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Monitoring snow depth change across a range of landscapes with ephemeral snowpacks using structure from motion applied to lightweight unmanned aerial vehicle videos

Richard Fernandes et al.

Correspondence to: Richard Fernandes (richard.fernandes@canada.ca)

Supplementary Material

S1. Ground Control Point Design

GCP targets at Gatineau consisted of both 30 cm square plywood (Figure S1a) and 15 cm diameter plastic disks (Figure S1b) suspended between 1 m and 1.3 m above ground level on fence posts or poles to avoid artificially increasing the accuracy of SD estimates by placing control points on the snowpack surface. The targets had a red background with a yellow cross (for boards) or black centre (for disks) marked with tape. Targets were cleaned prior to flights. Based on experience at Gatineau, GCP targets corresponding to plastic pylons, suspended on fence posts at ~1.3 m height (Figure S1c) were used at Acadia to reduce the need to clear snow from targets (e.g. Figure S1d) and to assist in identifying the centre of the GCP target within UAV imagery. Black tape was used to mark vertical stripes on the cones to increase their visibility.

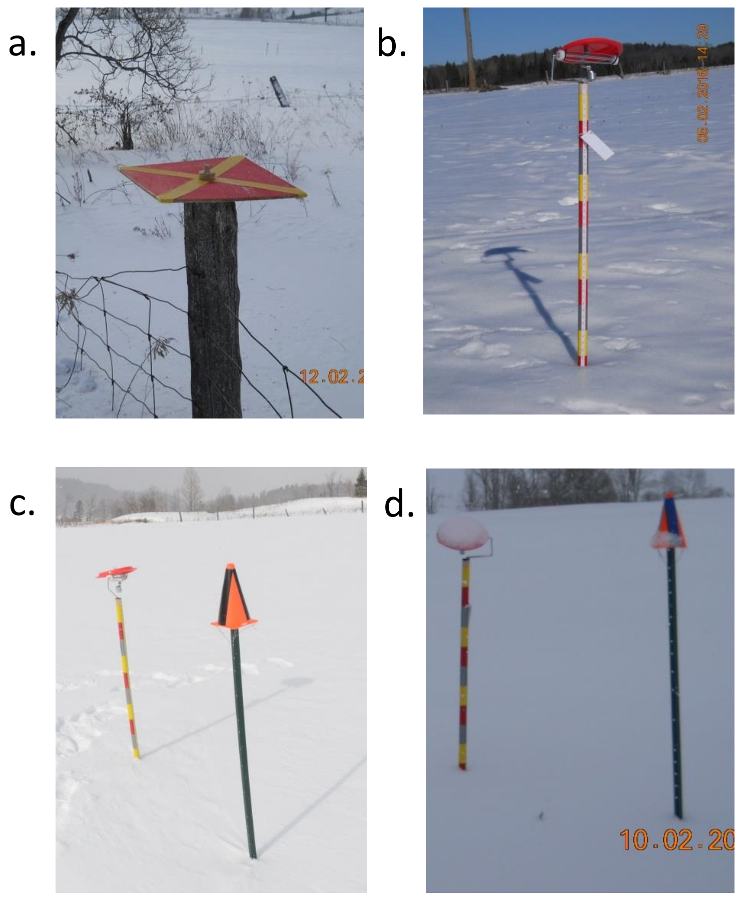

Figure S1. GCP Targets: a) square plywood b) disk on pole and c) snow free disk on pole and cone on pole d) snow covered disk on pole and cone on pole.

S2. In-Situ Snow Depth Estimation

In-situ ΔSD was estimated at each stake using the protocol described in Oakes et al. (2016). Stakes were covered with black all weather tape in addition to two red bands each 10 cm wide separated by 50 cm (Figure S2). For snow free conditions, the freeboard (F), defined as the stake height above the current surface, was determined from the plum-bob measurement. Otherwise, F was determined using an in-situ high resolution digital image. For each stake, a 14 Mpixel photograph (Nikon D7000 camera and 70-300 mm / f4.5 Nikon lens) was taken ~5 m parallel to the transect using manual focus and automatic exposure. To reduce precision errors due to localized snow melt or drifting at the stake, the point of intersection of the snow pack and the stake was visually determined by interpolating the snow pack horizon closest to the front of the stake (e.g. Figure S2) rather than within the well (or mound) of snow adjacent to the stake. The distance from the top of the stake to the edge of each visible red-tape band and to the midpoint of the snow pack intersection with the stake was measured in pixel units using Adobe Photoshop. Freeboard was then estimated using the ratio of distances in pixel units and the known distance between bands and converted to a vertical distance using measurements of the stake angle. The difference in F between two dates was used to estimate ΔSD at each stake. When comparing snow covered conditions, the uncertainty for measuring the ΔSD assuming independent errors in determining F is ~2.06 cm (95% confidence interval) for typical uncertainties in delineating F and the stake angle (Oakes et al. 2016). As both sources of uncertainty are spatially random the uncertainty in estimating the average snow depth using all 12 stakes in a transect is ~0.60 cm (95% confidence interval).

