Common-midpoint radar surveys of ice sheets: a tool for better ice and bed property inversions

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A copy of the related paper can be found here: (JGR-ES, 2016)

A copy of this poster can be found here:

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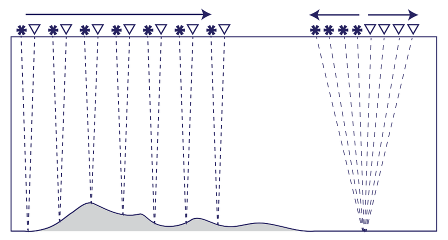
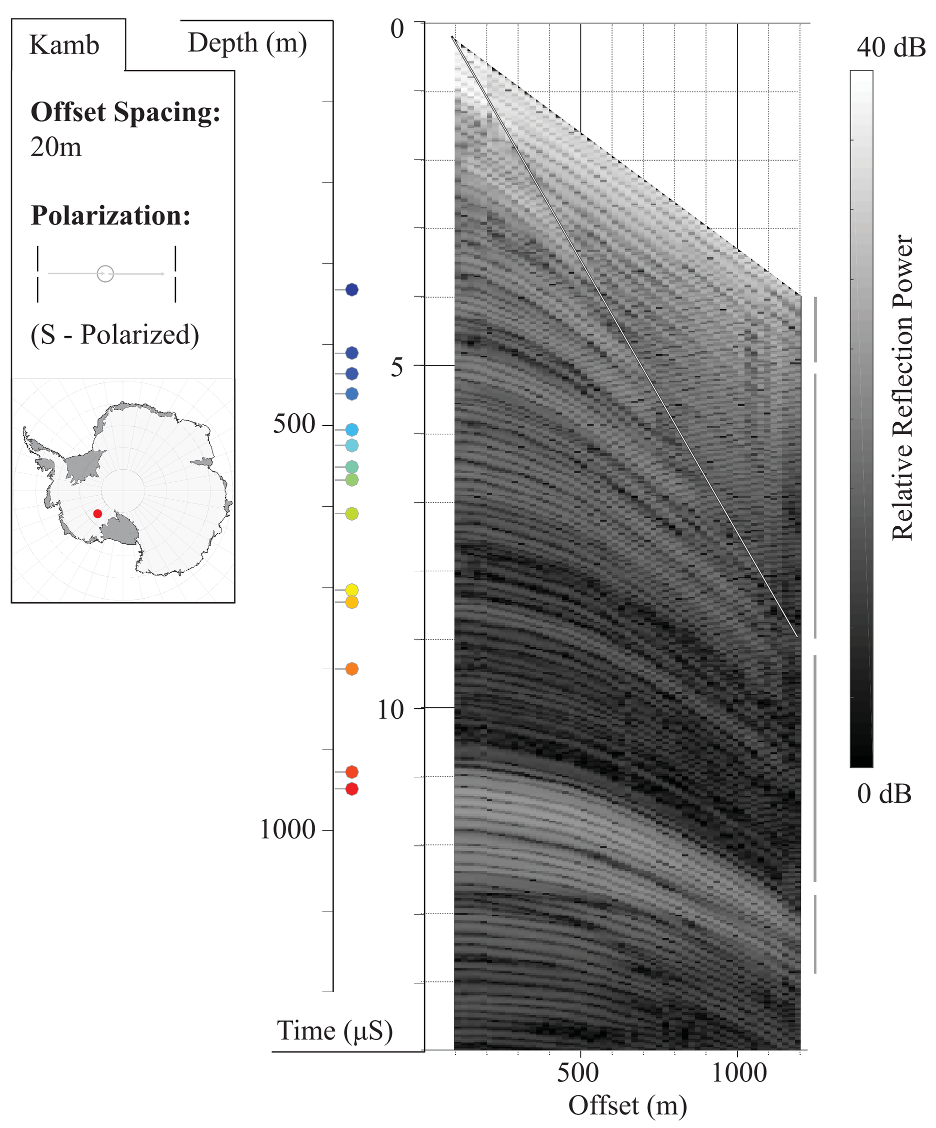
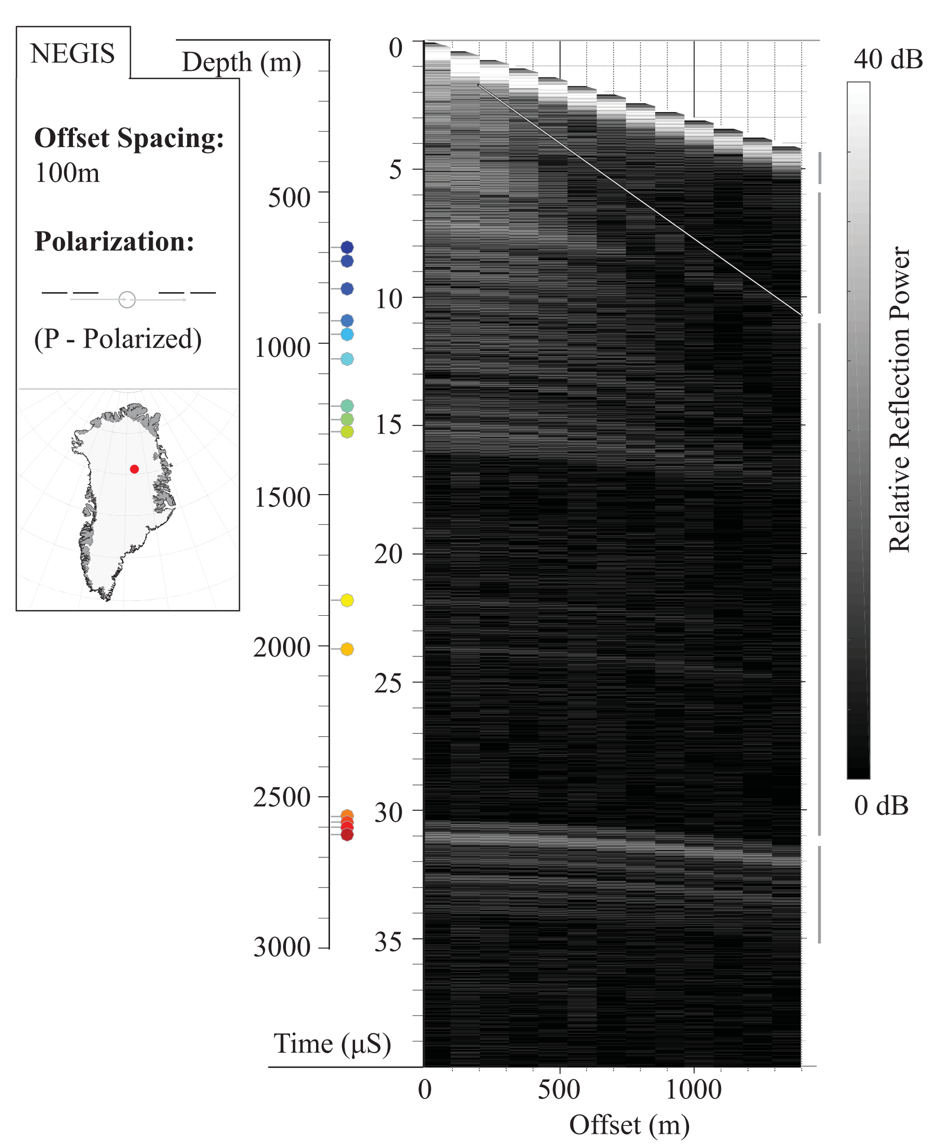
The Data

