

Analyzing satellite-derived 3D building inventories and quantifying urban growth towards active faults: a case study of Bishkek, Kyrgyzstan

C. Scott Watson ¹, John R. Elliott ¹, Ruth M.J. Amey ¹, and Kanatbek E. Abdrakhmatov ²

1. COMET, School of Earth and Environment, University of Leeds, LS2 9JT, UK

2. Institute of Seismology, National Academy of Sciences, Bishkek, Kyrgyzstan

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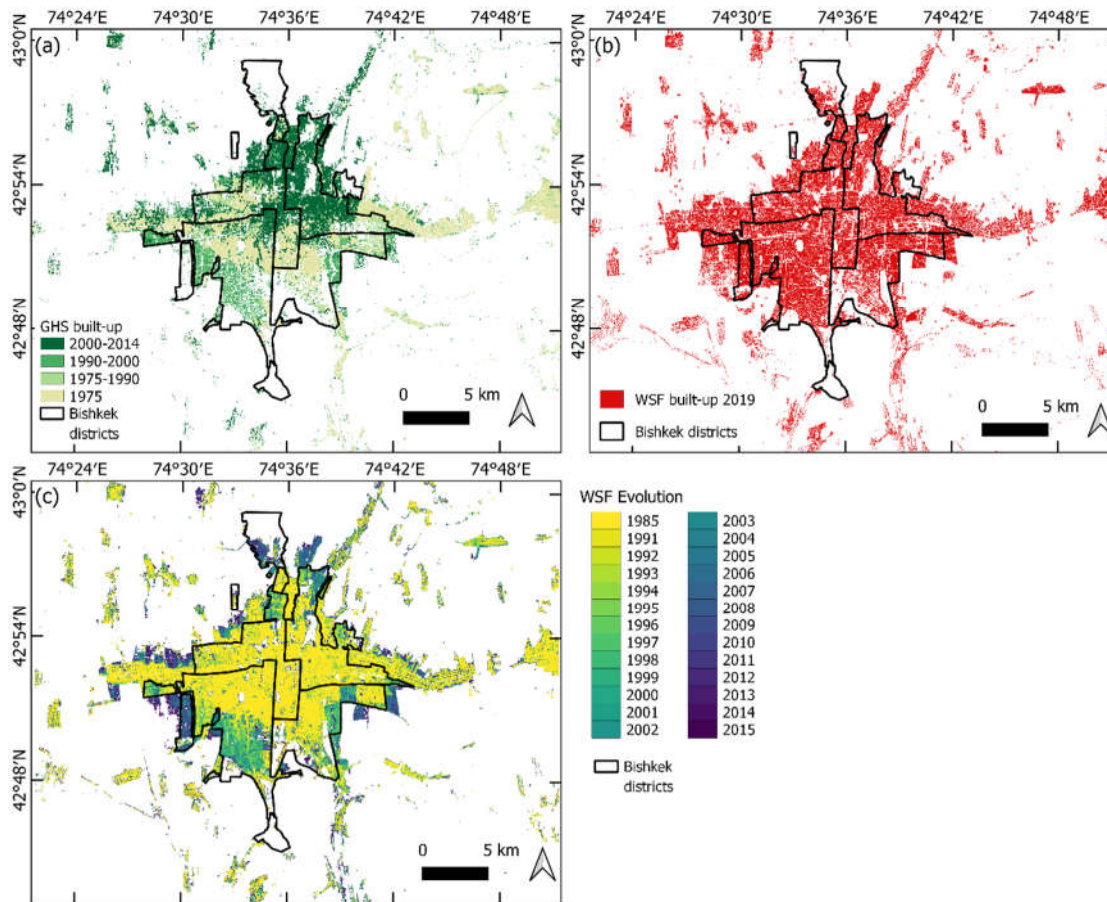


Figure S1. Bishkek's urban growth quantified by global datasets including the Global Human Settlement (a), World Settlement Footprint (b), and World Settlement Evolution (c).