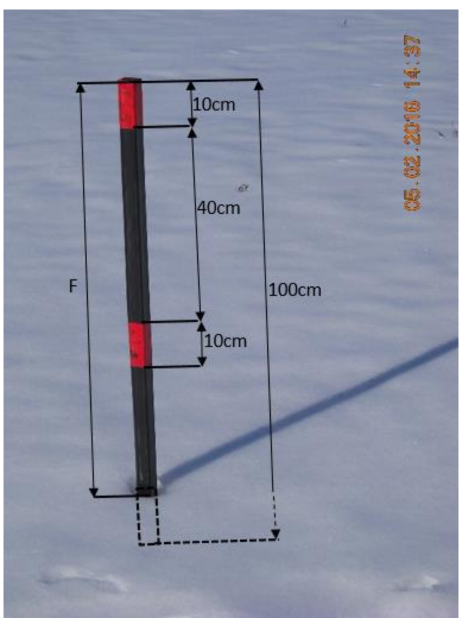

Figure S2**. In-situ snow stake measurements. Dashed lines correspond to locations below the snow surface.**

S3. UAV Specifications

Specifications of the Phantom 3 Professional UAV systems used in our study are provided in Table S1. For convenience, missions were constrained to a single P3P battery. Since surveys were to be conducted in cold and windy conditions a maximum flight time of 17.25 minutes was used for flight planning. The effective time for image acquisition was further reduced to 15 minutes to accommodate travel time to and from the launch location and to execute turns between flight tracks.

Table S1. UAV Specifications

Parameter	Value	Abbreviation
Mass	1280g	-
Operating Temperature	0 ^{0}C to 40 ^{0}C	T
Flight Time per Battery	23 minutes	t_{max}
Maximum Cruising Speed	16 m/s	v
Vertical Precision	0.5 m	δ_z
Horizontal Precision	1.5 m	δ_x
Lens Focal Length	3.66624 mm	c
Camera Aperture	f2.8	F
Diagonal Field of View	94^0	θ
Camera Sensor	Sony Exmor IMX377	-
Detector Size	1.55 µm	l
#Vertical Pixels	3044 pixels	-
#Horizontal Pixels	4072 pixels	-
Video Frame Rate	24 frames/s	f_{max}
Video Vertical Resolution	2160 pixels	n_y
Video Horizontal Resolution	4096 pixels	n_x
Video Effective Detector Size	1.57937 cm	l_e

S4. UAV Mission Parameters

Trial flights using parameters given in Table S2 were performed at both GN and GS on one sunny day (January 26, 2016) and one overcast day (February 2, 2017) with complete snow cover and processed using Pix4D Version 3.0. The lowest feasible H of 50 m (to ensure clearance of terrain and cover a 10 ha site using one battery) was selected to provide a best case estimate of the matches per key point, K, corresponding to the smallest feasible GSD.

Table S2. Mission parameters. The nominal 10ha study area assumes a rectangular region with 300 m transects.

Parameter	Value	Abbreviation
Height	50 m	H
Speed	3.5 m/s	v
Ground Sampling Distance	0.021 m	GSD
Effective Shutter Speed	<0.02 s	τ_e
Motion Blur	0.039 pixels	None
Track spacing	15 m	b_{ac}
Frame sampling interval	1 s	None
Across Track Overlap	82%	None
Along Track Overlap	93%	None
Minimum study area	10 ha	A

Figure S3 indicates that K followed an exponential distribution that was relatively consistent over the four flights. Key points with $K = 2$ matches were discarded as insufficiently accurate to include in the horizontal uncertainmty estimation. In this case, the average K over the four missions was 5.5 matches with a range of 4.3 matches to 7.4 matches. The two overcast dates had lower than average K while the sunny dates were above average.

