L3 discrete lidar processing and QA information for 2017 WREF 1

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See configuration management system for approval history.

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1 DESCRIPTION

1.1 Purpose

This document details the processing information used in the generation of the discrete lidar raster products (L3 products) from the NEON AOP (Airborne Observation Platform) which include a DTM (Digital Terrain Model, RD[09]), DSM (Digital Surface Model, RD[09]), CHM (Canopy Height Model, RD[11]), slope map (RD[12]) and aspect map (RD[12]), as well as simulated uncertainty of the point cloud. The raster products are developed from the point cloud (L1 product, LAS format). Processing is conducted through a shell script executed in cygwin, which calls several Lastools executables (https://rapidlasso.com/lastools/), as well as in-house Matlab©(http://www.mathworks.com/) scripts to automate the development of the raster products. The processing information contained here was used for processing the site termed 2017 WREF 1, flown with Optech, Inc Gemini 12SEN311 as part of payload P2C1 on dates 2017061916, 2017062117, 2017062122, 2017062215. The raster products are output in tiles, and stored in Geotiff format. All products are referenced to the ITRF00 datum and projected into the appropriate UTM zone. In addition to processing parameters used, this report also provides QA / QC information of the raster products. For further background information of the NEON LiDAR processing procedures for both the L1 and L3 products, the reader is referred to RD[08], RD[09], RD[10], RD[11] and RD[12], as well as Appendix A which contains a digram of the major components of the algorithm.

2 RELATED DOCUMENTS AND ACRONYMS

2.1 Applicable Documents

Applicable documents contain information that shall be applied in the current document. Examples are higher level requirements documents, standards, rules and regulations.

AD[01]	NEON.DOC.000001	NEON Observatory Design (NOD) Requirements
AD[02]	NEON.DOC.005003	NEON Scientific Data Products Catalog
AD[03]	NEON.DOC.005004	NEON Level 1-3 Data Products Catalog
AD[04]	NEON.DOC.005005	NEON Level 0 Data Product Catalog
AD[07]	NEON.DOC.002649	NEON configured site list

2.2 Reference Documents

Reference documents contain information complementing, explaining, detailing, or otherwise supporting the information included in the current document.

RD[01]	NEON.DOC.000008	NEON Acronym List
RD[02]	NEON.DOC.000243	NEON Glossary of Terms
RD[04]	NEON.DOC.001984	AOP flight plan boundaries design
RD[05]	NEON.DOC.005011	NEON Coordinate Systems Specification
RD[06]	NEON.DOC.001292	NEON L0-to-L1 discrete return lidar algorithm theoretical basis document
RD[07]	NEON.DOC.002890	NEON AOP Level 0 quality checks
RD[08]	NEON.DOC.003316	Discrete LiDAR Level-1 processing procedure
RD[09]	NEON.DOC.002890	NEON Elevation (DTM and DSM) Algorithm Theoretical Basis Document
RD[10]	NEON.DOC.002293	NEON discrete LiDAR datum reconciliation report
RD[11]	NEON.DOC.002387	NEON Ecosystem structure (canopy height model) algorithm theoretical basis document
RD[12]	NEON.DOC.003791	NEON Elevation (slope and aspect) algorithm theoretical basis document

2.3 Acronyms

Acronym	**Definition**
ITRF00	International Terrestrial Reference Frame 2000
UTM	Universal Transverse Mercator
AOP	Airborne Operations Platform
FBO	Fixed Base Operator
LMS	Laser Mapping Suite
SBET	Smoothed Best Estimated Trajectory

DTM	Digital Terrain Model
DSM	Digital Surface Model
CHM	Canopy Height Model

3 LAS files processed

Table 4 lists all of the LAS files that were noise filtered, with a selection of attributes. Files that were tiled, classified and used in the production of L3 products are noted in **green**. Not all files are processed into higher level products to allow for consistency in point density across the site and between yearly collects to avoid artifacts in higher level products. Additional information about the LAS files can be found in the processing report for LMS of the same site. Table 5 provides information on the spatial limits of each processed LAS files, and similar to Table 4 notes files that were tiled and used in the production of L3 products in **green**.

Table 4: Processed lines with attributes

Line	Total Records	GPS time min (s)	GPS time max (s)	Point Density (pts / m^2)
L001-1	28405240	159133.002010	159361.704994	3.42
L001-2	19545110	334472.501002	334609.002986	4.37
L001-3	42366351	334610.503011	334956.501990	3.40
L001-4	32181094	347053.001003	347319.503996	3.38
L001-5	8424565	347321.004006	347387.503989	2.87
L001-6	1384795	347389.004000	347400.723356	2.40
L001-7	18603191	404347.001011	404477.001996	4.30
L001-8	9107015	404274.001005	404345.001000	3.19
L001-9	31262552	404015.004005	404272.500992	3.30
L002-1	1166426	334008.001009	334015.001000	4.91
L002-2	5833484	334043.001006	334082.001996	4.01
L002-3	12332765	405245.003003	405323.002997	4.89
L003-1	11780979	333770.503005	333845.503999	4.53
L003-2	11647136	405506.005005	405579.999997	4.39
L004-1	11443836	333242.002004	333315.002997	4.62
L004-2	9039654	405803.002002	405859.002998	4.88
L005-1	11319198	332945.003007	333018.003992	4.26
L005-2	11953859	333498.005001	333575.000986	4.56
L005-3	11546552	406041.004009	406115.499994	4.34
L006-1	11977652	332686.000003	332761.000991	4.75
L006-2	11588219	406311.502012	406384.503000	4.57
L007-1	11836786	332387.502006	332461.502992	4.41
L007-2	12579288	406572.005010	406649.999993	4.65
L008-1	12067172	332122.504003	332200.004991	4.48
L009-1	12568691	331847.501010	331924.501995	4.92
L010-1	11861084	331606.503004	331680.003995	4.58
L011-1	12241231	331346.500005	331421.500994	4.78

L012-1	12464676	331108.502010	331185.002999	4.86
L013-1	12613550	330825.004000	330902.999995	5.09
L014-1	12260233	330572.502007	330649.002000	4.74
L015-1	12273227	330268.003008	330343.003996	4.74
L016-1	12434034	329995.000001	330070.500999	4.98
L017-1	12731831	329722.002001	329800.502998	4.90
L018-1	13474993	329465.005010	329546.499995	5.30
L019-1	13767691	329192.002001	329274.001992	5.38
L020-1	12138569	328928.004004	329005.004994	4.60
L021-1	11638670	328674.001007	328748.501993	4.57
L023-10	2065652	328226.001003	328244.000998	2.72
L023-1	7219976	328078.005012	328129.499996	3.84
L023-2	3775093	328185.001001	328218.000992	2.60
L023-3	1011770	328148.500004	328157.499987	3.16
L023-4	1039502	328018.504012	328026.003995	3.63
L023-5	249807	335404.502004	335406.001993	5.42
L023-6	386953	328171.501005	328175.000990	2.92
L023-7	3898856	335428.502006	335457.002994	3.79
L023-9	4351135	328040.004004	328072.005000	4.91
L024-1	27562665	327620.505006	327843.001989	3.29
L025-1	28938042	327192.000014	327422.502996	3.44
L026-1	27672040	326793.001012	327017.503991	3.26
L027-1	29029591	326323.502002	326559.003993	3.47
L028-1	28868675	325899.503018	326134.004999	3.41
L029-1	27055088	325284.502009	325498.503998	3.17
L030-1	29561118	324856.003008	325089.499988	3.54
L031-1	28189952	147683.502012	147908.003987	3.40
L032-1	28763894	148121.001012	148349.001989	3.45
L033-1	27762350	148524.504001	148744.000998	3.35
L034-1	30351103	148988.003017	149225.504989	3.61
L035-1	28052111	149435.001014	149650.002992	3.38
L036-1	31319359	149869.500008	150106.001987	3.71
L037-1	28881413	150278.504010	150501.500993	3.37
L038-1	29776494	150679.002011	150909.503991	3.53
L039-1	28401410	151083.501001	151306.502997	3.36

L040-1	28914640	151483.004009	151710.500997	3.46
L040-2	29073415	407071.005002	407295.001987	3.48
L041-1	28996428	151881.003007	152108.003994	3.47
L041-2	28634200	407488.005013	407707.001996	3.44
L042-1	29807035	152312.001014	152544.502993	3.58
L042-2	28284610	408203.003003	408419.499987	3.46
L043-1	27462402	152743.505006	152960.501994	3.32
L043-2	28592103	408627.003011	408847.500994	3.49
L044-1	28379750	153153.503001	153376.499995	3.47
L044-2	29208159	409041.003003	409266.000987	3.56
L045-1	28136739	153569.502010	153791.003988	3.44
L045-2	28893684	409464.003011	409685.999994	3.59
L046-1	28199059	153979.000000	154207.001993	3.38
L046-2	28842607	409873.503001	410101.499997	3.47
L047-1	27638325	154396.004007	154617.500000	3.32
L047-2	27907009	410307.003004	410525.499988	3.45
L048-1	28992252	154814.002006	155047.503994	3.46
L048-2	28568279	410704.502009	410930.504996	3.38
L049-1	28399590	155213.500005	155442.002000	3.42
L049-2	29316740	411126.502006	411355.503993	3.56
L050-1	27909129	155636.004013	155865.000999	3.22
L050-2	28215931	411547.501003	411774.503995	3.25
L051-1	28056531	156029.002002	156259.003991	3.27
L051-2	28133515	411960.501009	412186.502989	3.29
L052-1	27162063	156442.501001	156668.002992	3.21
L053-1	26704254	156837.004001	157059.500991	3.23
L054-1	27186353	157256.003011	157485.503986	3.16
L055-1	26452485	157653.001003	157878.002999	3.15
L056-1	27377764	158080.004013	158313.000990	3.27
L057-1	25345225	158530.003000	158748.003989	3.02
L057-2	25446511	346456.501006	346674.002990	2.94
L059-1	841746	328426.503005	328432.502991	3.60
L059-2	2212917	328436.503002	328451.003993	4.55
L059-3	4008663	347625.002007	347649.001998	5.68
L059-4	6625829	347654.002008	347696.501997	4.38

L060-1	11454264	347908.004290	347980.999998	4.72
L061-1	11656403	348169.502002	348244.503000	4.42
L062-1	11629960	348422.504008	348497.499995	4.59
L063-1	7195403	404804.005004	404878.499995	2.26
L069-1	12158303	335653.005010	335727.500999	4.92
L072-1	26343851	346038.002009	346265.003994	3.06
L073-1	25201428	345626.503003	345840.999993	2.97
L074-1	26878409	345227.500010	345454.501990	3.19
L075-1	27340712	344811.502001	345035.003995	3.29
L076-1	27711782	344405.004005	344634.499996	3.32
L077-1	27038141	343985.501006	344207.501988	3.32
L078-1	27055640	343569.003000	343800.503995	3.16
L079-1	26732969	343144.500000	343369.501992	3.23
L080-1	26757857	342714.503001	342945.503996	3.35
L081-1	23901809	342283.001006	342498.501993	2.88
L082-1	2378689	341950.004008	341970.503994	3.51
L082-2	927919	341846.004008	341854.003992	3.02
L082-3	1349925	342070.005007	342080.504999	3.75
L082-4	901126	341876.004004	341883.503989	3.07