Radar data have the power to do more than measure ice thickness, as the physics of EM wave propagation and reflection are sensitive to electrical properties that co-vary with glacialogically interesting properties of the system (e.g., temperature and water content). With several unknowns controlling reflection power, clever survey design must be used to properly constrain the properties of interest. In this study, we present two of the first common-midpoint (CMP) radar sounding experiments conducted through thick ice, and attempt to constrain both the ice conductivity and (through that) temperature profile of the ice column. Data were collected with a ground-based, 3 MHz radar system.





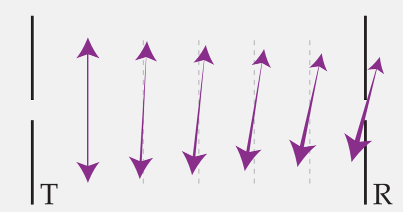


We know radar reflection power is controlled by the geometry of the system, the characteristics of the antennae, and the electrical properties of the ice and reflector. For common-offset data, many of these properties are unchanging from trace to trace, allowing us to attribute all variability in returned power to the englacial attenuation and reflector permittivity. However, common-offset data lack sufficient information to disentangle these two contributions, and therefore cannot uniquely identify the ice and substrate properties. **Common-midpoint radar data theoretically allow us to separate effects from ice and interface properties, but require accounting for the full complexity of the radar equation:**

$$P_r = \frac{P_t * A(\theta_t)^2 * B(\theta_F) * R(\theta_r,\varepsilon)}{S(z,\varepsilon_z)} * e^{-\alpha z}$$

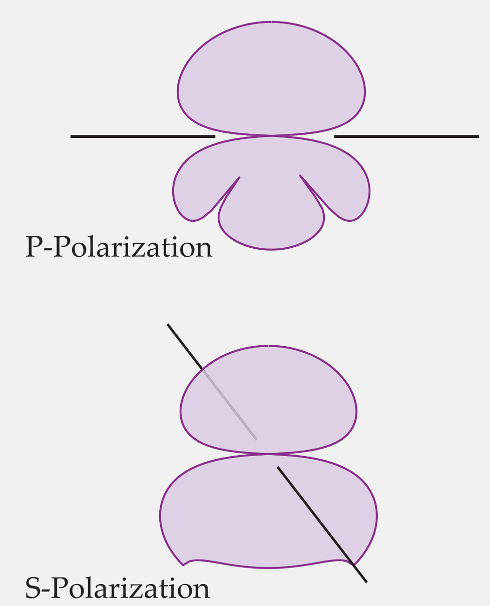
The Controls

Birefringence [$B(\theta_F)$] -
Ice is an anisotropic medium, which can drive changes in the polarization of EM waves during propagation. Previous work has shown that, for frequencies below 20 MHz, the effect on return power is negligible, so we ignore it here.



Antenna Radiation Pattern [$A(\theta_t)^2$] -
Radar antennae do not radiate energy equally well in all directions, so variability in the transmitted and received power as a function of angle must be taken into account when interpreting CMP data.

The radiation patterns for dipole antennae near the surface of the ice-sheet depend on the electrical properties of the firn column, resulting in large uncertainty in the introduced bias.

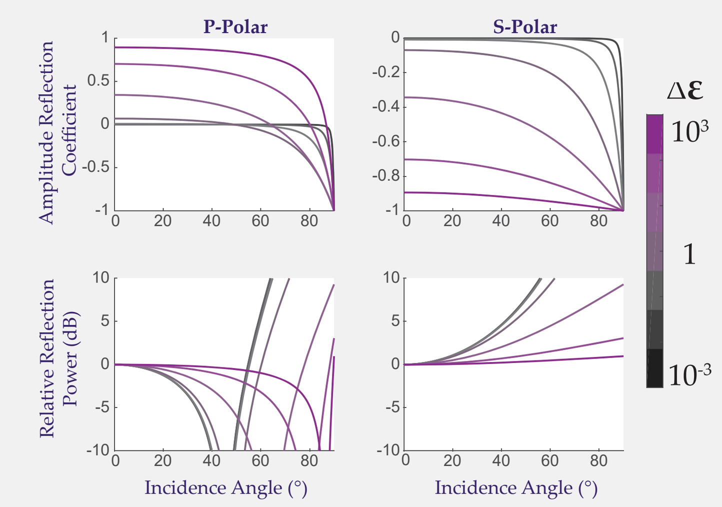


Bias Magnitude / Uncertainty:

	P-Polarized	S-Polarized
at 500m -	-44.9 ± 39.3 dB/km	13.7 ± 17.2 dB/km
at 2000m -	-10.5 ± 2.8 dB/km	2.9 ± 2.2 dB/km

Fresnel Reflection Characteristics [$R(\theta_r,\varepsilon)$] -
The reflection coefficient defining dielectric contrasts in the subsurface depends on the incidence angle of the traveling wave. Uncertainty in that angular dependence (not the actual magnitude of the reflection coefficient) will bias the inferred attenuation rates.