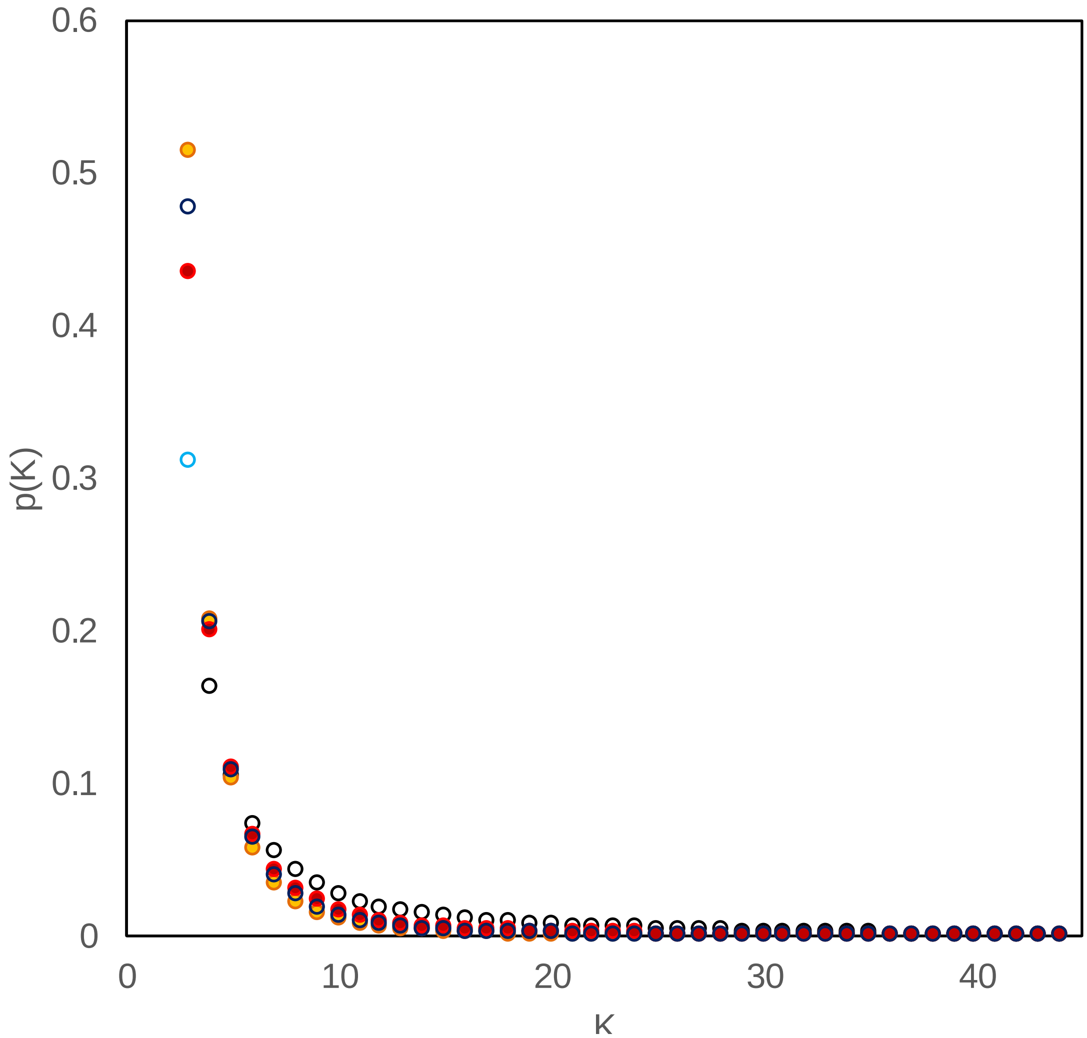

Figure S3. Empirical probability of observing *K* matches for key points acquired during four trial missions (filled symbols are for overcast dates)

S5. Post-Processing of UAV Video Imagery

I. The two videos were subsampled with a 1s interval and extracted as JPEG images together with ephemeris data to provide an initial location for each image. The 1s interval ensured the desired minimal along track overlap while minimizing computation.

II. Nominal geolocation uncertainty was specified as 5 m horizontal and 10 m vertical considering that the P3P was always operating within Wide Area Augmentation System coverage.

III. Camera parameters, including distortion, were initialized using the P3P Video specification with rolling shutter.

IV. An initial camera calibration and point cloud was produced using the Pix4D algorithm for feature matching and bundle adjustment with rolling shutter correction.

V. Each GCP was manually geolocated in as many (at least 10) JPEG images as feasible.

VI. Feature matching was repeated and internal and external camera parameters refined using bundle adjustment with rolling shutter correction at the highest quality setting.

VII. If the GCPs were not fit within 5 cm root mean square difference (RMSD) steps V. and VI. were repeated once.

VIII. The point cloud was densified using the Pix4D default two pixel sub-sampling of images.

IX. The resulting dense point cloud (PC) was exported to MATLAB in XYZ format.

X. To quantify the geolocation uncertainty of the point cloud the internal and external camera parameters were refined while holding out individual GCPs.

S6. Results of Point Cloud Processing.

Tables S3 and S4 list missions. Three missions were not processed due to issues with the recorded data. In one case (GS 26/01/2016) the camera was pointed horizontally rather than nadir looking down. In the other two cases (AA 23/02/2016 and AC 10/03/2016) the mission was aborted due to a communication error between the flight controller and the UAV. It was later determined this error was due to a conflict between automatic updates of the Lichee software and manual updates of the P3P control software.

Table S3. Results of point cloud processing at Gatineau. RMSD and Bias correspond to use of all available GCPs. Bold rows were not successful.