Table 5: Processed lines with bounding limits

Line	Min X (m)	Min Y (m)	Min Z (m)	Max X (m)	Max Y (m)	Max Z (m)
L001-1	570520.41	5076017.79	292.62	582780.09	5077397.43	1243.21
L001-2	587469.98	5076271.38	299.38	594764.17	5077463.05	1164.65
L001-3	569740.97	5076207.19	293.70	587498.72	5077460.39	1262.33
L001-4	570563.03	5076064.33	292.64	583756.64	5077389.19	1194.22
L001-5	583738.52	5076177.43	313.29	587606.49	5077433.28	850.50
L001-6	587623.10	5076381.63	301.69	588327.03	5077517.62	455.56
L001-7	587687.04	5076324.04	300.52	594516.05	5077322.28	1143.43
L001-8	583836.12	5076333.55	321.40	587607.89	5077376.15	850.54
L001-9	570548.51	5076223.13	293.62	583761.41	5077315.51	1198.08
L002-1	594127.20	5078495.96	948.16	594796.32	5078965.05	1181.77
L002-2	594084.18	5074923.20	644.41	594953.79	5077162.28	1139.59
L002-3	594076.20	5075064.05	656.77	594998.92	5079023.22	1297.18
L003-1	593724.97	5075036.28	749.79	594655.26	5079068.62	1297.28
L003-2	593708.41	5074967.08	683.17	594666.07	5078928.29	1295.83
L004-1	593394.72	5075248.80	859.40	594281.73	5079068.33	1291.22
L004-2	593365.50	5076092.93	915.44	594269.97	5078998.33	1291.16
L005-1	592907.64	5074947.99	824.73	593996.22	5079079.90	1251.96
L005-2	592994.90	5074946.59	829.64	593955.25	5078930.76	1262.79
L005-3	592999.13	5074994.65	832.26	594212.92	5078890.60	1272.73
L006-1	592532.22	5075007.25	832.96	593684.78	5079002.64	1246.39
L006-2	592493.53	5075064.09	835.84	593556.85	5078932.70	1212.63
L007-1	592152.67	5074927.81	818.78	593326.43	5079008.05	1187.77
L007-2	592192.37	5074811.04	757.37	593316.44	5078892.97	1123.46
L008-1	591942.17	5074994.21	750.69	592924.38	5078995.23	1120.43
L009-1	591537.25	5074958.34	708.62	592543.90	5078949.92	1078.65
L010-1	591267.73	5075074.27	672.85	592244.31	5078993.68	1057.59
L011-1	590871.42	5074943.51	602.65	591831.99	5078902.80	1049.22
L012-1	590589.93	5075012.64	543.86	591578.03	5079027.36	1020.54
L013-1	590232.78	5074932.23	503.34	591143.03	5078936.46	939.86
L014-1	589836.72	5075054.87	483.38	590877.47	5079034.32	956.33
L015-1	589337.92	5074929.48	369.16	590513.07	5078966.06	965.65
L016-1	589123.63	5075035.33	360.57	590155.91	5078970.49	940.18
L017-1	588720.06	5074885.53	342.47	589838.67	5079005.42	867.36

L018-1	588435.37	5074926.55	327.00	589515.03	5079026.02	785.15
L019-1	588017.53	5074886.99	310.47	589198.94	5078869.80	756.61
L020-1	587827.18	5074968.39	298.23	588799.58	5079012.49	787.50
L021-1	587496.39	5074895.87	280.12	588418.99	5078874.08	826.35
L023-10	583386.47	5070819.99	313.51	584293.21	5071859.32	519.67
L023-1	583123.08	5076776.15	318.73	584260.32	5079507.48	812.54
L023-2	583300.19	5072234.92	283.18	584295.57	5074084.76	486.57
L023-3	583247.41	5075418.34	290.85	584209.32	5075834.83	447.08
L023-4	583295.43	5082138.39	439.94	584055.26	5082576.18	675.91
L023-5	583507.94	5077473.14	367.64	584212.67	5077568.31	515.84
L023-6	583338.74	5074487.28	282.68	584204.34	5074715.71	445.30
L023-7	583366.09	5074871.30	282.01	584388.04	5076370.19	449.91
L023-9	583395.97	5079749.32	580.23	584027.67	5081465.15	857.20
L024-1	582954.36	5070963.24	283.68	584114.42	5082637.80	911.54
L025-1	582615.85	5070877.35	285.54	583798.08	5082565.72	930.93
L026-1	582342.76	5070855.53	286.59	583473.19	5082630.44	992.51
L027-1	581955.45	5070814.21	287.20	583278.76	5082527.55	1062.13
L028-1	581585.79	5070771.24	289.11	582989.38	5082640.04	1065.77
L029-1	581368.26	5070659.40	289.69	582693.61	5082488.14	1061.97
L030-1	581107.79	5070853.20	296.71	582343.71	5082540.56	963.83
L031-1	580871.59	5070859.18	299.48	581931.34	5082653.31	904.78
L032-1	580590.31	5070859.73	303.16	581673.75	5082657.43	862.48
L033-1	580236.13	5070873.57	304.86	581359.34	5082590.82	863.57
L034-1	579894.64	5070813.89	310.11	581174.97	5082555.27	854.18
L035-1	579656.38	5070844.54	316.43	580882.60	5082527.14	903.69
L036-1	579246.11	5070828.91	320.27	580592.68	5082578.77	991.06
L037-1	579012.69	5070854.22	322.30	580195.68	5082560.95	995.16
L038-1	578738.74	5070848.98	324.74	579915.34	5082553.46	983.25
L039-1	578486.06	5070848.64	327.67	579605.26	5082503.33	979.94
L040-1	578211.90	5070827.12	333.15	579261.47	5082502.83	960.38
L040-2	578204.07	5070834.55	330.27	579328.26	5082618.43	960.78
L041-1	577906.82	5070817.35	346.58	578961.59	5082513.92	993.75
L041-2	577908.78	5070782.47	346.55	579042.14	5082551.85	996.01
L042-1	577365.85	5070814.01	350.95	578818.24	5082492.73	1021.92
L042-2	577488.19	5070827.46	353.01	578731.30	5082503.92	1021.71

L043-1	577243.33	5070737.07	361.89	578418.95	5082491.58	1021.83
L043-2	577221.40	5070743.87	360.66	578438.36	5082430.45	1021.91
L044-1	576961.25	5070825.35	367.34	578126.82	5082443.88	996.93
L044-2	577040.40	5070824.72	367.74	578115.01	5082565.00	996.35
L045-1	576642.12	5070863.31	380.89	577872.82	5082468.38	998.14
L045-2	576723.08	5070753.49	378.77	577738.22	5082441.82	998.40
L046-1	576432.03	5070799.13	385.27	577532.27	5082502.37	997.50
L046-2	576416.32	5070772.30	382.64	577551.64	5082518.49	997.15
L047-1	576010.35	5070813.44	390.25	577288.71	5082532.27	1008.22
L047-2	576167.86	5070727.39	395.82	577183.97	5082282.59	1008.22
L048-1	575899.05	5070834.10	408.27	576928.08	5082453.34	1000.77
L048-2	575874.88	5070796.77	408.11	576921.97	5082527.07	1008.26
L049-1	575544.42	5070820.31	448.55	576656.90	5082502.08	1032.77
L049-2	575524.95	5070747.15	426.58	576621.91	5082477.14	1031.82
L050-1	575253.21	5070774.16	490.13	576310.87	5082493.50	1078.99
L050-2	575260.67	5070853.29	488.66	576348.49	5082542.93	1079.78
L051-1	574966.24	5070765.79	535.19	576094.55	5082526.69	1088.55
L051-2	575005.48	5070741.01	555.48	576020.97	5082403.70	1088.62
L052-1	574610.30	5070782.67	558.45	575753.28	5082461.53	1096.30
L053-1	574408.63	5070790.24	561.16	575450.57	5082369.89	1126.75
L054-1	574070.47	5070718.96	564.36	575193.99	5082417.36	1241.60
L055-1	573825.31	5070740.92	568.43	574873.75	5082456.13	1375.97
L056-1	573397.41	5070784.22	572.01	574687.55	5082410.85	1376.82
L057-1	573190.68	5070738.51	582.83	574420.76	5082399.35	1348.80
L057-2	573192.17	5070667.35	583.24	574419.38	5082365.06	1338.67
L059-1	587290.77	5075005.70	280.06	588051.05	5075380.81	462.89
L059-2	587258.27	5075535.23	288.34	588188.41	5076289.43	475.68
L059-3	587138.60	5077570.48	401.98	588011.05	5078860.91	841.88
L059-4	587164.39	5075080.40	281.03	588027.54	5077329.43	629.10
L060-1	586808.50	5074995.01	281.21	587854.03	5078890.59	951.34
L061-1	586403.31	5074789.72	277.70	587409.87	5078836.24	919.05
L062-1	586066.20	5074922.58	338.35	587133.15	5078895.55	880.57
L063-1	585687.43	5074762.79	324.92	586748.92	5078780.05	850.88
L069-1	583705.13	5074922.62	281.88	584608.12	5078867.06	715.05
L072-1	572885.79	5070815.90	587.69	574182.59	5082564.34	1409.95

L073-1	572560.75	5070713.92	599.38	573916.54	5082395.67	1414.42
L074-1	572350.22	5070770.13	616.78	573459.65	5082500.86	1332.67
L075-1	572082.84	5070691.81	630.28	573135.91	5082387.15	1274.10
L076-1	571777.14	5070697.53	644.40	572848.32	5082502.74	1231.37
L077-1	571567.17	5070713.94	662.70	572616.65	5082412.87	1222.80
L078-1	571240.39	5070694.33	693.87	572307.69	5082528.94	1247.68
L079-1	570919.60	5070640.02	713.74	572015.82	5082328.80	1311.03
L080-1	570539.95	5070715.73	740.64	571701.02	5082496.61	1313.11
L081-1	570250.61	5070567.27	746.64	571487.53	5082371.82	1312.52
L082-1	570115.26	5075937.29	852.85	571099.09	5076993.94	1277.07
L082-2	570141.72	5070744.86	872.76	571051.14	5071274.46	1078.36
L082-3	570028.20	5081873.94	957.92	570868.16	5082479.43	1285.81
L082-4	570168.53	5072330.21	836.97	571071.32	5072895.84	1042.50

4 Parameters used in processing

Table 6 details the processing parameters used in the creation of the L1 to L3 discrete LiDAR data products. In the following description, parameters used are **boldface**, and reference to lastools are italicized. Additional information on any of the implemented lastools can be found at https://rapidlasso.com/lastools/ . The **interpolation distance** is the maximum length allowed for a given triangular edge in the TIN algorithm during the creation of the DSM, DTM and ground level of the CHM (see RD[9] and RD[11]). This allows gaps in the raster products up to this size to be interpolated and filled. The **raster spatial resolution** is the cell size of all of the raster products. The **no data value** specifies the value in the rasters which represents an absence of observed or interpolated data.The **vertical datum correction** is a correction applied to the elevation coordinate in the delivered LAS files due to an incorrect application of the Geoid12A model in LMS processing (see RD[10] for additional details). The **overlap grid step** is used in the QA analysis of the data, where rasters are created from the ground classified LAS files and the elevations are compared in cells which overlap between adjacent strips. The overlap grid step is the cell size used in the overlapped rasters. See Section 5 for the results of this analysis

The **tile size** is the dimensions of tiles used in the processing and delivery of the raster products. The **buffer size** is the distance added to each tile boundary to ensure seamless continuation of data across tile boundaries, which is removed for delivered products. **Noise step** and **noise isolated** are two parameters used in the lasnoise function to classify noise points. All noise points are maintained in the LAS files, and classified as class 7 (according to ASPRS (2009)). Noise points are not used in processing of the raster products.