Over the range of reasonable englacial reflector permittivity contrasts (10^{-3} - 10^{-1}), the uncertainty in the angular dependence is small, making power correction possible.

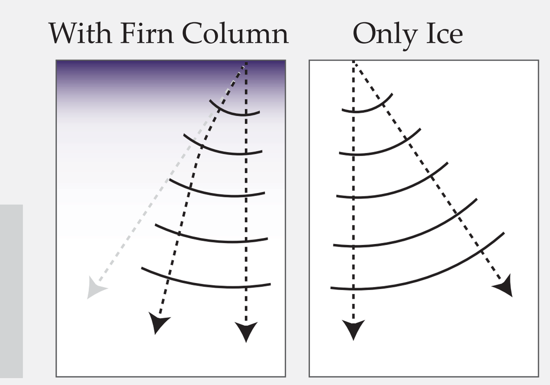


Bias Magnitude / Uncertainty:

	P-Polarized	S-Polarized
at 500m -	-19.7 ± 0.0 dB/km	16.1 ± 0.0 dB/km
at 2000m -	-4.6 ± 0.0 dB/km	4.2 ± 0.0 dB/km

Net Wave-Spreading Effect [$S(z,\varepsilon)$] -
Spherical spreading corrections are commonly applied to account for changes in energy density as the area of the radar wave-front grows with distance. But in the presence of a firn column, the down-going energy is concentrated by refraction.

The variability in the focusing with angle must be removed.



Bias Magnitude / Uncertainty:

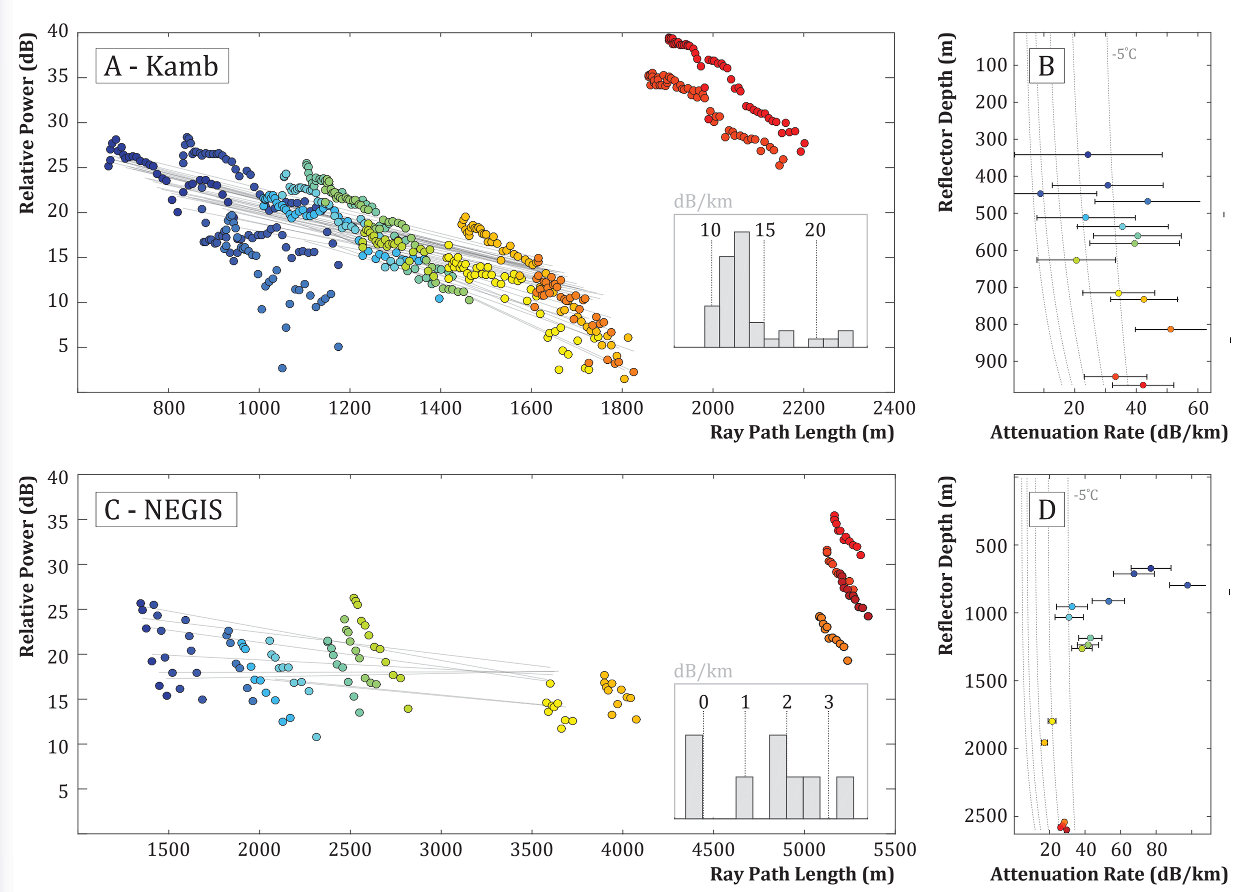
at 500m -	6.5 ± 0.9 dB/km
at 2000m -	1.6 ± 0.2 dB/km

