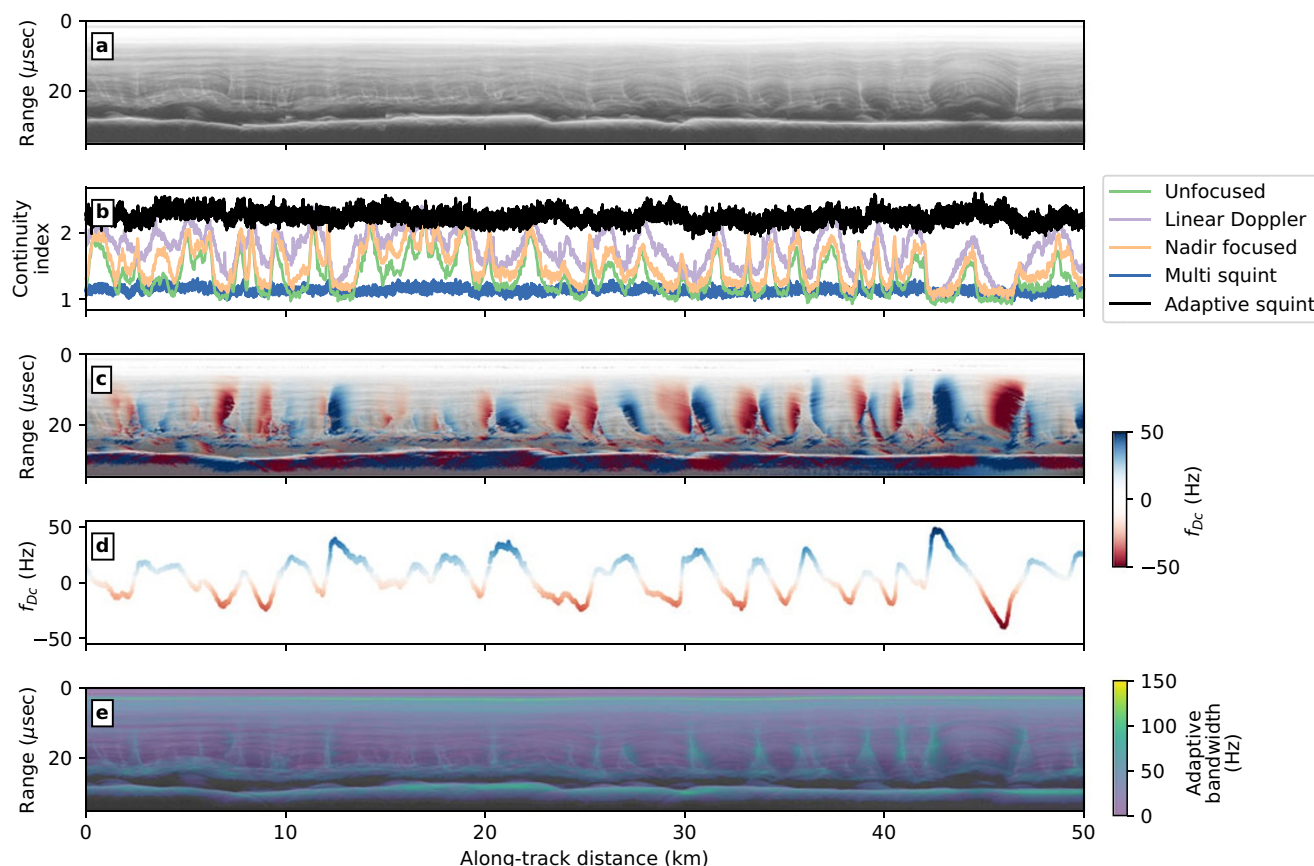


Figure 9. Comparison of layer continuity between processing techniques. (a) Adaptively squinted image from across Academy Glacier (location in Fig. 7b). (b) Layer continuity calculated with equation (7) for the profile section in (a), processed with all methods from Fig. 2 as well as the multi- and adaptively squinted techniques. (c) Doppler centroids overlain on the unfocused Doppler image. (d) Depth-averaged Doppler centroid. (e) Adaptive Doppler bandwidth, which can be used as a measure of specularity.

has a lower continuity index everywhere, but this is due to how the index is calculated, not that the layers are not resolved continuously. That is, the multi-squinted image has higher noise, so the contrast between the noise floor and the reflection SNR is smaller and therefore the vertical gradient calculation in equation 7 is smaller everywhere. Aside from two slight dips in continuity at the most steeply dipping layers (~ 42 and 45 km along track), the variations in continuity for the multi- and adaptively squinted images are not interpretable above the noise of layer reflectivities.

