Supplementary Material

1. UAV Specifications

 $Specifications \, of \, the \, Phantom \, 3 \, Professional \, UAV systems \, used \, in \, our \, study \, are \, provided \, in \, Table \, S1.$

Parameter	Value	Abbreviation
Mass	1280g	-
Operating Temperature	0 °C to 40 °C	Т
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	с
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_{χ}
Video Effective Detector Size	1.57937 cm	l_e

Table S1. UAV Specifications

- 2. 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.

3. Results of Point Cloud Processing.

Date	Site	Imag	ges	Matches	А	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 S2. Results of point cloud processing at Gatineau. RMSD and Bias correspond to use of all available GCPs. Bold rows were not successful.

Date	Site	Im	ages	Matches	А	GSD	GC	RMSD		Bias			
							Р						
		#	#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

Table S3. Results of point cloud processing at Acadia. RMSD and Bias correspond to use of all available GCPs. Bold rows were unsuccessful.

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

4. 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 S1 to S5 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 S1. Automated matching key points (orange) along snow stake transects (blue shading) for typical mission at GN.



Figure S2. Automated matching key points (orange) along snow stake transects (blue shading) for typical mission at GS T1.



Figure S3. Automated matching key points (orange) along snow stake transects (blue shading) for typical mission at AA.



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



Figure S1. Automated matching key points (orange) along snow stake transects (blue shading) for typical mission at AC.