Supplemental Information for Brief Communication: Evaluating Snow Depth Measurements from Ground-Penetrating Radar and Airborne Lidar in Boreal Forest and Tundra Environments during the NASA SnowEx 2023 Campaign

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S1 Ground-Penetrating Radar Systems and Methods

We operated four ground-penetrating radar (GPR) systems to cover the five field sites, including two surface-coupled 1.0 GHz center-frequency PulseEkko Pro single transceiver/receiver systems, an air-coupled 1.0 GHz center-frequency PulseEkko Pro single transceiver with dual polarization receivers system, and a surface-coupled 1.6 GHz GSSI single transceiver/receiver system. The PulseEkko Pro systems have a 6 dB bandwidth of 500–1500 MHz, whereas the GSSI system has a 6 dB bandwidth of 800–2400 MHz. Each GPR used a GPS system to provide locations for collected traces: the air-coupled PulseEkko Pro used a Geode dGPS system (±0.5 m accuracy), the two sled-coupled PulseEkko Pro GPRs used Emlid RS2 rovers with Emlid RS2 bases located nearby for post-kinematic processing (±0.5 m accuracy), and the sled-coupled GSSI GPR used a commercial-quality GPS system (±3 m accuracy).

The two-way travel times (*twtt*) of the snow-ground interface were manually identified for all single-polarization GPR datasets (e.g., McGrath et al., 2019), but the *twtt* for the dual-polarization GPR dataset was obtained by utilizing the coherent reflection between the two receivers (further details provided in Meehan et al., 2024). The *twtt* can be converted to snow depth with an estimate of the snowpack radar velocity (v_s; Daniels, 2004)

$$v_s = \frac{c}{\sqrt{\varepsilon_s}}, \quad (1)$$

where c is the speed of electromagnetic energy in a vacuum and ε_s is the dielectric permittivity of the snowpack. Snowpack conditions were dry during our surveys, thus, the relative permittivity can be approximated from the bulk snow density (ρ_s) through an empirical relation (Kovacs et al., 1995)

$$\sqrt{\varepsilon_s} = 1 + \frac{0.845 \times \rho_s}{1000}. \quad (2)$$

Snow density was sampled in snow pits adjacent to the surveyed transects using 1000 cm^3 wedge samplers at 10 cm intervals along two columns in the snow pit. If density measurements differed by more than 10% for a single layer, a third measurement was acquired. For layers with three measurements, we excluded the measurement with the largest difference. We then calculated bulk snow densities as the column average. Finally, snow depth (Ds) is calculated as

$$D_s = \frac{twtt}{2} \times v_s. \quad (3)$$

Supplemental Tables

Table S1: Daily snow depth accumulation measurements during the March 2023 SnowEx campaign. Measurements from Farmers Loop/Creamer's Field (FLCF) were obtained from the Creamer's Field SNOTEL station (Site ID: 1302). Measurements obtained from the Caribou/Poker Creek Research Watershed (CPCRW) and Upper Kuparuk-Toolik (UKT) field sites were collected on storm interval boards. No measurements were available from the Bonanza Creek Experimental Forest (BCEF). Arctic Coastal Plain (ACP)snow depth accumulation was estimated from precipitation measurements (estimated snow density = 75 kg m^{-3}) obtained from the NOAA AK Deadhorse 3 S weather station. Trace indicates accumulated snow depth of <0.01 m.

Date	FLCF	CPCRW	UKT	ACP
8 March	0 m	Trace	0.18 m	0.02 m
9 March	0.03 m	0.08 m	0 m	0 m
10 March	0.03 m	0.02 m	0 m	Trace
11 March	0 m	No Observation	0.02 m	Trace
12 March	0 m	Trace	No Observation	0.02 m
13 March	0.05 m	No Observation	0.03 m	0 m
14 March	0 m	No Observation	0 m	0 m
15 March	0 m	No Observation	0 m	0 m

Table S2: Boreal forest 2023 snow depth means and standard deviations (std) from GPR, excavated depth, and lidar transect profiles. Snow densities used to calculate radar velocity for the GPR snow depths are also given.