Date	Site	Images		Matches	A	GSD	GCP	RMSD			Bias		
		#	#cal	#/image	ha	cm	#	x cm	y cm	z cm	x cm	y cm	z cm
2016-01-26	GN	803	800	6981	12.66	2.04	7	7.8	6.6	4.3	-0.05	-38	-.012
2016-01-26	**GS**	**0**											
2016-02-02	GN	881	871	13074	12.86	2.00	6	16	11	2.7	0.06	0	0.24
2016-02-02	GS	1005	997	6042	14.92	2.35	6	12.4	17.0	18.3	0.02	0.13	-0.33
2016-02-10	**GN**	**868**	**280**	**318**	**3.21**	**1.61**	**0**						
2016-02-10	GS	877	618	729	12.8	2.53	7	0.3	1.0	1.1	0	0	0
2016-02-12	**GN**	**883**	**319**	**119**	**6.54**	**2.01**	**0**						
2016-02-12	GS	880	702	710	13.75	2.25	7	0.5	1.0	0.3	0	0	0
2016-02-17	**GN**	**882**	**325**	**451**	**7.47**	**2.01**	**0**						
2016-02-17	GS	876	723	450	15.16	2.56	6	0.8	0.8	0.9	-0.04	0.01	0.07
2016-02-18	GN	867	851	1455	12.71	2.01	7	0.75	1.37	2.78	0	0	-0.02
2016-02-18	GS	879	856	2040	15.05	2.42	8	1.09	1.20	1.09	0.01	0.00	-0.05
2016-02-22	GN	885	873	3319	12.46	1.75	7	0.52	1.22	1.57	-0.01	-0.01	-0.11
2016-02-22	GS	873	870	2846	23.83	2.32	9	1.80	1.16	1.03	0	0	0
2016-02-29	**GN**	**905**	**327**	**1200**	**0**	**0.1**							
2016-02-29	GS	864	783	580.61	14.42	2.21	8	1.3	1.0	0.6	-0.02	0	0
2016-03-04	GN	892	863	1597	11.79	1.84	7	0.5	0.7	1.0	0	-0.01	-0.02
2016-03-04	GS	867	805	1541	17.13	2.51	8	0.9	1.4	0.6	0	0	0
2016-03-17	GN	947	911	2496	14.11	2.09	7	1.23	2.14	2.08	0	0	0
2016-03-17	GS	859	852	3104	13.99	2.42	6	1.9	3.7	1.7	0.03	0.06	-0.03
2016-03-21	GN	937	932	6442	13.98	1.85	7	1.51	0.83	3.16	0	-0.01	0.08
2016-03-21	GS	931	931	7553	16.45	2.17	8	3.39	1.67	0.80	0.01	0.01	-0.01
2016-03-26	GN	923	916	2714	16.15	2.01	7	1.06	0.73	1.87	0.01	0	-0.13

2016-03-26	GS	931	907	14237	17.48	2.16	8	4.6	1.9	0.6	-0.07	-0.04	0.15
2016-04-19	GN	1096	927	13143	16.37	2.85	7	1.21	1.52	2.11	0.03	0.02	0.15
2016-04-19	GS	1185	971	14209	17.25	2.9	8	1.86	1.92	1.10	0.05	-0.06	0.16

Table S4. Results of point cloud processing at Acadia. RMSD and Bias correspond to use of all available GCPs. Bold rows were unsuccessful.