As one alternative to layer continuity, the Doppler centroids can be used to estimate layer dip (Arenas-Pingarrón and others, 2025) (Fig. 9c and d). Then, there is a sign (up- or down-dipping) associated with the layers. Similar work has done the same layer-dip estimation, even for radars that are not phase coherent, through alternative image processing techniques (Panton, 2014; Holschuh and others, 2017; Delf and others, 2020), but with less capability to recover the stratigraphy itself. The Doppler centroid can also be used to guide explicit tracking of individual layers (MacGregor and others, 2015, their Fig. 3).

5.2. Cross-track layer folds

The along-track resampling and squinted steering methodology discussed here is useful for resolving radiostratigraphy that dips in the along-track direction. However, englacial stratigraphy is three-dimensional and therefore commonly has some cross-track

dipping component as well. Multi-element antenna arrays are increasingly being used for cross-track beam steering (Paden and others, 2010) and swath mapping of off-nadir cross-track reflections (e.g., Holschuh and others, 2020; Hoffman and others, 2023). In theory, a multi-element array or a gridded survey enables a measurement for three-dimensional dip angle (similar to the Doppler centroid, but in the cross-track direction as well).

Although that is beyond the scope of this article, we can identify features in the along-track image which are *not* well resolved with along-track focusing, even with our improved methodology, and argue that they are likely associated with interference from cross-track reflections, with some shape out of the plane of the image (not necessarily perfectly orthogonal) (Fig. 10). To do so, we first point out that synclines (i.e., concave up layers or sets of layers) can lead to multiple peaks within one range row of the Doppler spectrum of the unfocused along-track image (Fig. 10a and b) if the same layer lies on multiple points of equal range from the radar instrument (Fig. 10c). These multiple reflections create a downward cone of anomalous stratigraphy in the unfocused image, which is migrated away with focusing if the syncline is positioned in line with the profile (Fig. 10d and e). However, since the focusing is along the flight track only, it does not migrate any cross-track features and those artifacts in the unfocused image are then persistent into the focused one. Anomalous high power in the focused image may then indicate some analogous syncline in the cross-track direction (Fig. 10f), especially if more careful focusing (e.g., with a