Site	Date	Transect ID	Bulk Snow Density (kg m^{-3})	GPR Mean (m)	GPR std (m)	Excavated Mean (m)	Excavated std (m)	Lidar mean (m)	Lidar std (m)
FLCF	7 March	DN013	207	0.56	0.06	0.48	0.05	0.40	0.10
		CN069	253	0.58	0.05	0.56	0.05	0.36	0.05
	8 March	WN104	197	0.85	0.04	0.51	0.11	0.52	0.07
		DN040	218	0.74	0.02	0.42	0.13	0.49	0.14
	9 March	WB032	163	0.64	0.02	0.60	0.09	0.03	0.08
	10 March	EB100	187	0.54	0.08	0.59	0.09	0.36	0.09
	11 March	DN091	193	0.60	0.05	0.73	0.03	0.51	0.07
	13 March	DB106	208	0.48	0.08	0.60	0.06	0.31	0.01
BCEF	10 March	WB497	204	0.76	0.07	0.69	0.08	0.45	0.06
	13 March	DB337	208	0.63	0.07	0.55	0.10	0.49	0.06
	14 March	SA326	225	0.81	0.08	0.76	0.09	0.65	0.06
	15 March	WA437	198	0.96	0.06	0.74	0.15	0.73	0.03
CPCRW	8 March	DB247	214	0.84	0.05	0.71	0.10	0.61	0.06
	9 March	DB254	207	0.80	0.04	0.80	0.04	0.41	0.12
	11 March	WN281	193	0.95	0.07	0.91	0.13	0.72	0.03
		WA282	208	0.77	0.03	0.79	0.05	0.70	0.03
	14 March	EA229	250	0.73	0.05	0.72	0.11	0.74	0.06

Table S3: Arctic Coastal Plain 2023 snow depth means and standard deviations (std) from GPR, excavated depth, and lidar transect profiles. Snow densities used to calculate radar velocity for the GPR snow depths are also given.

Date	Transect ID	Bulk Snow Density (kg m^{-3})	GPR Mean (m)	GPR std (m)	Excavated Mean (m)	Excavated std (m)	Lidar mean (m)	Lidar std (m)
11 March	A557	317	0.31	0.05	0.25	0.07	0.44	0.02
	N556	234	0.31	0.06	0.30	0.05	0.58	0.01
12 March	A500	256	0.45	0.10	0.41	0.09	0.55	0.07
	N501	243	0.30	0.03	0.28	0.02	0.39	0.04
	N502	256	0.18	0.05	0.17	0.05	0.37	0.02
13 March	A522	255	0.42	0.02	0.43	0.03	0.62	0.02
	A523	295	0.41	0.07	0.30	0.05	0.45	0.03
	I529	283	0.26	0.05	0.24	0.06	0.41	0.03
	N524	311	0.26	0.05	0.28	0.06	0.56	0.02
14 March	N547	276	0.30	0.02	0.20	0.04	0.42	0.01
	A548	255	0.32	0.06	0.34	0.05	0.52	0.03
	I549	359	0.40	0.04	0.39	0.04	0.50	0.05
	N546	247	0.37	0.10	0.32	0.09	0.56	0.03

Table S4: Upper Kuparuk-Toolik 2023 snow depth means and standard deviations (std) from GPR, excavated depth, and lidar transect profiles. Snow densities used to calculate radar velocity for the GPR snow depths are also given.

Date	Transect ID	Bulk Snow Density (kg m^{-3})	GPR Mean (m)	GPR std (m)	Excavated Mean (m)	Excavated std (m)	Lidar mean (m)	Lidar std (m)
8 March	N659	291	0.46	0.02	0.49	0.06	0.61	0.01
9 March	A784	225	0.45	0.05	0.38	0.05	0.47	0.03
	N787	238	0.70	0.27	0.80	0.17	0.76	0.11
	N789	274	0.53	0.10	0.57	0.14	0.57	0.06
	N786	231	0.72	0.06	0.56	0.10	0.69	0.08
	N788	250	0.92	0.06	0.64	0.04	0.81	0.05
	A790	291	0.38	0.07	0.42	0.07	0.42	0.03
10 March	A766	220	0.46	0.08	0.49	0.07	0.30	0.07
	N762	225	0.39	0.05	0.41	0.04	0.31	0.06
	A760	226	0.54	0.09	0.54	0.06	0.39	0.03
	A759	229	0.42	0.10	0.44	0.09	0.39	0.04
11 March	N730	214	0.39	0.04	0.47	0.03	0.29	0.08
	A739	233	0.40	0.03	0.40	0.04	0.26	0.03
15 March	D698	229	0.39	0.04	0.42	0.08	0.48	0.08

Supplemental Figures

Figure S1: Photo mosaic of Transect DN013 from 7 March 2023 in Farmers Loop/Creamer's Field. Approximate length is 10 m.