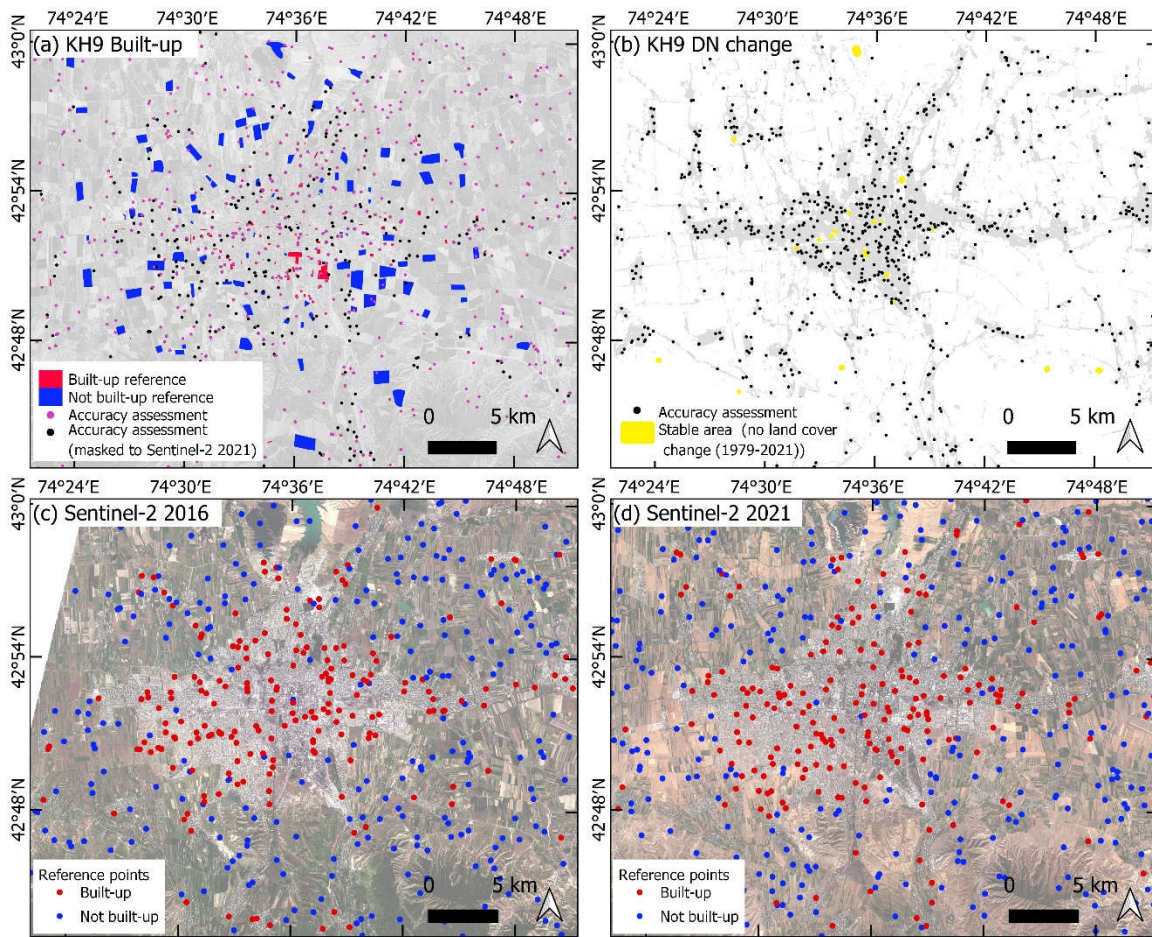


Figure S2. (a) Reference polygons used as training data for the KH-9 built-up classification. Accuracy assessment points are also shown for the KH-9 built-up classification, and the KH-9 classification masked to the built-up area classified using 2021 Sentinel-2 imagery. (b) Stable areas used to quantify DN values for masking out areas of insignificant change when investigating areas of the city that underwent redevelopment or vegetation growth. Accuracy assessment points are also shown for the DN change analysis. Accuracy assessment points for the deep learning classification applied to Sentinel-2 imagery from 2016 (c) and 2021 (d).