Date	Site	Images		Matches	A	GSD	GCP	RMSD			Bias		
		#	#cal	#/image	ha	cm	#	x cm	y cm	z cm	x cm	y cm	z cm
2016-02-06	AA	735	734	5718	6.13	1.96	6	4.2	5,3	0.8	0.4	0.04	0.08
2016-02-06	AB	668	665	7033	7.9	2.1	5	4.1	7.5	2.0	0.1	0.12	0.13
2016-02-06	AC	701	675	8267	7.08	1.84	5	2.7	5.1	1.7	-0.01	0.17	0.12
2016-02-10	AA	873	828	2428	6.77	1.98	4	0.5	2.7	0.5	0	-0.05	0
2016-02-10	AB	833	801	3531	8.78	2.12	6	0.7	0.4	0.9	-0.11	0.08	-0.18
2016-02-10	AC	828	814	3860	7.12	1.85	5	0.4	0.9	0.4	0.02	-0.05	-0.09
2016-02-18	AA	867	835	7184	7.48	2.18	4	0.9	2.6	0.2	-0.01	-0.01	0.02
2016-02-18	AB	850	801	8004	7.69	2.15	6	1.0	0.5	1.0	-0.11	0.10	-0.18
2016-02-18	AC	852	682	8746	7.27	1.98	5	0.5	0.6	0.3	0.01	-0.02	-0.04
2016-02-19	AA	838	791	7998	6.46	2.25	7	3.6	4.6	1.9	0.31	0.16	-0.33
2016-02-19	AB	842	830	10221	8.41	2.12	6	1.5	0.8	1.0	-0.23	0.15	-0.32
2016-02-19	AC	839	825	9265	7.12	1.84	5	0.5	0.7	0.4	0.02	-0.03	-0.04
2016-02-23	**AA**	**0**											
2016-02-23	AB	891	867	14811	9.82	2.12	6	1.4	1.0	1.3	-0.24	0.21	-0.35
2016-02-23	AC	888	878	8413	7.10	1.86	6	0.72	0.32	2.8	-0.30	0.36	0.15
2016-03-04	AA	885	840	8721	7.39	2.21	4	0.8	2.1	0.4	0	0	-0.01
2016-03-04	AB	887	865	10999	8.20	2.15	6	1.6	0.8	1.1	-0.32	0.22	-0.44
2016-03-04	AC	820	818	8877	7.12	1.86	5	0.4	0.5	0.3	0	-0.01	-0.03
2016-03-06	AA	914	802	7684	6.25	2.19	4	1.8	2.2	1.0	0.01	-0.02	-0.06
2016-03-06	AB	877	834	14445	9.15	2.15	6	1.69	0.66	1.42	0.08	-0.05	0.48
2016-03-06	AC	805	801	11396	9.56	1.93	3	0.97	0.74	0.28	0	0.01	-0.02
2016-03-08	AA	891	889	7889	7.80	2.07	4	0.89	2.4	0.46	0	0	0
2016-03-08	**AB**	**935**	**236**	**15880**	**7.73**	**2.04**	**0**						
2016-03-08	AC	815	811	8814	7.80	2.06	5	0.4	0.5	0.7	0.01	-0.03	-0.05
2016-03-10	AA	880	874	6723	7.40	2.19	4	0.7	2.4	1.1	0.03	-0.07	-0.05
2016-03-10	AB	843	796	8988	7.64	2.08	6	0.9	0.4	2.5	0.02	-0.02	-0.02

2016-03-10	**AC**	**0**											
2016-03-11	AA	857	833	8048	6.28	2.17	4	0.83	1.95	0.21	0.02	-0.07	-0.04
2016-03-11	AB	861	840	8930	6.89	2.15	6	1.3	0.4	0.8	-0.12	0.08	-0.18
2016-03-11	AC	800	797	8586	7.88	2.02	5	0.5	0.6	0.5	0.02	-0.04	-0.08
2016-03-14	AA	857	835	7995	6.91	2.16	4	0.8	2.0	0.2	0	0	-0.01
2016-03-14	AB	863	806	10489	8.06	2.15	6	0.8	0.8	0.7	-0.07	0.06	-0.12
2016-03-14	AC	802	785	8414	7.28	1.91	5	0.1	0.6	0.3	0.01	-0.02	-0.04
2016-03-20	AA	883	880	9116	8.45	2.22	4	0.5	1.8	1.1	0	-0.02	-0.04
2016-03-20	AB	862	834	11849	7.92	1.96	6	1.6	1.4	1.4	-0.38	0.43	-0.63
2016-03-20	AC	780	777	11200	7.22	1.85	5	0.4	0.7	0.4	0.01	-0.04	-0.06
2016-03-23	AA	855	748	1381	6.01	2.1	6	9.1	5.8	1.1	0.11	0.06	-0.16
2016-03-23	AB	862	835	2194	19.42	2.14	8	3.5	4.7	1.1	-0.09	-0.09	-0.16
2016-03-23	AC	787	767	4424	7.13	2.01	5	3.5	6.1	4.6	0	-0.01	-0.04
2016-03-24	AA	861	801	2726	6.44	2.15	4	0.07	2.0	1.8	0	0	-0.01
2016-03-24	AB	860	839	466	8.61	2.14	6	0.9	0.2	0.6	0	0	0
2016-03-24	AC	776	772	3452	7.0	1.92	4	0.26	0.44	0.10	0	0	0
2016-03-26	AA	884	813	3040	8.26	2.28	7	0.60	2.3	0.60	0.01	-0.03	0
2016-03-26	AB	882	760	3314	8.41	2.12	5	0.90	0.55	0.27	0	0	0
2016-03-26	AC	793	778	3925	7.39	1.96	5	0.5	0.3	0.3	0.01	-0.02	-0.04
2016-03-30	AA	901	888	8100	6.85	2.23	7	4.4	5.4	2.0	0.57	0.35	-0.31
2016-03-30	AB	876	872	10129	7.62	2.2	6	5.2	6.3	2.8	-0.45	0.37	-0.68
2016-03-30	AC	825	807	8672	7.53	1.96	5	3.9	3.3	0.48	-0.02	0.07	0.09
2016-04-14	AA	868	850	5926	7.57	2.17	4	0.8	2.1	0.5	-0.06	0.05	0.08
2016-04-14	AB	880	853	7180	7.47	2.15	6	1.3	0.6	2.2	-0.06	0.04	-0.14
2016-04-14	AC	771	758	4977	7.11	1.88	5	0.4	0.2	0.5	0.01	-0.03	-0.08

S7. Sample Automated Keypoint Matches in Vicinity of Transects

We investigated the location of PIX4D automated keypoint matches in the vicinity of transects for all missions. Figures S4 to S8 provide typical examples of automated key point matches for the study sites. We observed that automated keypoint matches were rarely located on snow stake targets.