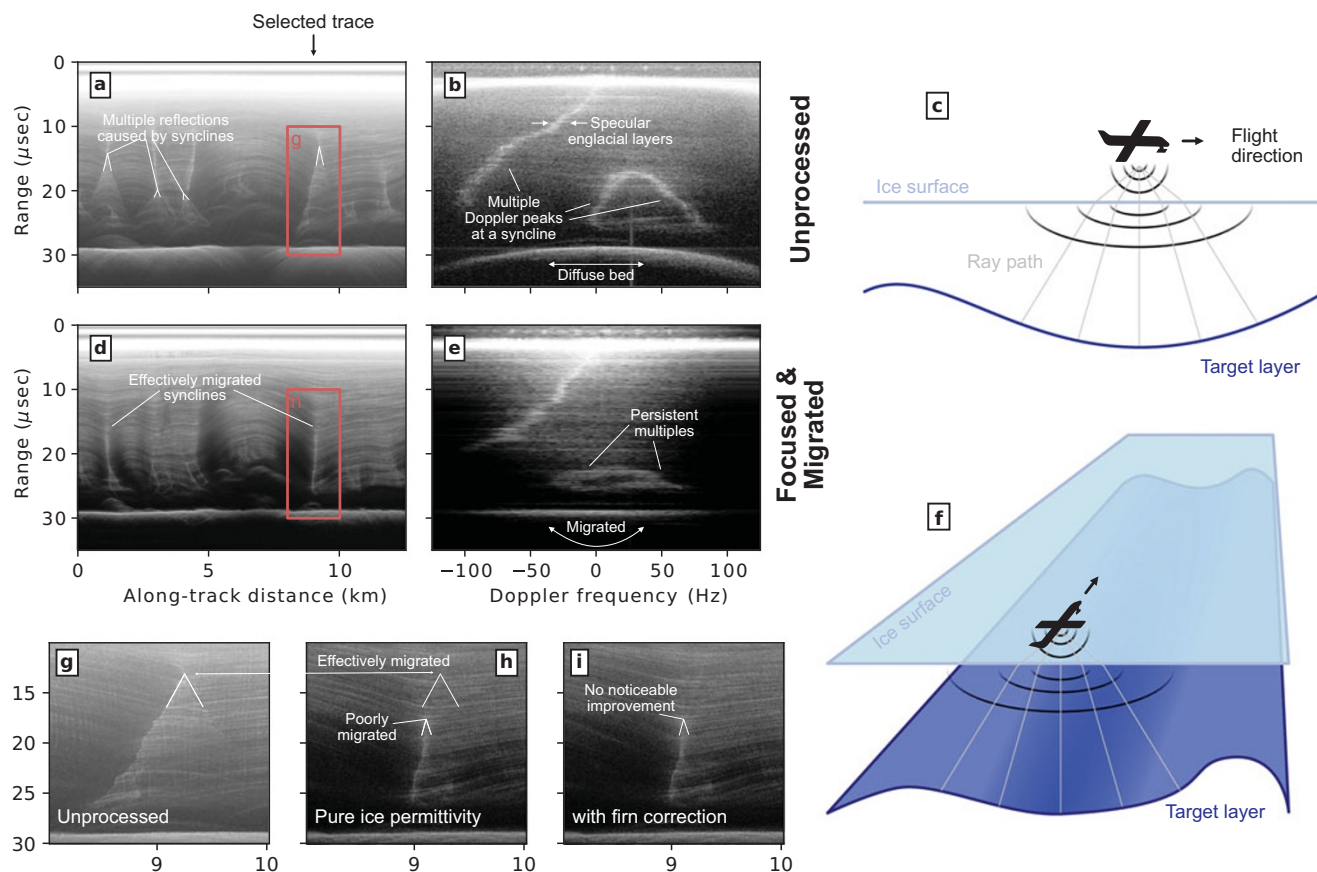


Figure 10. Doppler analysis before and after range migration and focusing. (a) Pulse-compressed image as in Fig. 2a. (b) Doppler spectra from the pulse-compressed image at the selected trace location indicated in (a). (c) Illustration of an along-track concave up layer which creates multiple reflections with the same range. (d) Resampled (to 0.5 m spacing) and focused image as in Fig. 3c. (e) Doppler spectra after focusing to demonstrate the effect of migration on subsurface targets. (f) Illustration of a cross-track syncline. Three panels show a smaller inset image for: (g) pulse compressed; (h) focused; and (i) focused with a firn-density correction. The multiple reflections that are effectively migrated are associated with an along-track syncline, and those that are poorly migrated are associated with a cross-track syncline.

firn correction for permittivity) does not improve the migration (Fig. 10g–i).

5.3. Specularity

Englacial layers are typically specular, especially compared to the ice-bed interface. A measure of specularity can be calculated from the Doppler spectra, where a narrow Doppler peak indicates a specular reflector and a wide Doppler peak indicates a diffuse reflector (Fig. 10b). For instance, past studies on specularity have used the difference in coherent power between apertures of different sizes (e.g., Schroeder and others, 2013; Young and others, 2016), with the wider aperture having lower SNR for specular reflectors because it stacks in more noise from portions of the Doppler spectra outside what is reflected by the target. Those analyses have typically been used to characterize the ice-bed interface; for instance, because a wet bed, and especially a subglacial lake, is expected to be more specular than a dry bed or one with significant subglacial roughness (e.g., Chu and others, 2021; Haris and others, 2024). Such a two-aperture comparison works particularly well for nadir targets, but dipping specular targets may have *higher* SNR in the wider aperture if the narrower aperture did not appropriately resolve the target.

Our adaptive aperture processing accommodates dipping targets, so it can also yield a more robust specularity estimate based on the selected bandwidth of the adaptive aperture. A narrow

bandwidth is associated with a specular target and wide with diffuse, as can be seen in Fig. 9e where the bed has a larger adaptive bandwidth than the englacial layers. One notable exception is that the syncline features discussed before have a large adaptive bandwidth because of their multiple peaks in Doppler space, which all need to be included across the aperture. Taking these adaptive-aperture bandwidths, they can be used as their own data product in the same way that the Doppler centroids can be. Expanded use cases from previous the specularity estimates (e.g., Schroeder and others, 2013; Young and others, 2016) are predominantly for dipping targets which are not centered on zero Doppler. For example, one could use this methodology to examine the scattering effects of entrained material in basal ice (e.g., Winter and others, 2019; Hills and others, 2024) or hypothesize formation mechanisms for the echo-free zone and basal units (e.g., Yan and others, 2025; Young and others, 2025).

6. Summary

In this work, we described how SAR processing can be optimally used to resolve along-track dips within the englacial radiostratigraphy, for which the destructive interference has long been a topic of interest in the glaciology literature (e.g., Karlsson and others, 2009; Holschuh and others, 2014, 2017; Castelletti and others, 2019). Improved resolution of folded englacial layers can lead to superior and more robust radioglaciological interpretations; for example, of

snow accumulation (Medley and others, 2013), ice dynamics in the accumulation zone (e.g., near a Raymond Arch; Martín and others, 2014), dynamics in streaming ice (Jansen and others, 2024) and paleo ice flow (Conway and others, 2002). Two additional analyses are necessarily calculated in our SAR methodology and optionally output as separate data products from the main radar image, layer dip through the Doppler centroid and specularity through the adaptive Doppler bandwidth. We also showed that derived data products from radiostratigraphy, such as a layer continuity index, are strongly dependent not only on the higher-level signal extraction approach but also on the lower-level SAR processing methods. Additional and more detailed analyses may be possible in areas with complex radiostratigraphy, even with RES data from previous missions, by using squinted focusing methods to illuminate englacial targets.

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An additional Python-based squinted SAR algorithm is available at <https://github.com/benhills/squintsar> with a frozen version (Hills, 2025a).

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