The **ground grid step**, **ground search parameter** and **ground offset** are parameters used to classify ground points with the lasground algorithm. These parameters are optimized for natural (non-urban) environments. All ground points are given classification 2 according to ASPRS(2009). The **planar parameter** is used in the lasclassify algorithm, which identifies vegetation and buildings. Vegetation is classified as 5, and buildings as 6 according to ASPRS (2009).

Thin subcircle and **thin stepsize** are used in the lasthin algoritm to thin the point cloud prior to CHM creation. The **CHM interval** is the length of the elevation bands used during CHM creation and the **CHM height** is the maximum height elevation bands will be created, following the Khosravipour (2014) algorithm and detailed in RD[11]. The **CHM interpolation distance** is the maximum length of a triangle allowed during CHM creation, therefore, true gaps in the canopy below this distance may be filled.

Table 6: Processing parameters

Parameter	**Value**
DSM / DTM max interpolation Distance (m)	250
Raster Spatial Resolution (m)	1
No data value	-9999
Vertical datum correction (m)	0.378
Overlap grid step (m)	5
Buffer (m)	25
Tile side length (m)	1000
Noise step (m)	4
Noise Isolated (pts)	5
Ground Grid Step (m)	10
Ground search parameter	extra_fine
Ground offset (m)	0.15
Planar	0.1

Thin subcircle (m)	0.1
Thin step size (m)	0.5
CHM Interval (m)	5
CHM max interpolation distance (m)	3
CHM height (m)	53.628

5 QA Analysis

5.1 Coverage

Figure 1 provides a footprint of all lines flown and the associated coverage, while Figure 2 provides the coverage of files that were tiled, classified and used in generation of higher level products, listed in **green** in Table 4 and Table 5. Figure 3 provides an overwiew of the discrete return LIDAR intensity across the acquisition area.

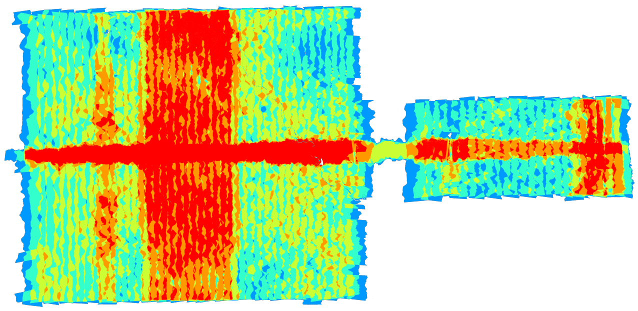

Figure 1: Flightline overlap map of all LAS files

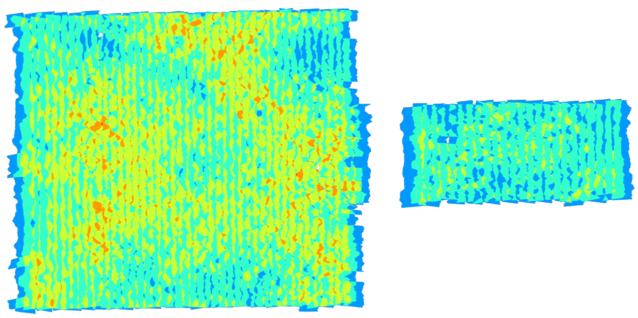

Figure 2: Flightline overlap map of selected LAS files

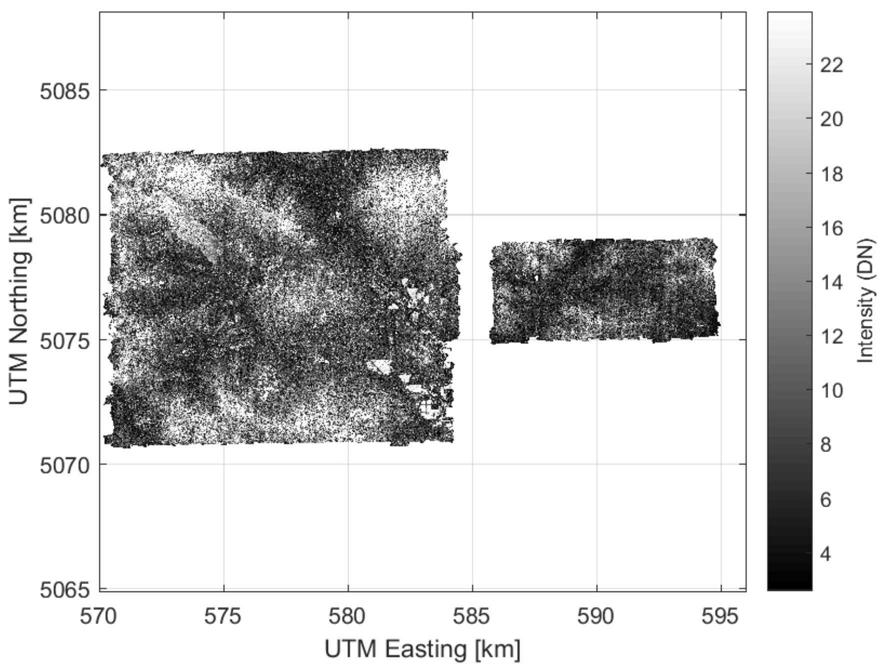

Figure 3: Intensity map

5.2 Relative elevation difference

Figure 4 shows the difference in elevation of ground points in overlapping strips, and Figure 5 provides a histogram of the elevation differences. Elevation differences are calculated by creating separate rasters of each line with a spatial resolution equivalent to the overlap grid step specified in Table 6 of Section 4. Generally we expect the histogram to show a Gaussian distribution with a mean near zero. Errors can be potentially larger than the expected accuracy of LiDAR due to the size of the overlap grid step. This is particularly relevant in sloped areas where elevation differences can be attributed to the location of the return within the overlap grid step area as opposed to the relative accuracy of the sensor. Therefore, Figure 4 and Figure 5 can be used as processing quality indicators, but should not be interpreted as the overall accuracy of the LiDAR sensor.

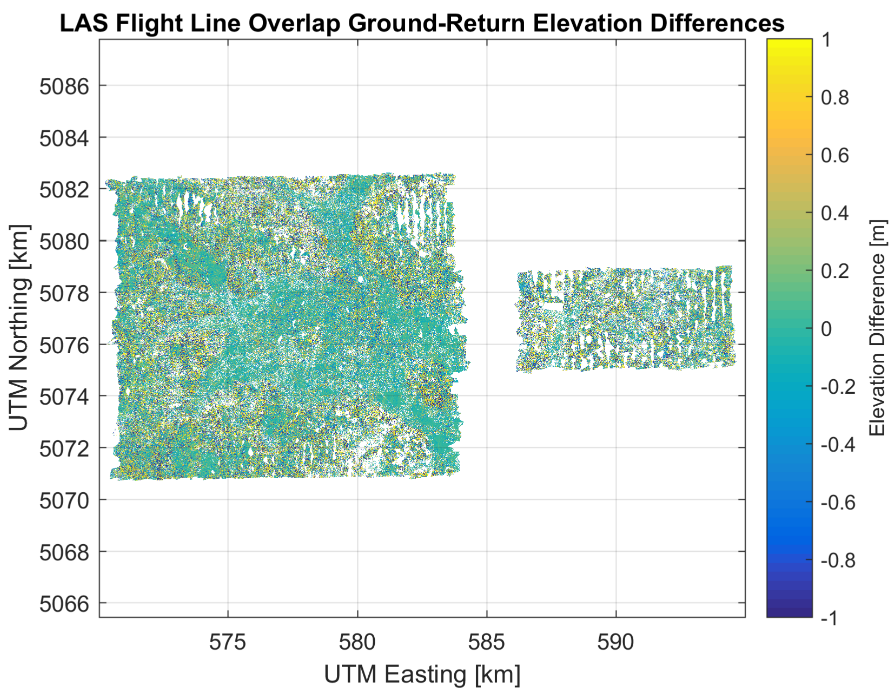

Figure 4: Elevation difference map

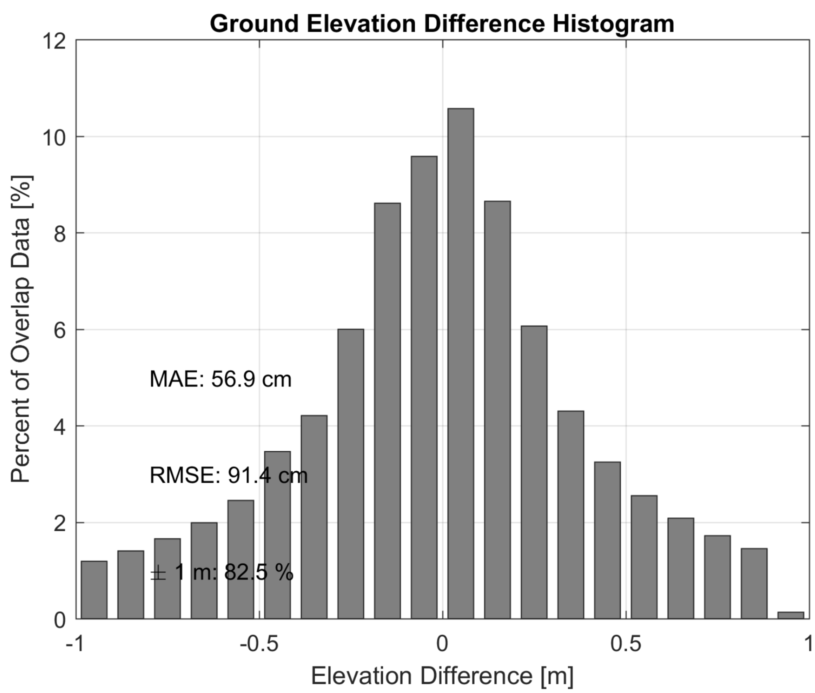

Figure 5: Elevation difference histogram

5.3 Point density

Figure 6 and Figure 7 provide a map and histogram respectively that quantify the number of points per square meter that were acquired, Figure 8 and Figure 9 show a similar map and histogram using only points classified as ground. Figure 10, Figure 12 and Figure 13 provide a map, histogram and cumulative histogram respectively of the longest triangular edge of a TIN triangle used in creation of a raster cell in DSM, which utilizes all available LiDAR points. The histogram can extend up to a maximum of the interpolation distance specified in Table 6 of Section 4. Figure 10, Figure 14 and Figure 15 provide a similar map, histogram and cumulative histogram, except only the ground points are used. Generally, longer triangular edges will be necessary in interpolating only the ground points (used in DTM, CHM, slope map and aspect map) because vegetated areas will prevent some pulses from reaching true ground.