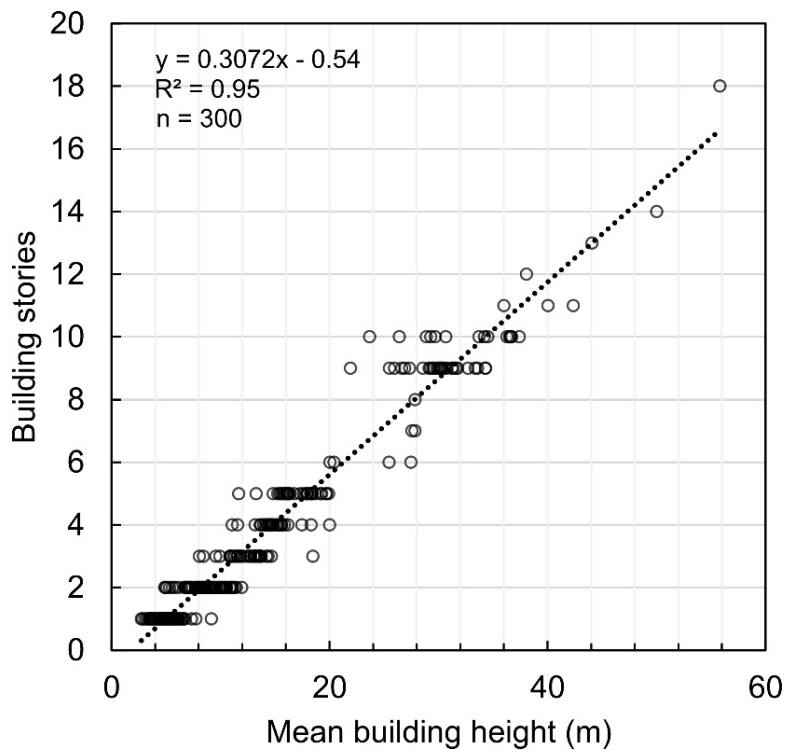


Figure S3. Relationship between the number of building stories and building height for a sample of 300 buildings in Bishkek. Building stories were derived by counting vertical window occurrence in Google Street View (imagery from 2015). Building heights were derived from the 2013 Pleiades data.