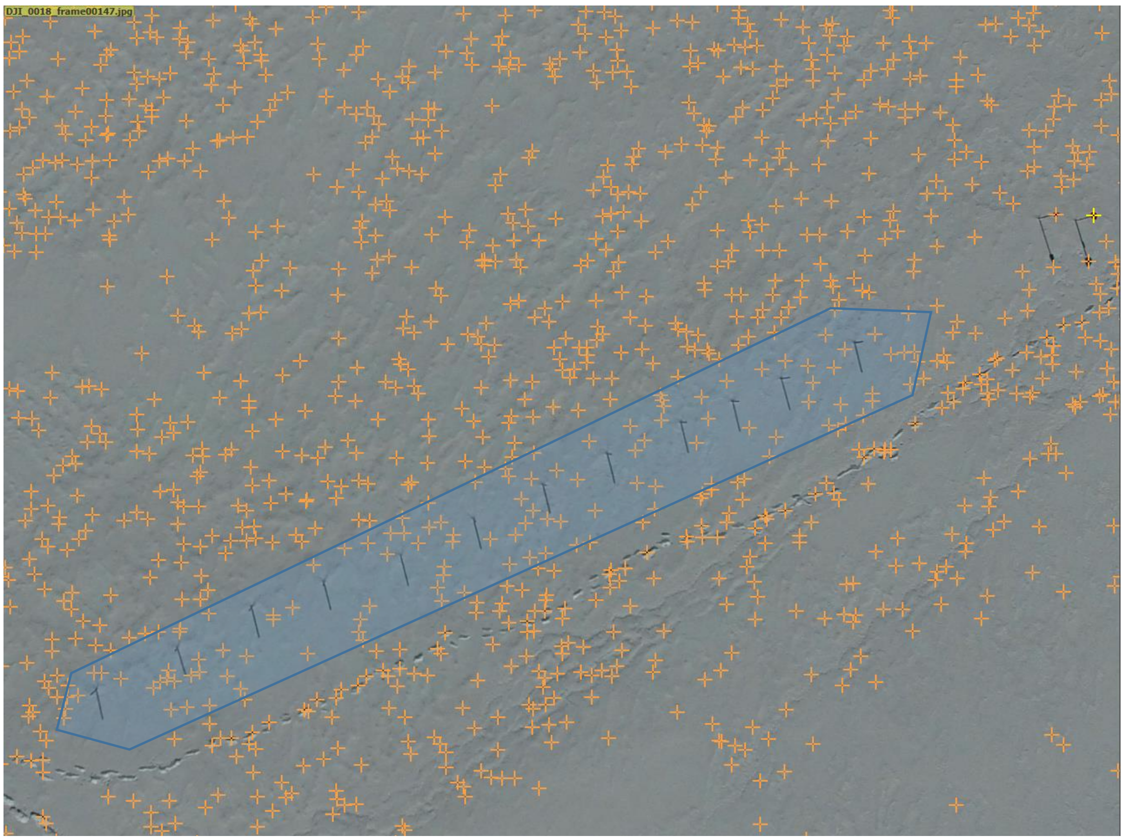

Figure S4. Automated matching key points (orange) along snow stake transects (blue shading) for typical mission at GN.