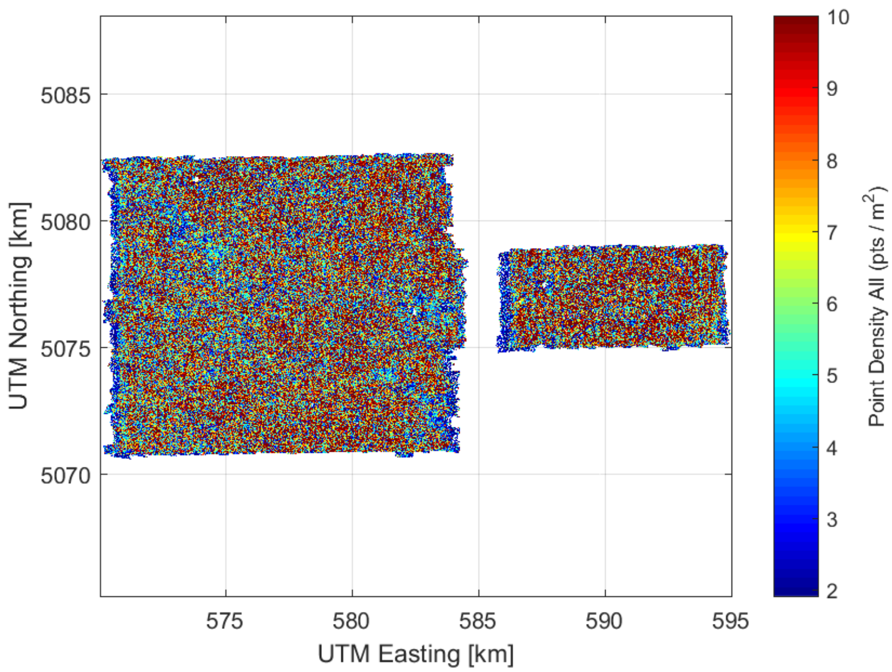

Figure 6: Point Density map with all points

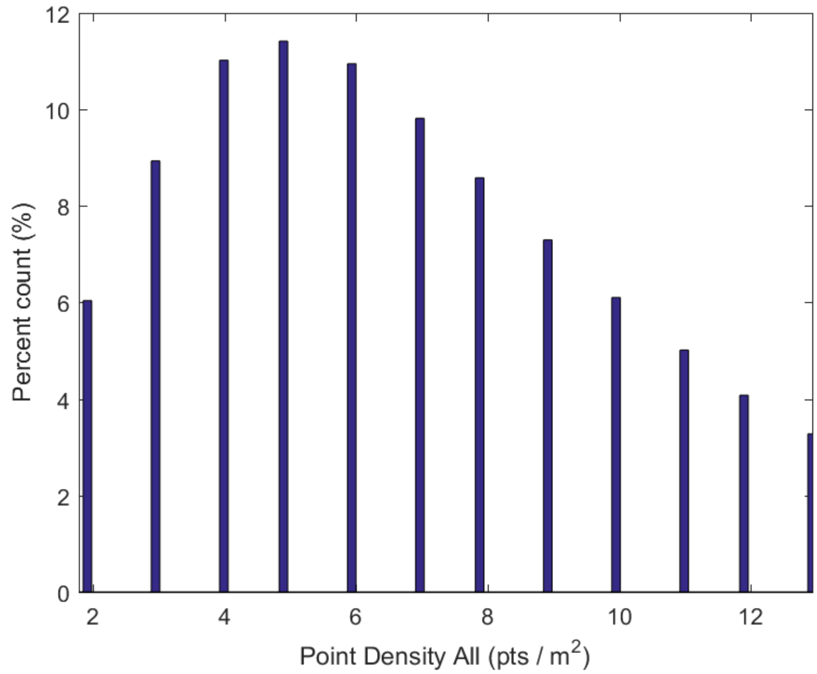

Figure 7: Point Density histogram with all points

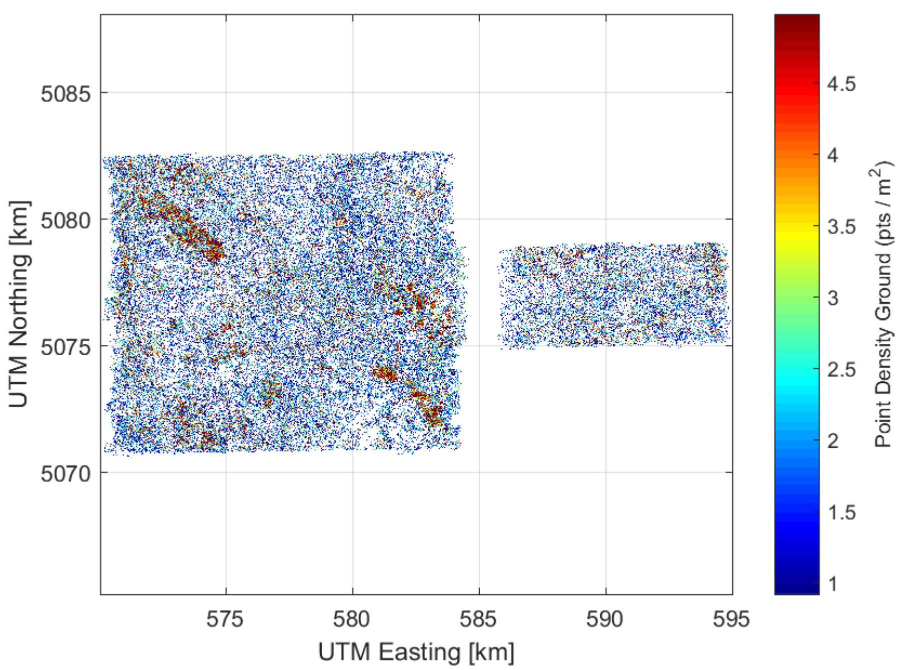

Figure 8: Point Density map with ground points

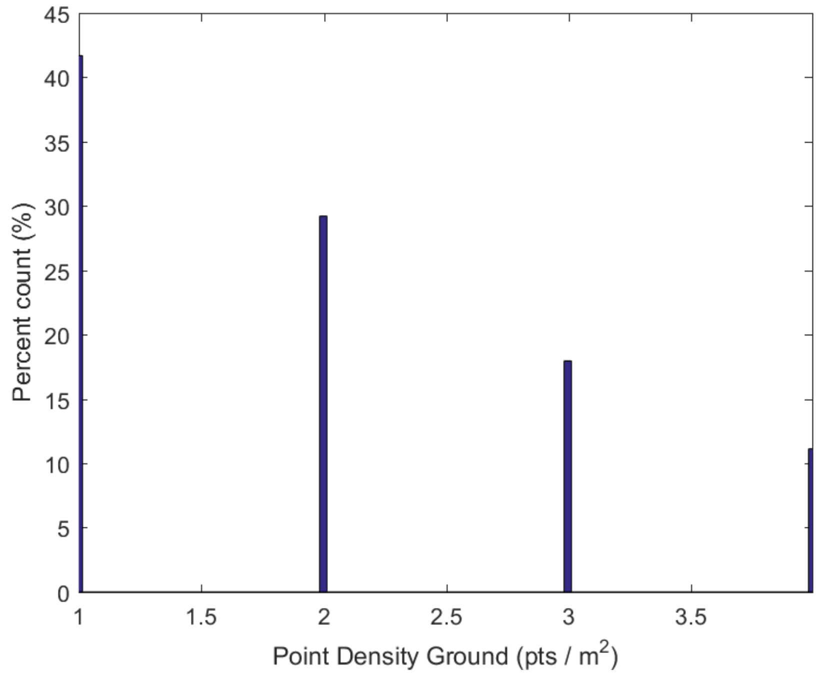

Figure 9: Point Density histogram with ground points

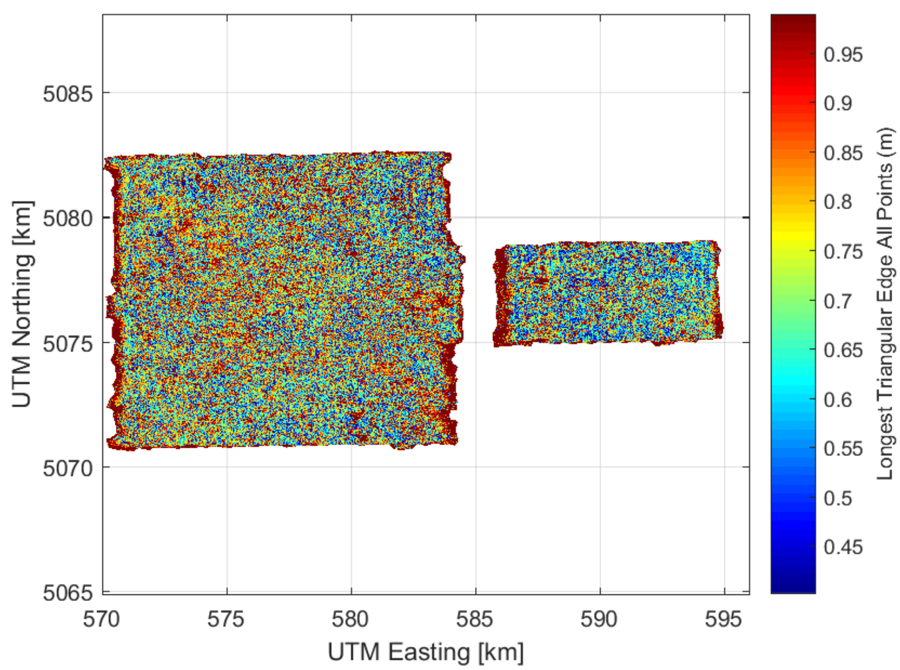

Figure 10: Map of the longest triangular edge in TIN when interpolating all points

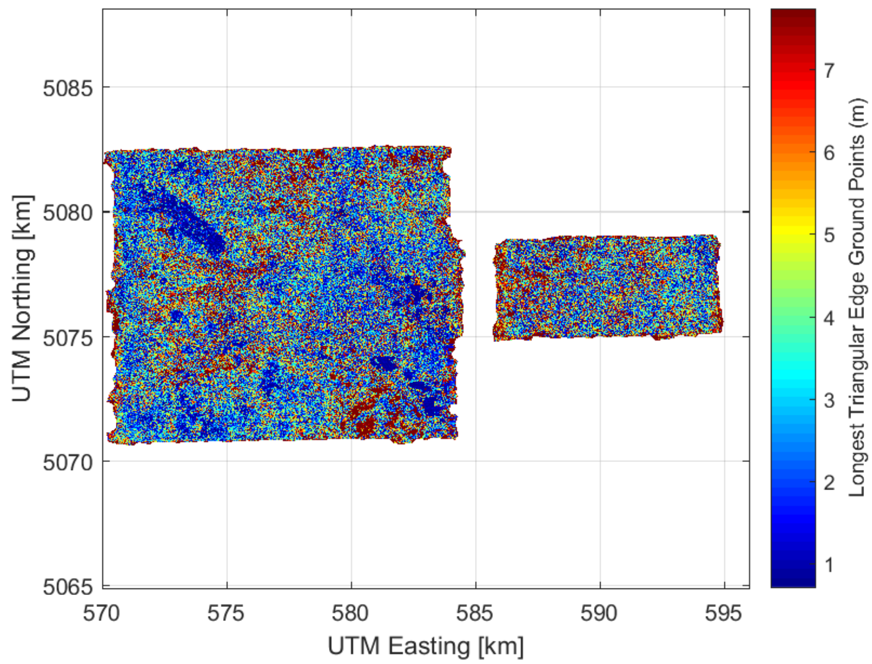

Figure 11: Map of the longest triangular edge in TIN when interpolating only ground points