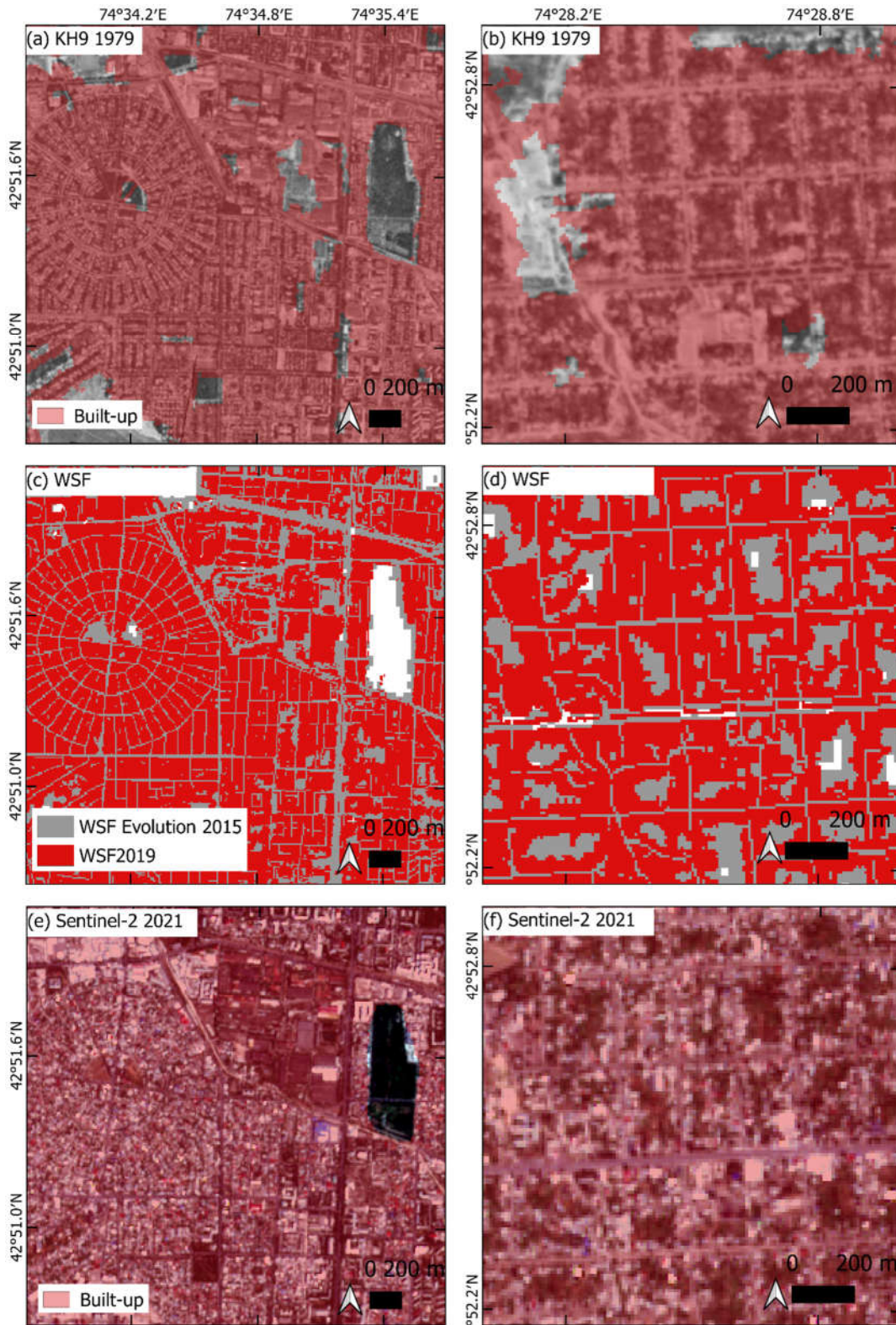


Figure S4. Examples of built-up area classification for the KH-9 analysis (a–b), World Settlement Footprint (c–d), and Sentinel-2 2021 (e–f). Panels in the left column (a, c, e) and right column (b, d, f) show the built-up classifications over two areas of Bishkek.

Tables

Table S1. Optical satellite image IDs used in this study.