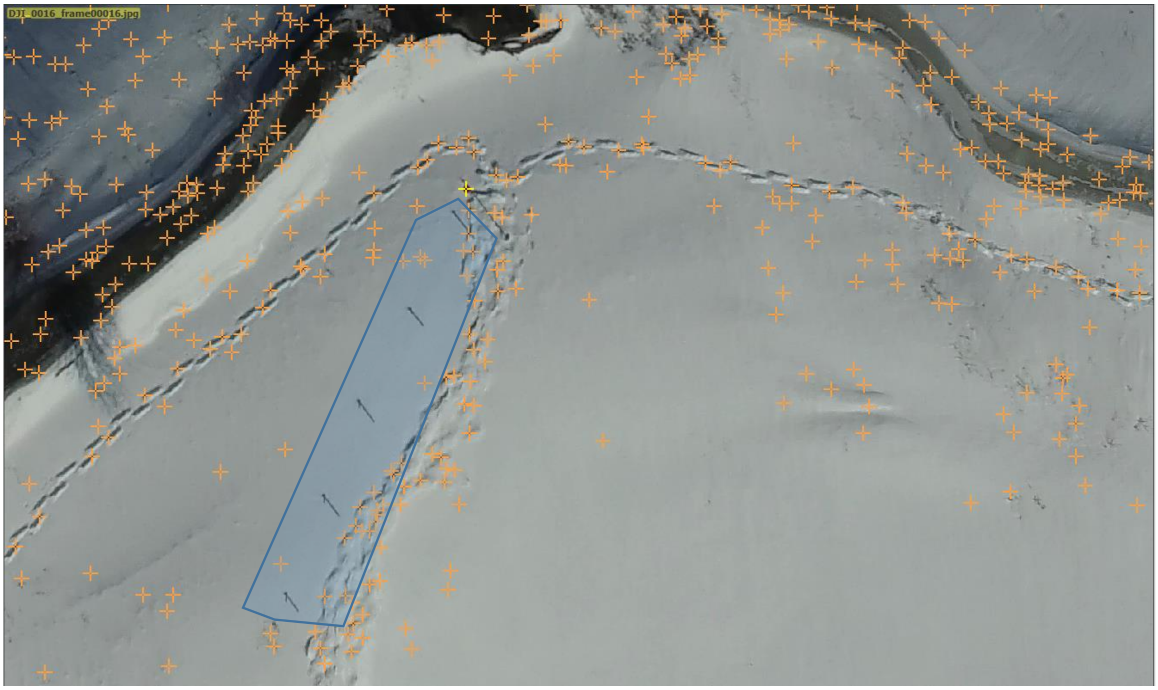

Figure S5. Automated matching key points (orange) along snow stake transects (blue shading) for typical mission at GS T1.

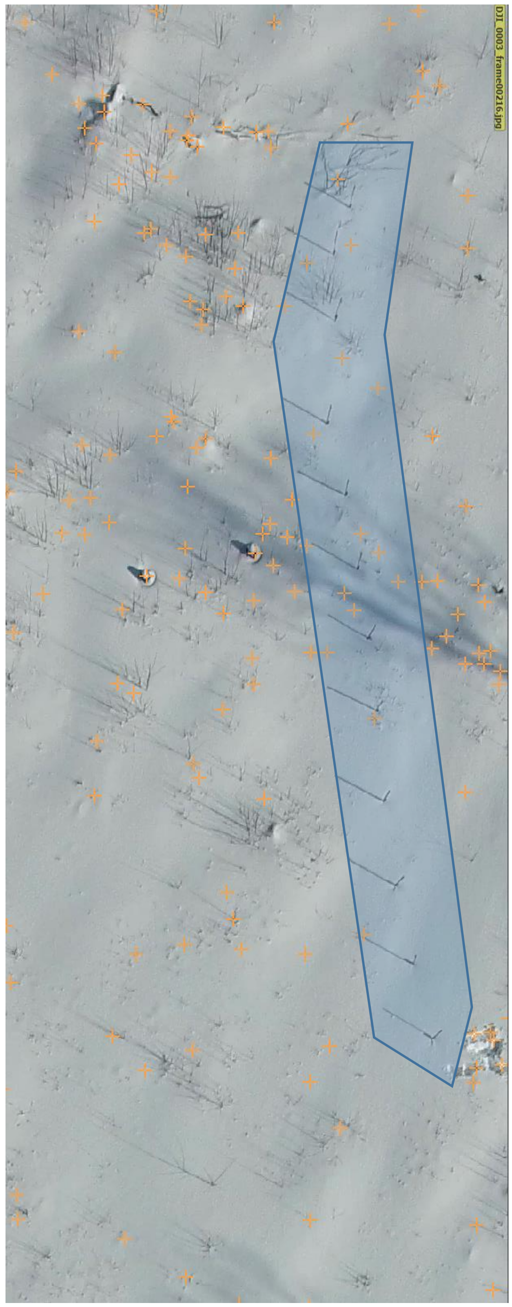

Figure S6. Automated matching key points (orange) along snow stake transects (blue shading) for typical mission at AA.