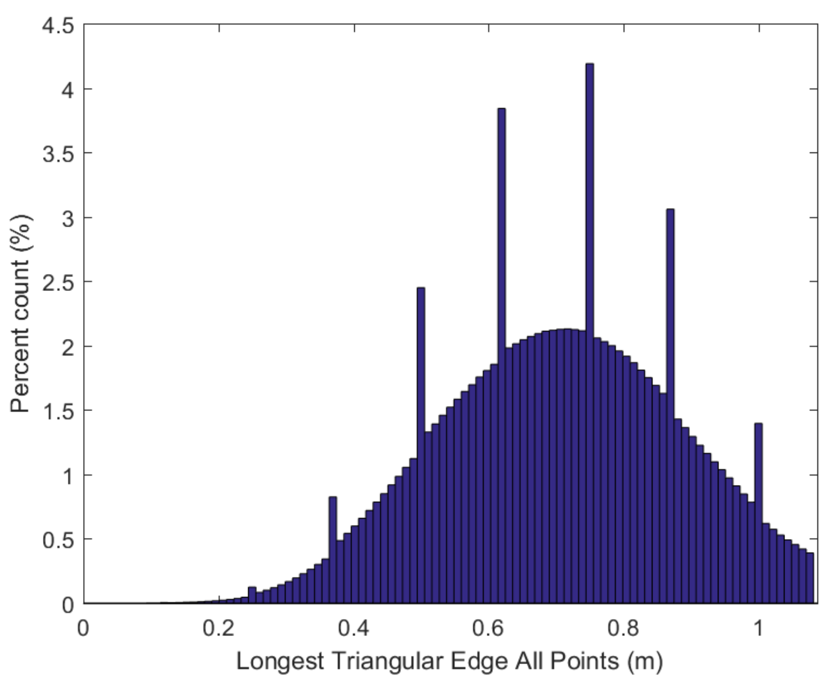

Figure 12: Histogram of the longest triangular edge in TIN when interpolating all points

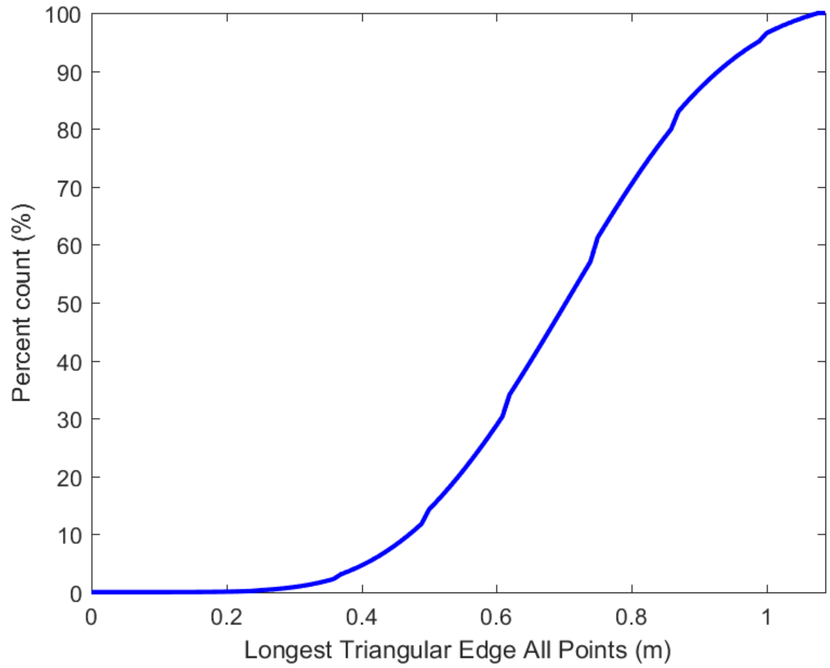

Figure 13: Cumulative histogram of the longest triangular edge in TIN when interpolating all points

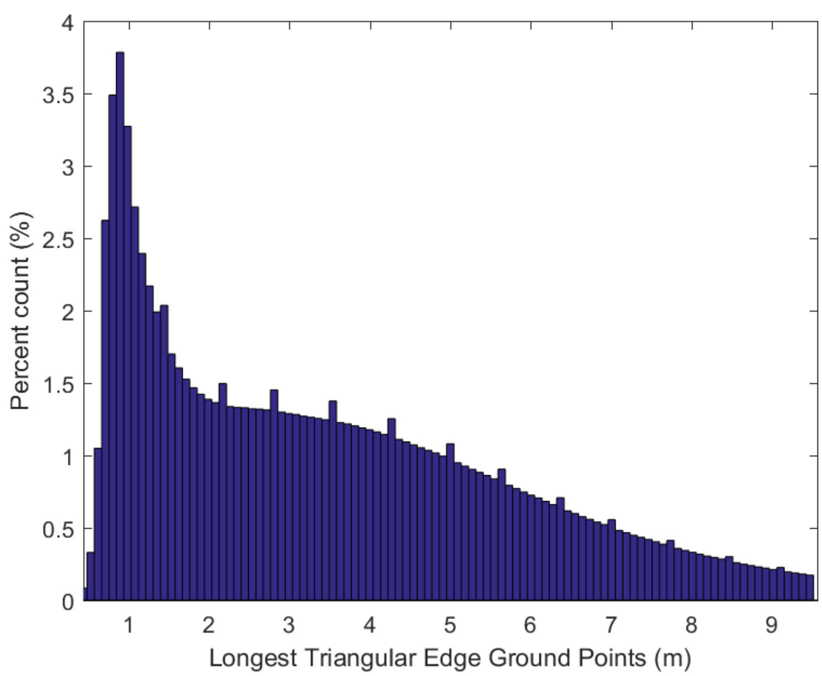

Figure 14: Histogram of the longest triangular edge in TIN when interpolating only ground points

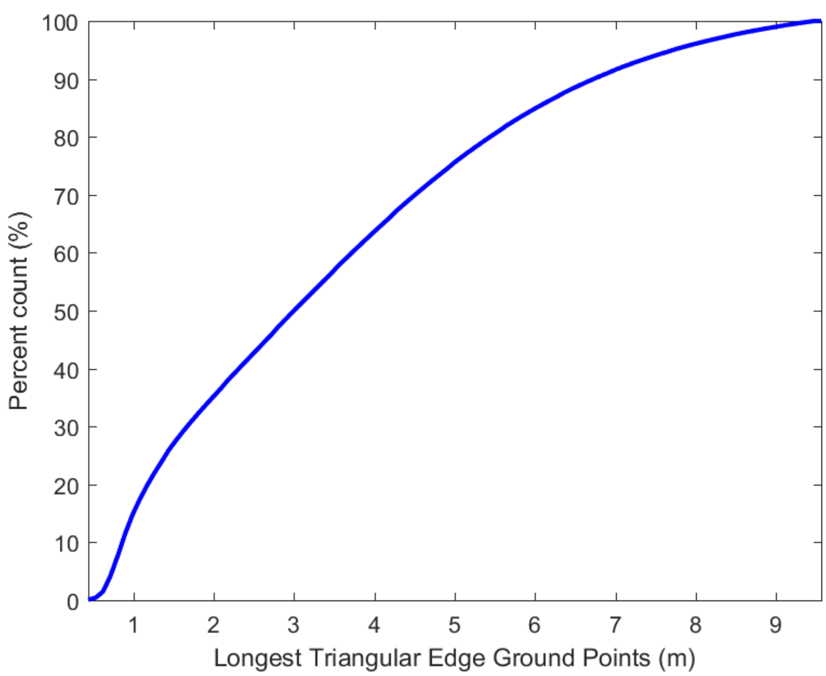

Figure 15: Cumulative histogram of the longest triangular edge in TIN when interpolating only ground points

5.4 Banding Analysis

Figure 16 shows histograms of the laser pulse intensity in opposing directions of the scan mirror from the first LAS file listed in Table 4. Table 7 shows the associated statistics of each histogram and the percent relative difference in the means. If the percent relative difference in the means is larger than 20%, it indicates an optical misalignment exists in the LiDAR sensor and a re-calibration is necessary.

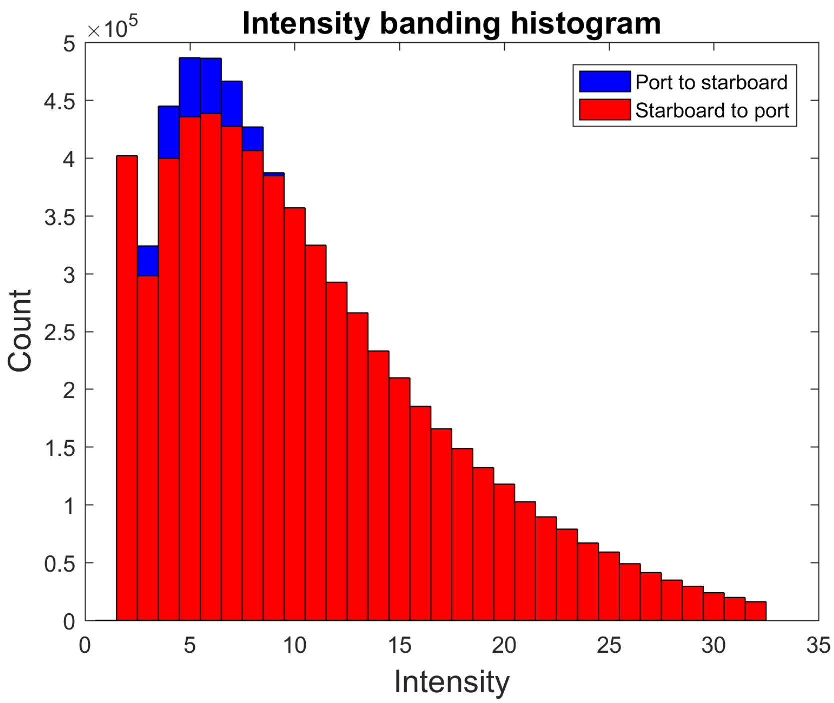

Figure 16: Intensity banding histogram

Table 7: Intensity banding statistics

Statistic	**Value**
Mean intensity of port to starboard direction	8.7
Mean intensity of starborad to port direction	9.7
St.dev of port to starboard direction	5.9
St.dev of starboard to port direction	6.6
Percentage difference of directions	10.2

5.5 Discrete LiDAR L3 products and histograms

Figure 17, Figure 19, Figure 21, Figure 24, and Figure 26 show the resulting L3 product rasters including the DTM, DSM, CHM, slope map, and aspect map respectively, Figure 18, Figure 20, Figure 22, Figure 25, and Figure 27 show their respective histograms. The histograms in Figure 18 and Figure 20 show all of the data, as any values that create long tails on the histograms identify that noise points have been incorrectly used in processing. Figure 22 and Figure 25 show only 99 % of the data, as these histograms tended to have inherently long tails due to large values which obscured details in the main body of the histogram. Figure 23 was also included to display the derivation of the maximum height used in processing the canopy height model, listed in Table 6 and described in Section 4 and RD[11].