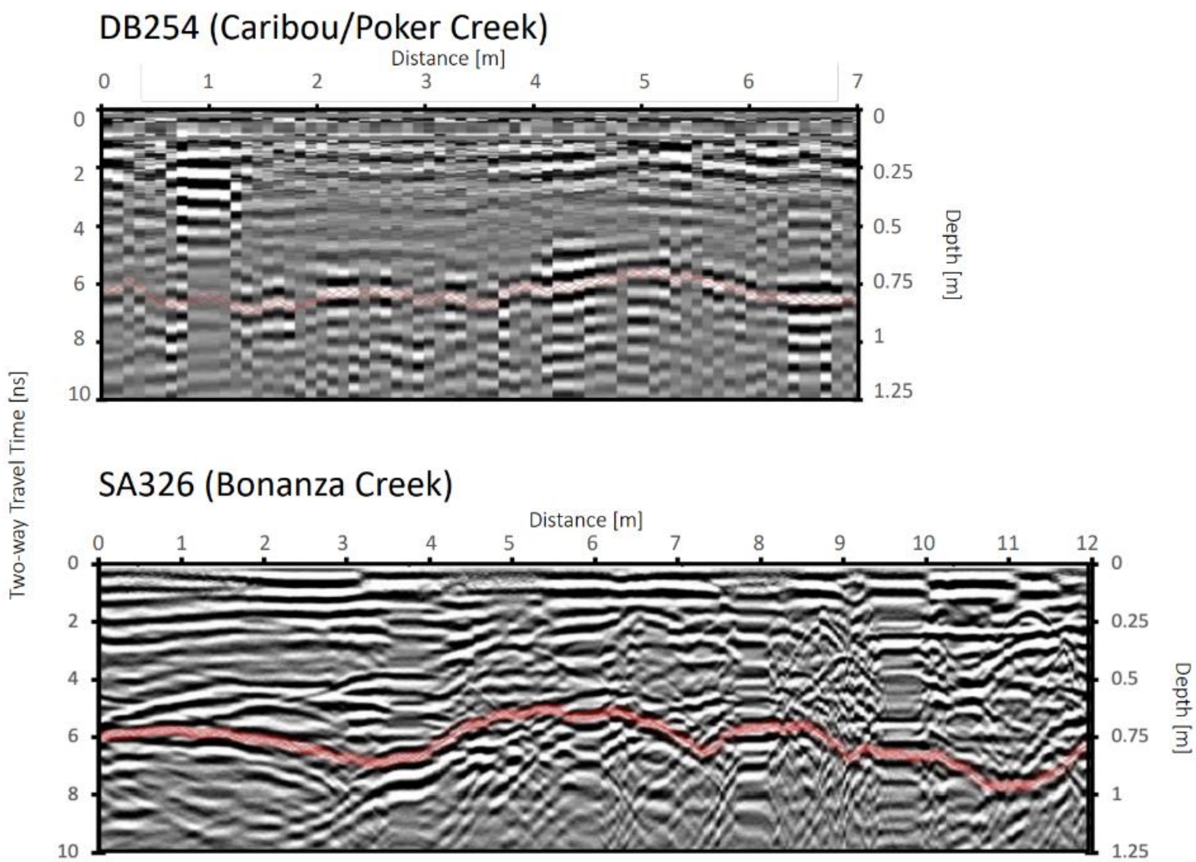

Figure S2: Radargrams showing transects DB254 from Caribou/Poker Creek Research Watershed and SA326 from Bonanza Creek Experimental Forest. Transect DB254 was surveyed team with the 1.0 GHz GPR and, whereas transect SA326 was surveyed with the 1.6 GHz GPR, demonstrating the resolution difference between GPRs.