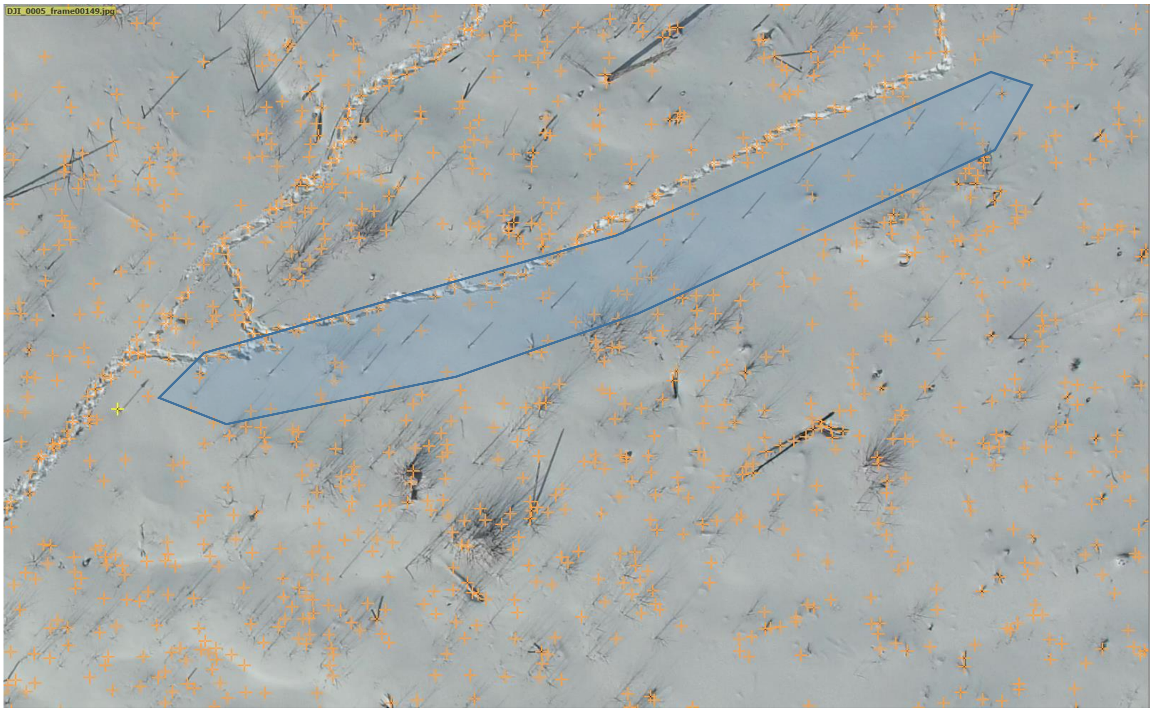

Figure S7. Automated matching key points (orange) along snow stake transects (blue shading) for typical mission at AB.

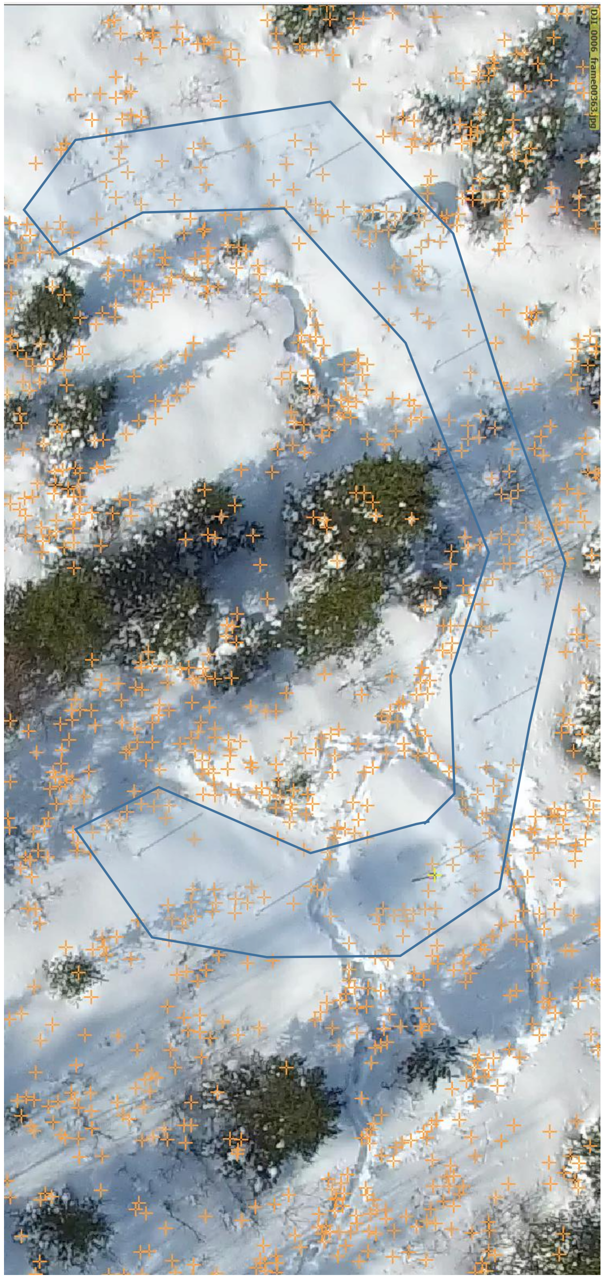

Figure S8. Automated matching key points (orange) along snow stake transects (blue shading) for typical mission at AC.