The corrections discussed here are all for a ground survey, using dipole antennae and a 3 MHz pulse frequency. Correction values will differ for surveys with a different radar configuration.

When these contributions to return power are removed, all remaining power variability should be from attenuation.

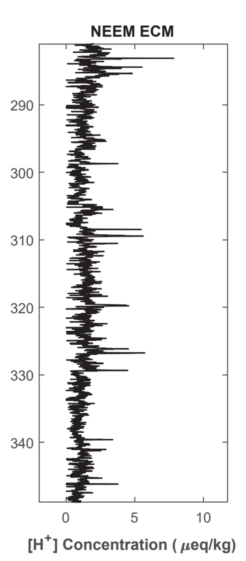
The Results

Individual reflectors were picked, their reflection power was corrected for the biases described above (plotted in A,C), and the attenuation rates were computed (B,D). Full-column, depth averaged attenuation rates were also computed using common-offset methods, and provided as histograms in (A,C).



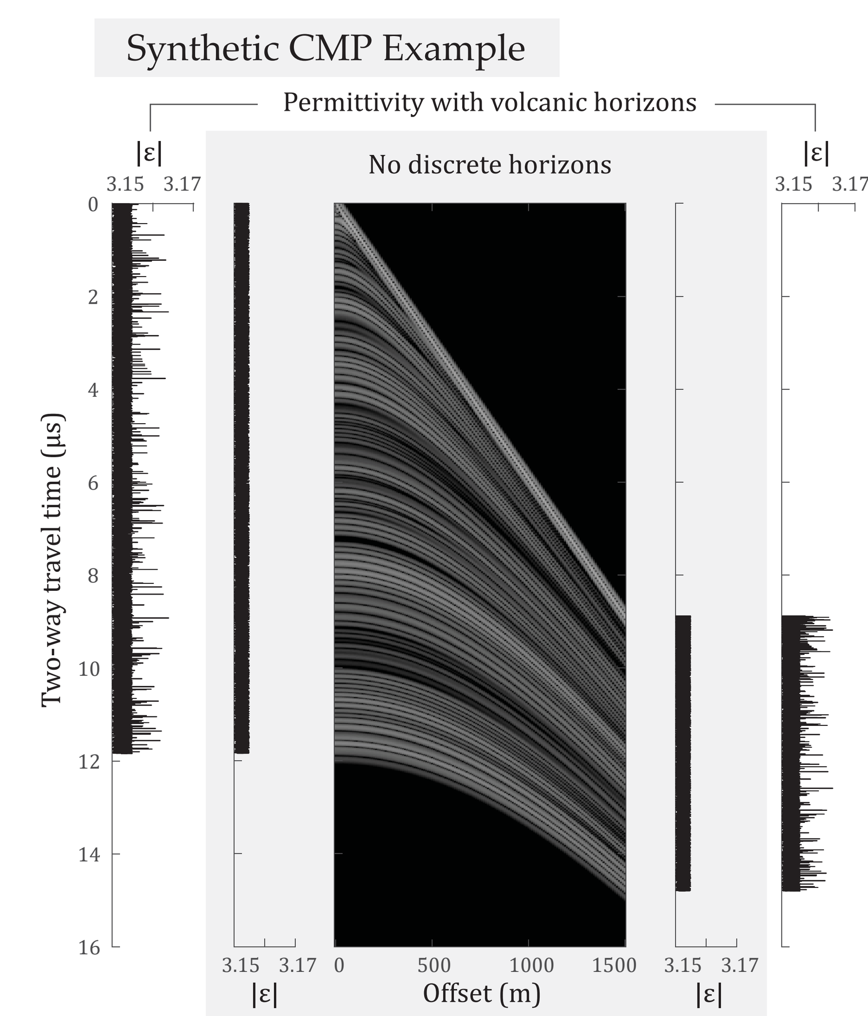
Attenuation rates computed using common-offset methods fell far below those computed using CMP methods, which consistently produced results outside of the reasonable range.