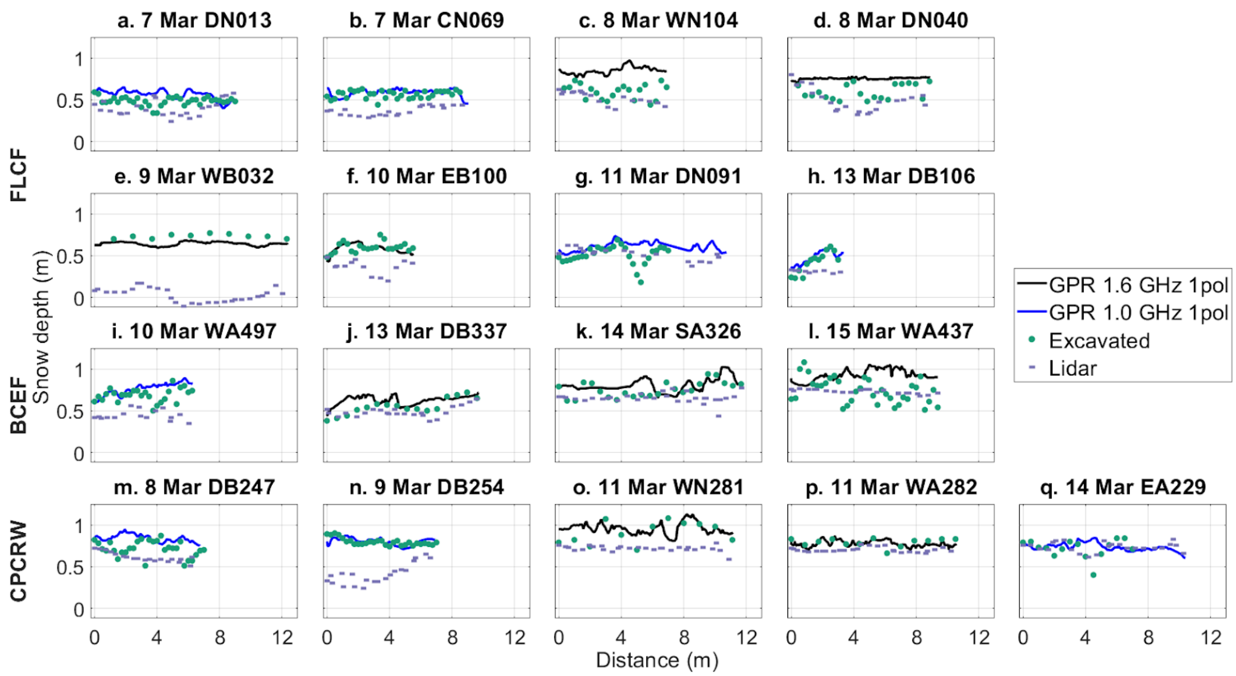

Figure S3: Snow depth profiles at the boreal forest for the (a–h) Farmer's Loop/Creamer's Field (FLCF), (i–l) Bonanza Creek Experimental Forest (BCEF), and (m–q) Caribou/Poker Creek Research Watershed (CPCRW) field sites. GPR snow depth profiles were collected by the CRREL 1.6 GHz GPR system and the Colorado State University 1.0 GHz GPR system. Subplots are labeled by transect numbers.