Sensor	Date	Image ID	Type*
KH-9	21 Jun	DZB1215-500445L005001	P
	1979	DZB1215-500445L006001	P
Pleiades 1A	02 Nov 2013	IMG_PHR1A_P_201311020601148_SEN_4171456101	P
		IMG_PHR1A_P_201311020600371_SEN_4171456101	P
		IMG_PHR1A_P_201311020600579_SEN_4171456101	P
		IMG_PHR1A_MS_201311020601148_SEN_4171456101	MS
		IMG_PHR1A_MS_201311020600371_SEN_4171456101	MS
		IMG_PHR1A_MS_201311020600579_SEN_4171456101	MS
WorldView-2	10 Oct 2019	19OCT10061235-P2AS-011789242010_01_P001	P
		19OCT10061333-P2AS-011789242010_01_P001	P
		19OCT10061235-M2AS-011789242010_01_P001	MS
		19OCT10061333-M2AS-011789242010_01_P001	MS
PlanetScope PSB.SD	19 Mar 2021 – 15 Apr 2021	20210319_050619_97_242d_1B_AnalyticMS	MS
		20210319_050622_32_242d_1B_AnalyticMS	MS
		20210319_050624_68_242d_1B_AnalyticMS	MS
		20210319_051318_00_2251_1B_AnalyticMS	MS
		20210319_051320_25_2251_1B_AnalyticMS	MS
		20210319_051322_51_2251_1B_AnalyticMS	MS
		20210324_050457_31_2442_1B_AnalyticMS	MS
		20210324_050459_79_2442_1B_AnalyticMS	MS
		20210324_055334_99_2408_1B_AnalyticMS	MS
		20210324_055337_26_2408_1B_AnalyticMS	MS
		20210325_051425_61_2251_1B_AnalyticMS	MS
		20210325_051427_87_2251_1B_AnalyticMS	MS
		20210325_051430_12_2251_1B_AnalyticMS	MS
		20210327_051418_89_227e_1B_AnalyticMS	MS
		20210327_051421_16_227e_1B_AnalyticMS	MS
		20210327_051511_79_222f_1B_AnalyticMS	MS
		20210327_051514_14_222f_1B_AnalyticMS	MS
		20210403_051052_16_2441_1B_AnalyticMS	MS
		20210403_051054_45_2441_1B_AnalyticMS	MS
		20210403_055537_59_2426_1B_AnalyticMS	MS
		20210403_055539_85_2426_1B_AnalyticMS	MS
		20210408_051206_27_227e_1B_AnalyticMS	MS
		20210408_051208_57_227e_1B_AnalyticMS	MS
		20210408_051210_86_227e_1B_AnalyticMS	MS
		20210408_055609_44_2412_1B_AnalyticMS	MS
		20210408_055611_79_2412_1B_AnalyticMS	MS
		20210408_055614_14_2412_1B_AnalyticMS	MS
		20210410_050315_69_2434_1B_AnalyticMS	MS
		20210410_050318_03_2434_1B_AnalyticMS	MS
		20210410_050320_37_2434_1B_AnalyticMS	MS
		20210411_050150_38_241b_1B_AnalyticMS	MS
		20210411_050152_72_241b_1B_AnalyticMS	MS
		20210411_050342_26_2456_1B_AnalyticMS	MS
		20210411_050344_74_2456_1B_AnalyticMS	MS
		20210411_051242_16_222f_1B_AnalyticMS	MS
		20210411_051244_51_222f_1B_AnalyticMS	MS
		20210411_051246_86_222f_1B_AnalyticMS	MS
		20210412_050212_77_2445_1B_AnalyticMS	MS

		20210412_050215_11_2445_1B_AnalyticMS	MS
		20210412_050217_45_2445_1B_AnalyticMS	MS
		20210415_050208_40_242b_1B_AnalyticMS	MS
		20210415_051457_74_2233_1B_AnalyticMS	MS
		20210415_051459_95_2233_1B_AnalyticMS	MS
Sentinel-2	10 Jun 2016	20160610T055206_20160614T013109_T43TDH	MS
	08 Jun 2017	20170608T055641_20170608T060226_T43TDH	MS
	23 Jun 2018	20180623T055641_20180623T060540_T43TDH	MS
	13 Jun 2019	20190613T055639_20190613T060236_T43TDH	MS
	14 Jun 2020	20200614T054639_20200614T054940_T43TDH	MS
	27 Jun 2021	20210627T055641_20210627T055934_T43TDH	MS
	WorldView-3 (Google Earth Basemap)	11 Apr 2021	Maxar IDs: 104001006869470 and 040010068A89A0
22 Jul 2021		Maxar ID: 104001006C038C0	
25 Oct 2021		Maxar ID: 104001006F17740	
*P – Panchromatic. MS - Multispectral			

Table S2. Comparison between field-measured building heights and those derived from the DSM-DTM difference for Pleiades and WorldView-2 data.