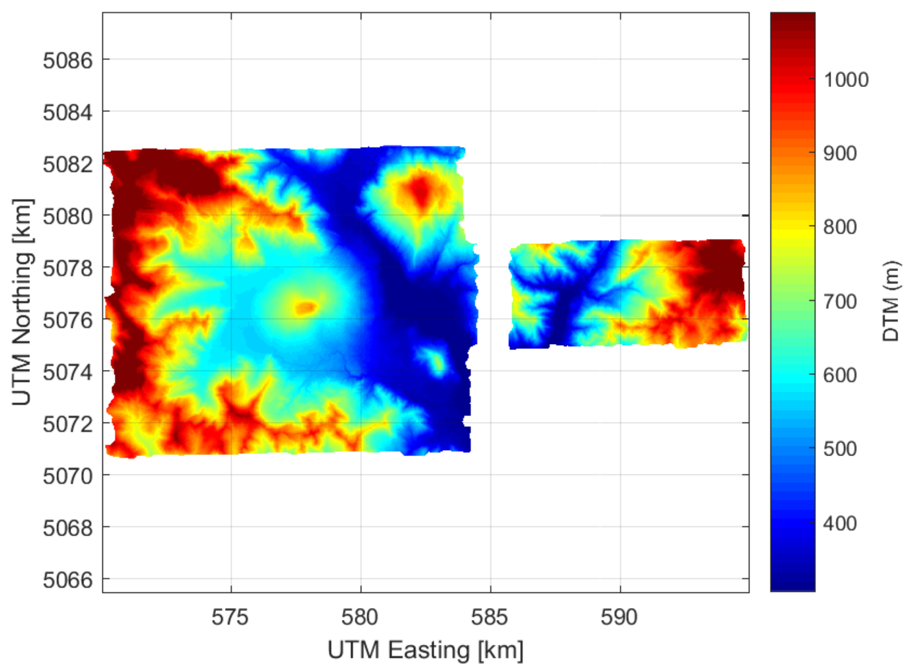

Figure 17: DTM elevation map

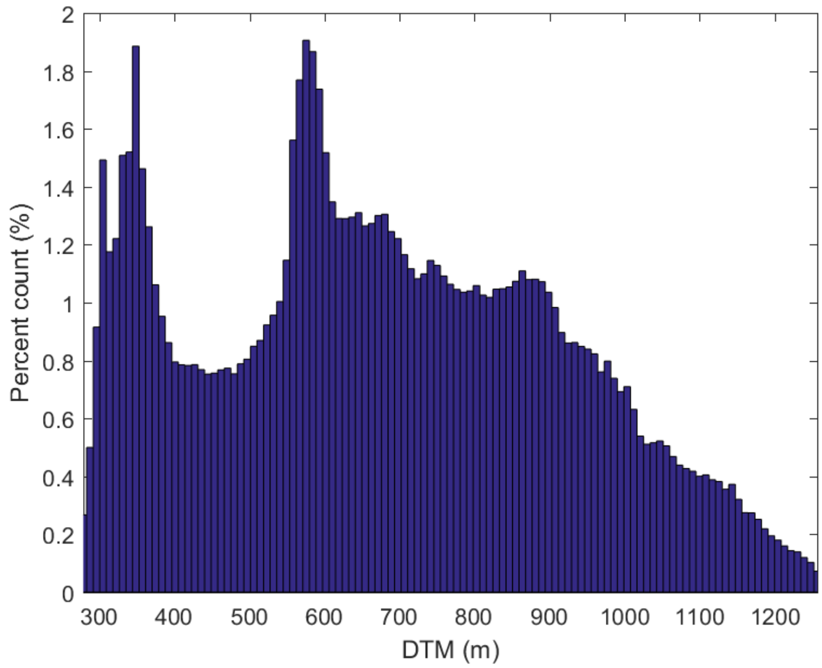

Figure 18: DTM elevation histogram

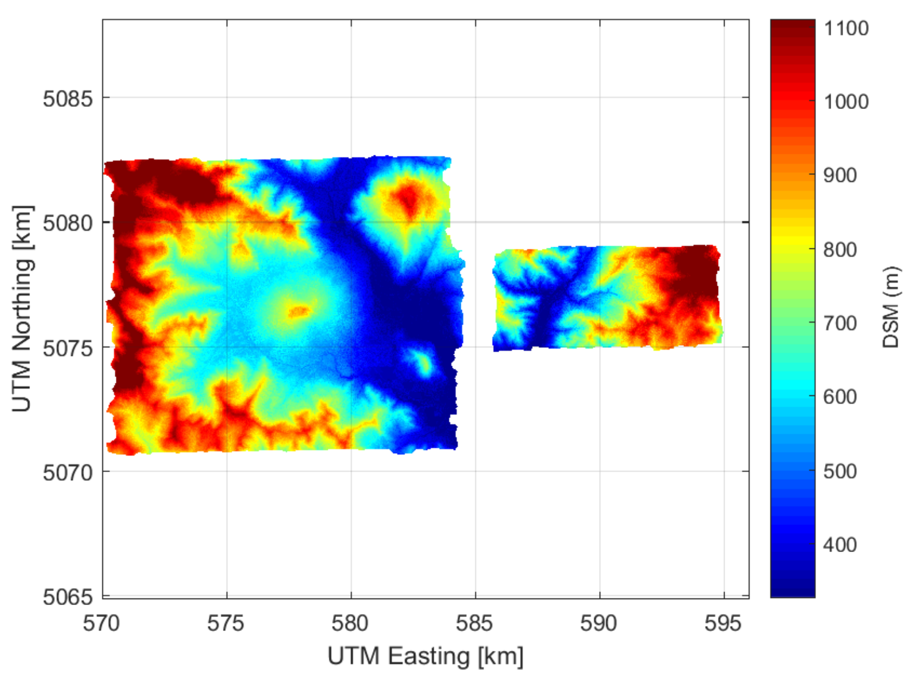

Figure 19: DSM elevation map

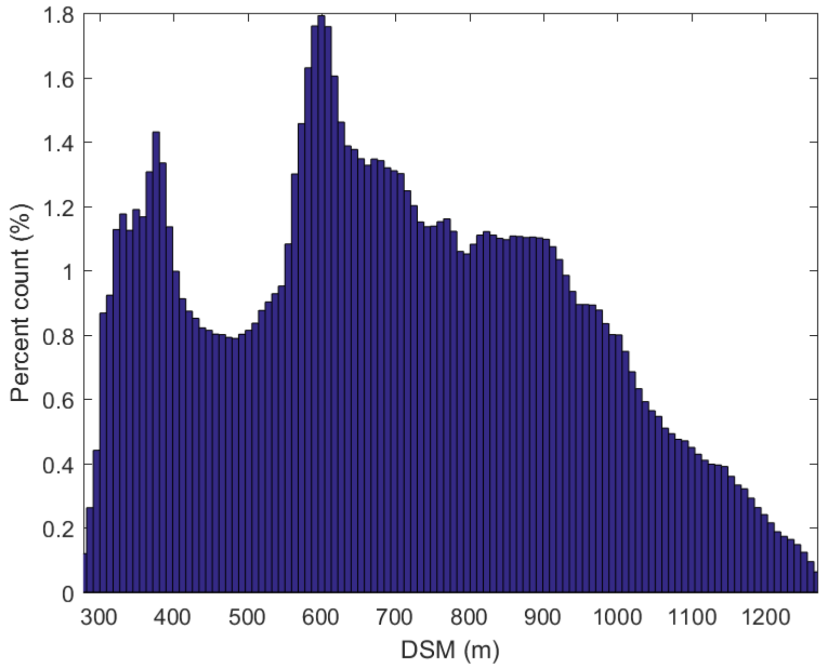

Figure 20: DSM elevation histogram

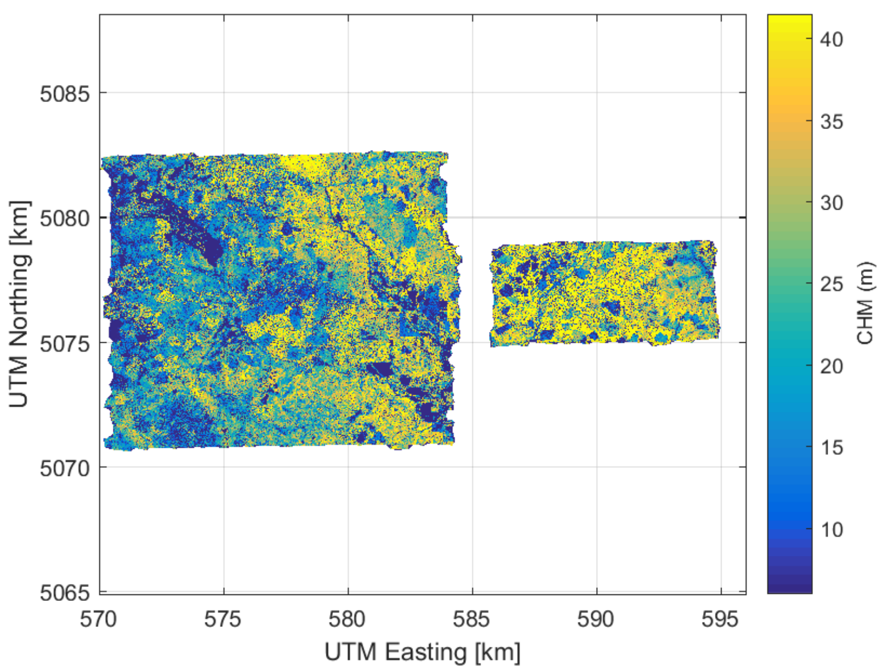

Figure 21: Canopy Height Model

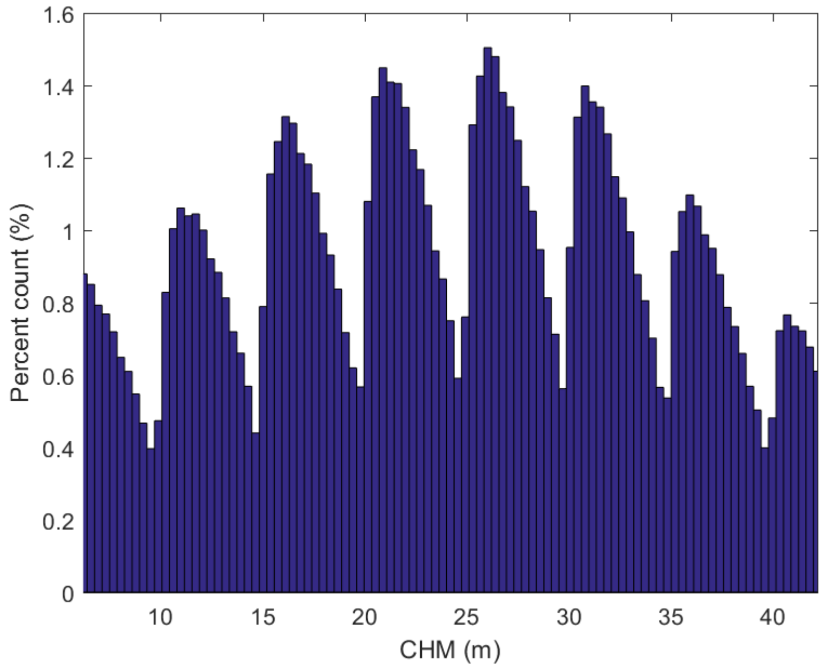

Figure 22: Canopy Height Model histogram

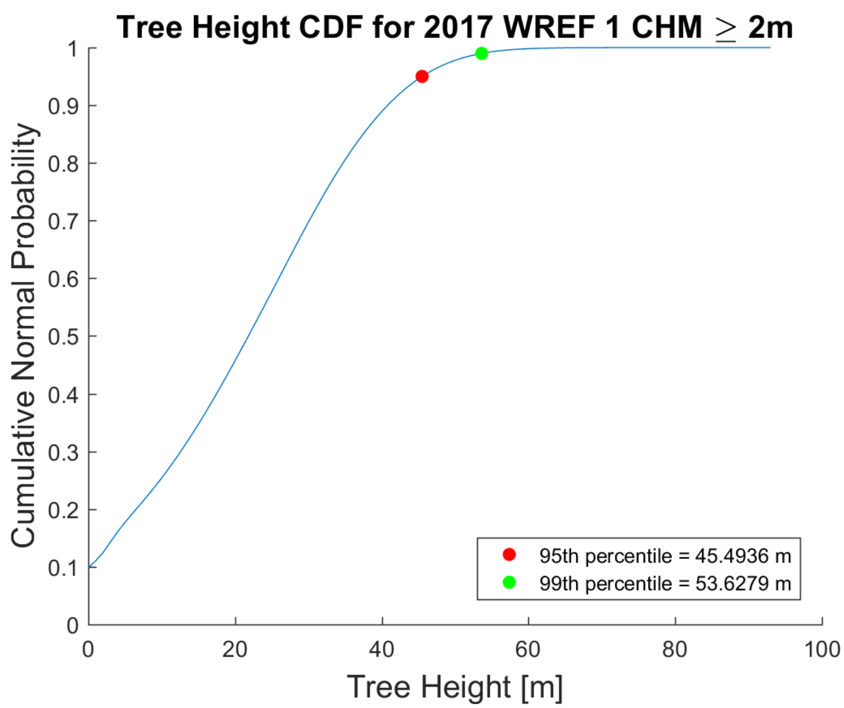

Figure 23: CHM CDF with 95th and 99th height percentiles

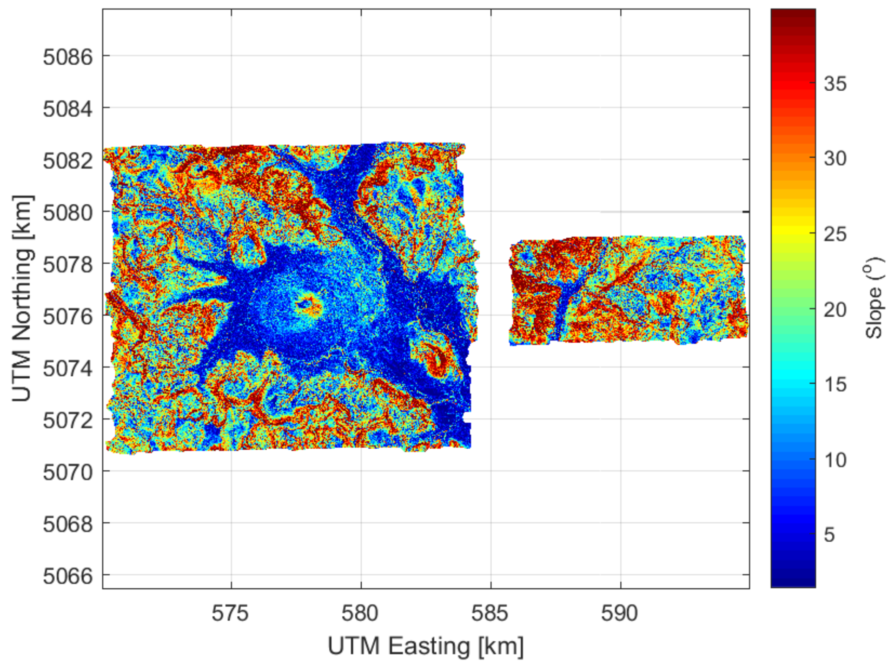

Figure 24: Slope map

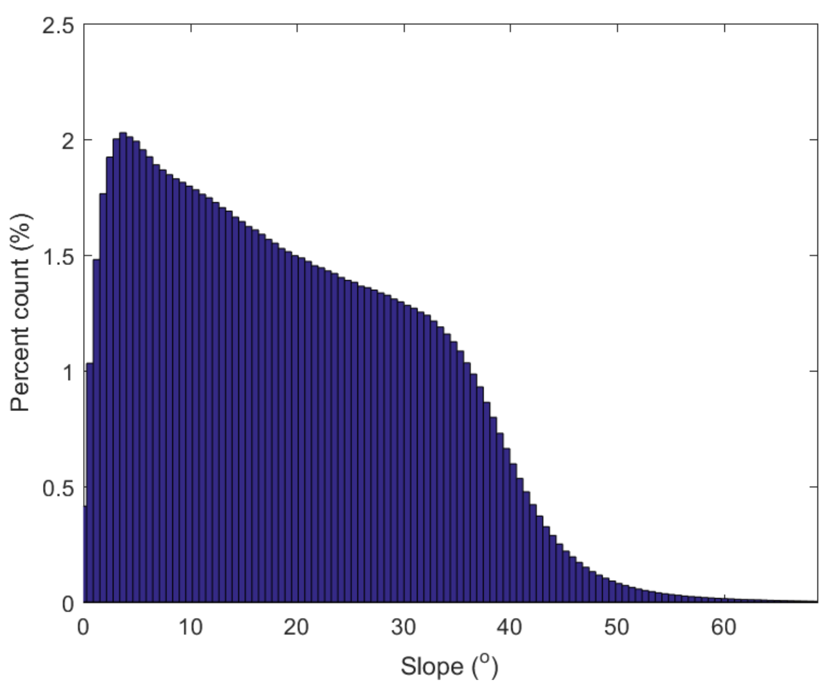

Figure 25: Slope histogram

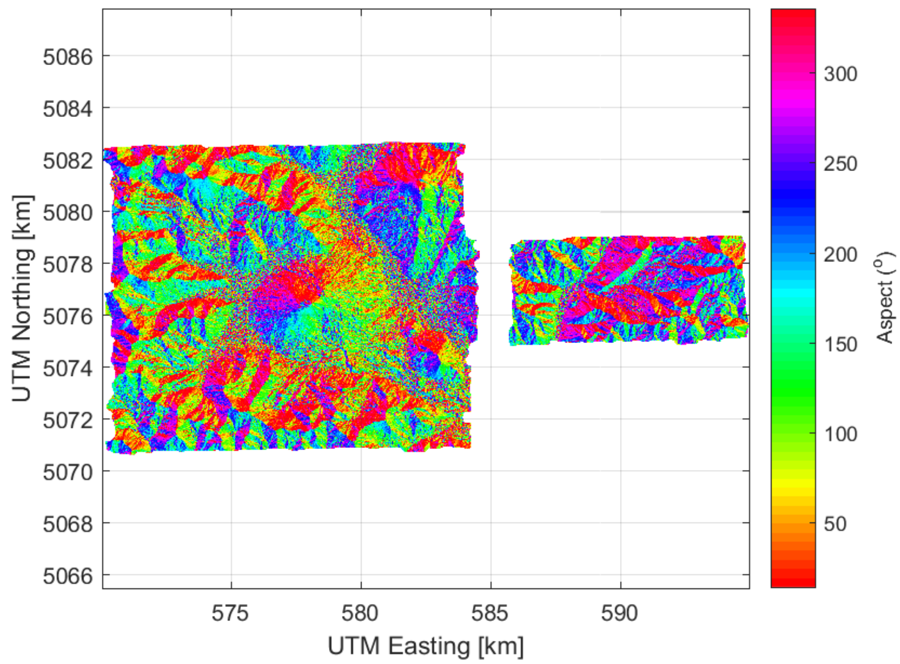

Figure 26: Aspect map

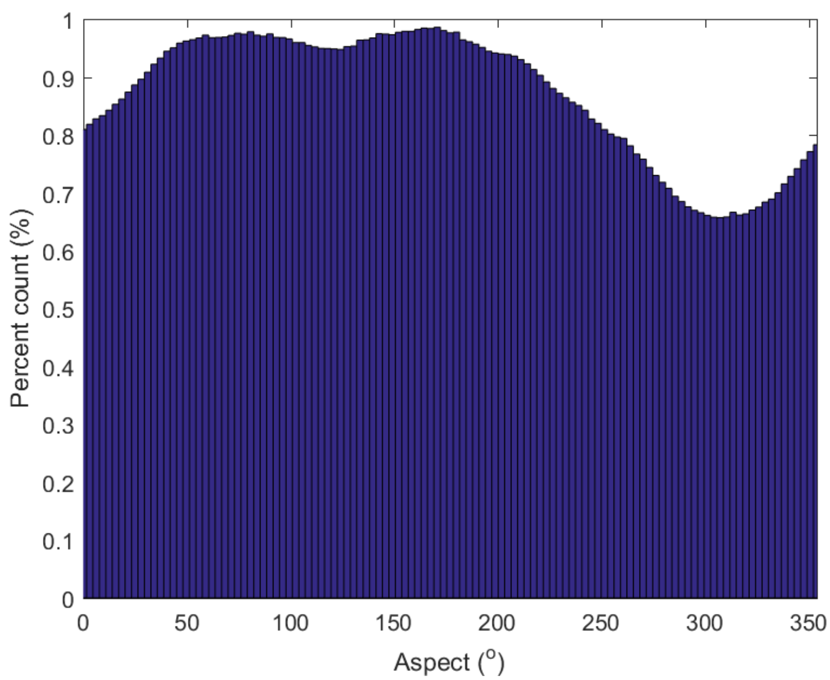

Figure 27: Aspect histogram

5.6 Simulated uncertainty

Figure 28 and Figure 29 provide a respective map and histogram of the simulated vertical uncertainty in the LiDAR survey. In overlap areas, the maximum vertical uncertainty from either line was selected. All simulated uncertainty values are given at standard confidence (68%), and can be expanded to 95% by multiplying by a factor of 1.96. Figure 30 and Figure 31 provide a similar repective map and histogram, derived from the semi-major axis of the horizontal error ellipse for each point. Error simulations follow the algorithm described in Goulden and Hopkinson (2010) and implement the uncertainty values for each subsystem specified in Table 8. Uncertainty in the trajectory can be seen in the associated SBET QAQC document associated with the flight day(s). The range uncertainty is determined from yearly calibration flights at the Boulder airport. Note that simulated uncertainty is based solely on the instrument sub-systems and does not take into account uncertainty introduced by external surface features or vegetation, please see Goulden and Hopkinson (2010) and Goulden and Hopkinson (2014) for further details.