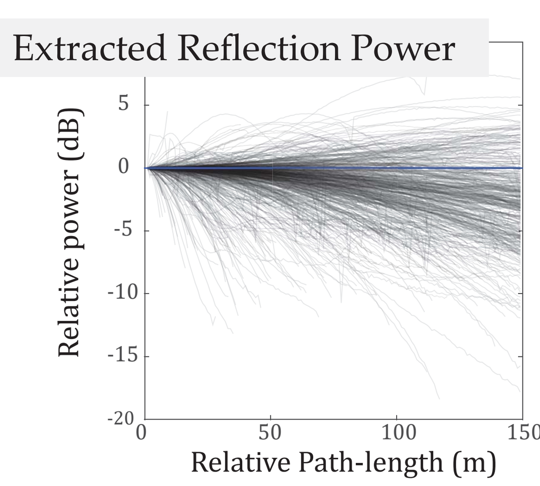
The Complication

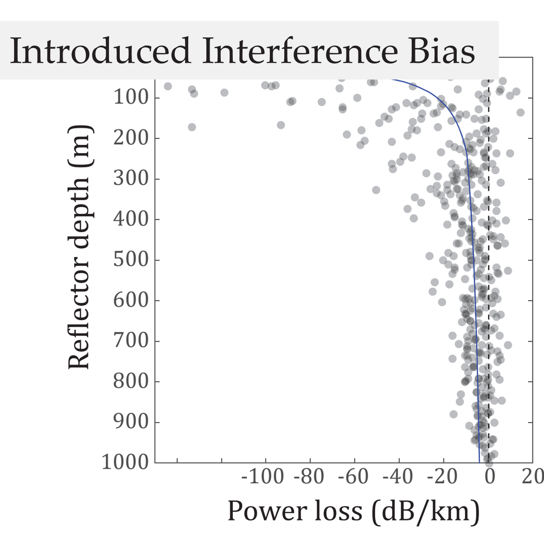


As shown in the conductivity log to the left, measured from the NEEM Ice Core, englacial reflections are unique dielectric layers are far thinner than the radar wavelength (~68m). As a result, the reflection strength is dictated by the interferences of many sub-wavelength layers.

When we model synthetic CMPs (figures to the right), we find that the effective layer thinning that results from the hyperbolic move-out for englacial layers results in enhanced destructive interference, on average reducing returned power with increasing transmission angle.







The Conclusion

Englacial reflections result from the integrated effect of many sub-wavelength interfaces. The packet of interfaces over which the radio wave integrates changes depending on the source-receiver offset, leading to an unaccounted-for source of power variability that cannot be removed from the signal.

Acknowledgments

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