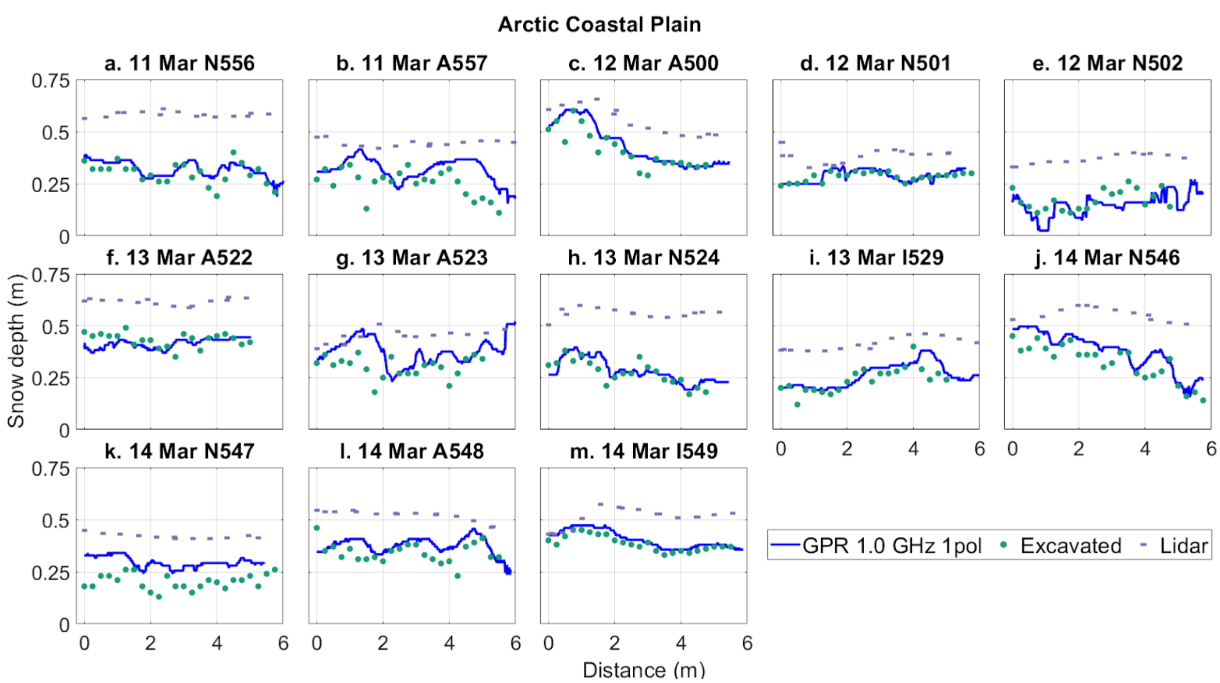

Figure S4: Snow depth profiles at the Arctic Coastal Plain tundra field site organized by date and transect number. GPR snow depth profiles were collected by the University of Wyoming 1.0 GHz GPR system.

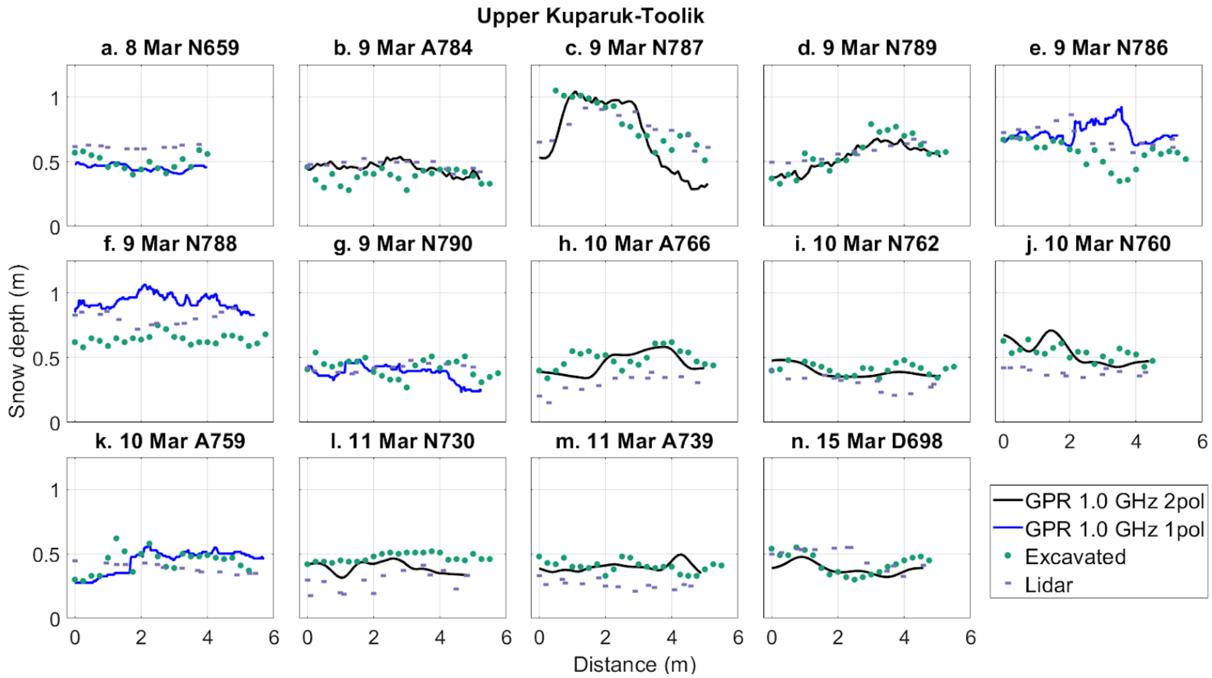

Figure S5: Snow depth profiles at the Upper Kuparuk-Toolik tundra field site organized by date and transect ID. GPR snow depth profiles were collected by the University of Wyoming 1.0 GHz GPR system and the CRREL dual-polarization 1.0 GHz GPR system.

Data Availability

GPR, lidar, and snow pit data are archived with the NSIDC DAAC (Bonnell and McGrath, 2024; Larsen, 2024; Mason et al., 2024; Meehan and Rowland, 2024; Webb, 2024). Creamer's Field SNOTEL data are available at https://wcc.sc.egov.usda.gov/nwcc/site?sitenum=1302. NOAA AK Deadhorse 3 S weather station data are available at https://www.ncei.noaa.gov/access/crn/sensors.htm?stationId=1793.

Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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