Table 8: Uncertainty values used in error simulations

Subsytem	**Uncertainty (68 % confidence)**
Laser Ranger	0.06 m
Scan Angle	0.003 ^{o}
Beam Divergence Angle	0.8 mRad
GPS - Horizontal	˜3-5 cm (see SBET QA document)
GPS - Vertical	˜5-8 cm (see SBET QA document)
IMU - Roll	˜0.005 ^{o} (see SBET QA document)
IMU - Pitch	˜0.005 ^{o} (see SBET QA document)
IMU - Yaw	˜0.008 ^{o} (see SBET QA document)

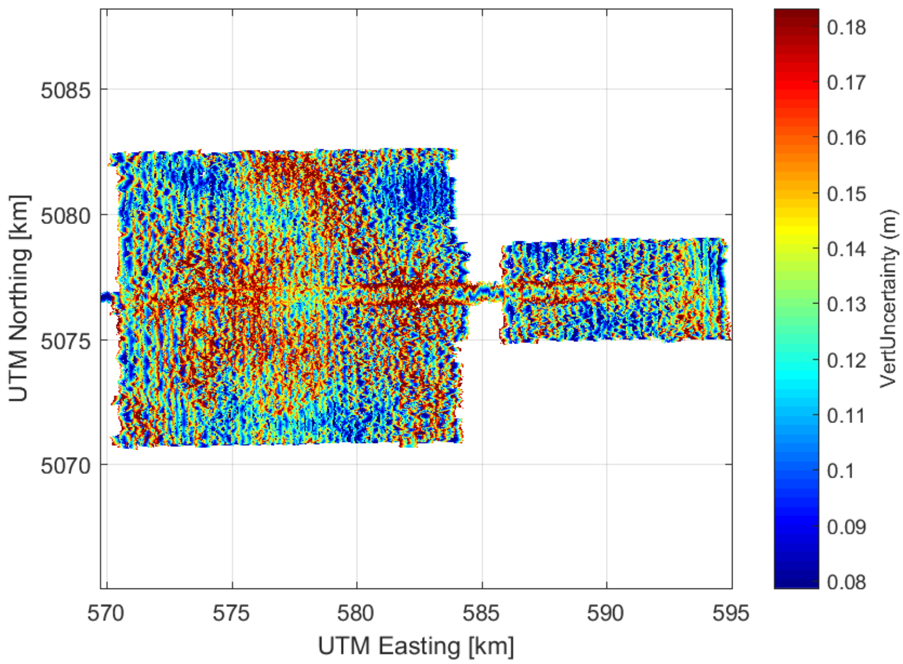

Figure 28: Vertical Uncertainty map

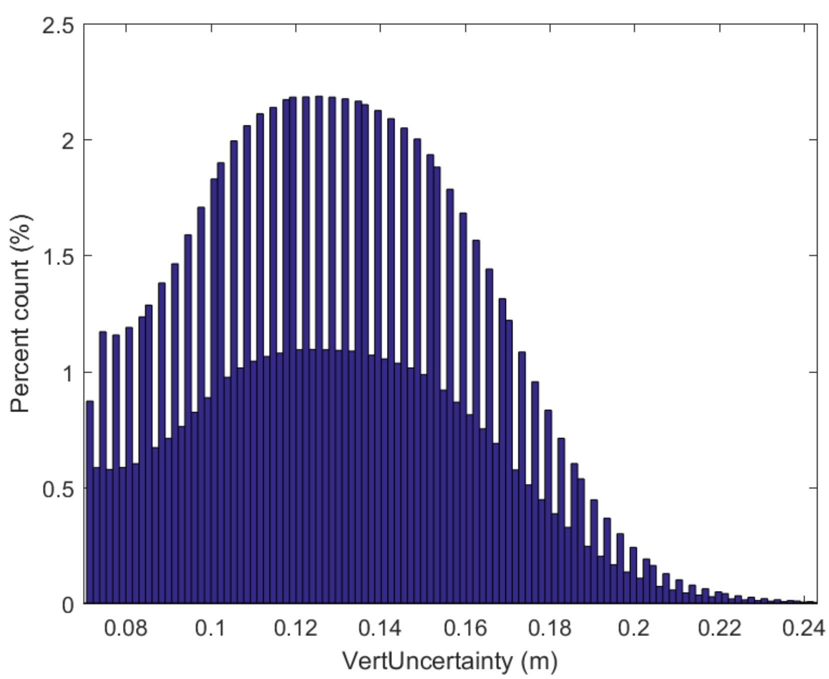

Figure 29: Vertical Uncertainty histogram

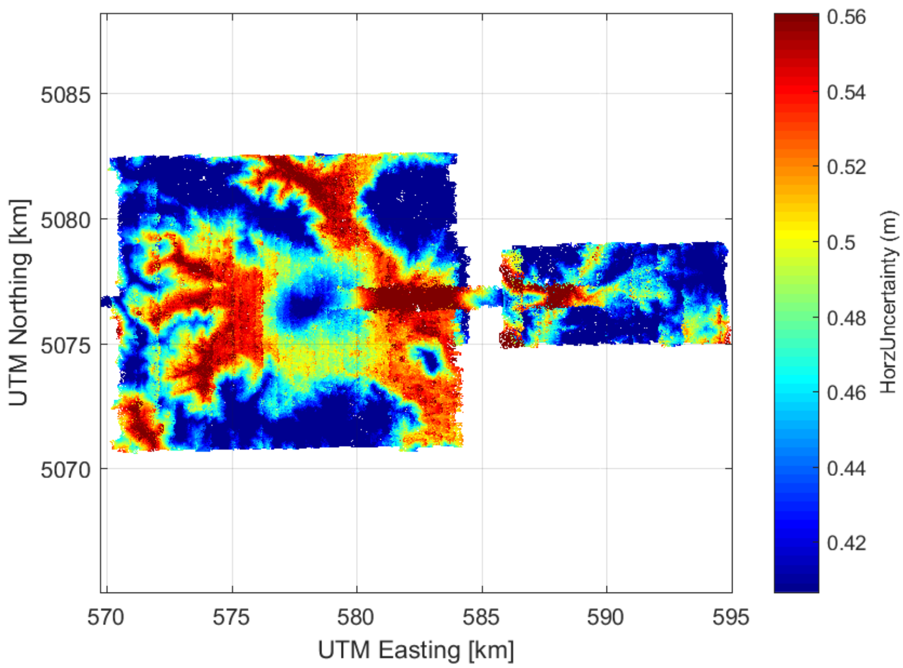

Figure 30: Horizontal Uncertainty map

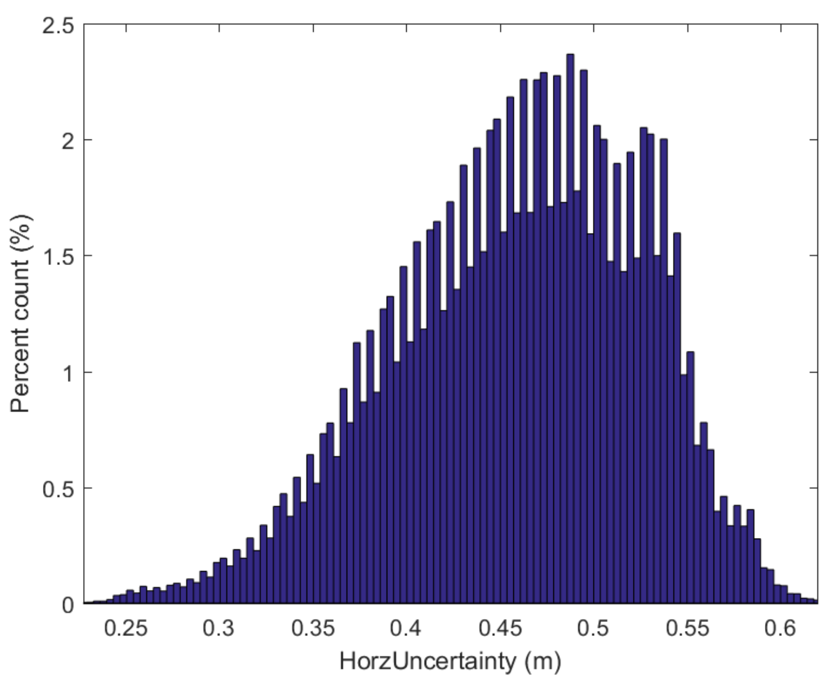

Figure 31: Horizontal Uncertainty histogram

6 References

ASPRS (2009). Las specification, version 1.3-r10. The American Society of Photogrammetry and Remote Sensing (ASPRS).

Goulden and Hopknson (2010). The forward propagation of integrated system component errors within airborne lidar data, *Photogrammetric Engineering and Remote Sensing*, 76(5), 589-601

Goulden and Hopkinson (2014). Mapping simulated error due to terrain slope in airborne lidar observations, *International Journal of Remote Sensing*, 35(20), 7099-7117

Khosravipour, A., Skidmore, A. K., Isenburg, M., Wang, T., and Hussin, Y. A. (2014). Generating pit-free canopy height models from airborne lidar, *Photogrammetric Engineering and Remote Sensing*, 80(9), 863-872.

Appendix A

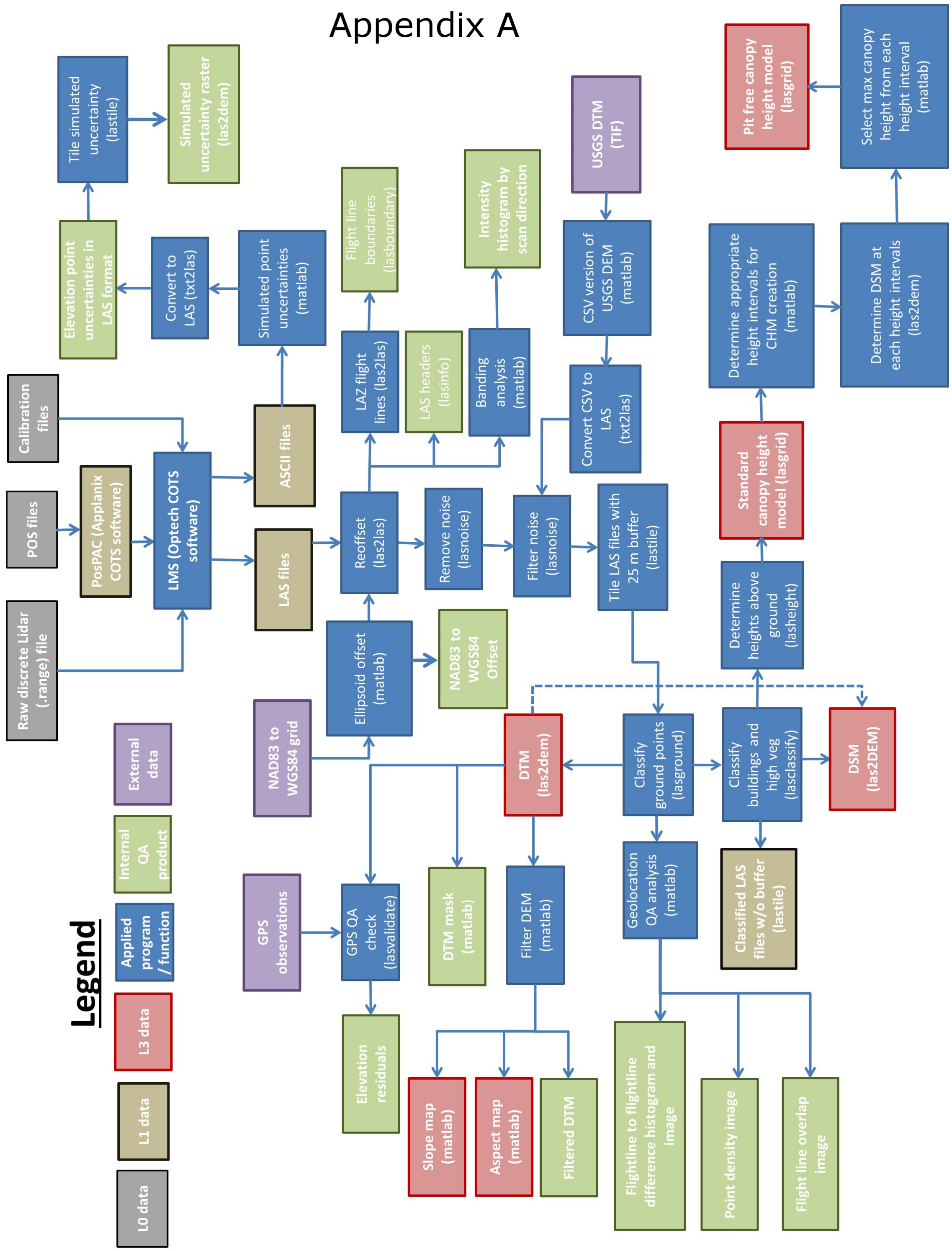

Figure 32: Algorithm flow for creation of L3 data lidar data products and simulated uncertainty