Building ID	Field height (2019) (m) ± Standard Deviation	Pleiades (2013) DSM- DTM height (m) ± Standard Deviation	WorldView-2 (2019) DSM-DTM height (m) ± Standard Deviation
1	16.3 ± 0.2	17.9 ± 0.7	17.6 ± 0.7
2	16.6 ± 0.1	18.2 ± 0.4	18.7 ± 0.7
3	16.7 ± 0.2	18.5 ± 1.8	18.4 ± 0.5
4	17.2 ± 0.9	14.6 ± 1.1	14.8 ± 1.4
5	26.7 ± 0.2	Not built	25.9 ± 3.8
6	28.8 ± 0.2	29.8 ± 0.6	29.5 ± 0.6
7	28.8 ± 0.1	30.3 ± 0.6	22.5 ± 5.9
8	31.4 ± 0	32.7 ± 0.8	31.8 ± 0.6
9	31.7 ± 0.1	27.6 ± 8	30.5 ± 1.1
10	32.7 ± 0.1	34.1 ± 1.2	34.5 ± 2.5
11	57.2 ± 1.9	57.7 ± 0.8	58 ± 1.2

Table S3. KH9 1979 built-up area accuracy assessment (masked to Sentinel-2 2021 built-up extent) using 500 validation points. The validation points were used to report area-adjusted classification confidence intervals and producer's, user's, and overall accuracy percentages (see: Olofsson et al., 2014, Olofsson et al., 2013). Briefly, these error-adjusted metrics use the validation points to weight the classified areas accounting for omission or commission within each class. Confidence intervals are the same where the number of classes equals two, since errors are dependent. Overall accuracy is the correctly mapped proportion of the area. Producer's accuracy is the proportion of the area in a class according to the reference (ground truth) information that is also mapped as that class. User's accuracy is the proportion of the area mapped as a class that belonged to that class according to the reference information.

	Built-up	Not built-up
Classified area (km ²)	171.3	165.6
Error-adjusted area (km ²)	153.4	183.4
95% confidence interval area (km ²)	11.1	11.1
Producer's accuracy (%)	87.0	79.4
User's accuracy (%)	78.0	88.0
Overall accuracy (%)	82.9	

Table S4. Sentinel-2 2016 accuracy assessment.

	Built-up	Not built-up
Classified area (km ²)	310.1	975.7
Error-adjusted area (km ²)	272.7	1013.0
95% confidence interval area (km ²)	24.0	24.0
Producer's accuracy (%)	91.4	94.0
User's accuracy (%)	80.4	97.6
Overall accuracy (%)	93.4	

Table S5. Sentinel-2 2021 accuracy assessment.

	Built-up	Not built-up
Classified area (km ²)	337.3	1008.3
Error-adjusted area (km ²)	292.7	1052.8
95% confidence interval area (km ²)	22.5	22.5
Producer's accuracy (%)	94.4	94.2
User's accuracy (%)	82.0	98.4
Overall accuracy (%)	94.3	

Table S6. KH9 1979 land cover change accuracy assessment.

	No change	Digital number decrease (vegetation increase)	Digital number increase (built-up redevelopment)
Classified area (km ²)	108.1	59.1	58.1
Error-adjusted area (km ²)	116.5	43.9	64.8
95% confidence interval area (km ²)	6.8	4.1	6.1
Producer's accuracy (%)	76.1	92.6	66.3

User's accuracy (%)	82	68.8	74
Overall accuracy (%)		76.4	

Table S7. Acquisition information for tri-stereo (Pleiades) and stereo (WorldView-2) imagery.

Sensor/ Acquisition date	Image ID	Details
Pleiades-1A/ 02 November 2013	PHR1A_P_201311020601148_SEN_4171456101	Incidence Angle: 12.10° Incidence Angle (Across Track): 1.38° Incidence Angle (Along Track): 12.03° Orientation angle: 180.00° Sun azimuth: 167.42° Sun elevation: 31.63°
	PHR1A_P_201311020600579_SEN_4171456101	Incidence Angle: 4.35° Incidence Angle (Across Track): 3.84° Incidence Angle (Along Track): 2.05° Orientation angle: 179.98° Sun azimuth: 167.14° Sun elevation: 31.8°
	PHR1A_P_201311020600371_SEN_4171456101	Incidence Angle: 12.32° Incidence Angle (Across Track): 6.83° Incidence Angle (Along Track): -10.35° Orientation angle: 179.98° Sun azimuth: 167.15° Sun elevation: 31.58°
WorldView-2/ 10 October 2019	19OCT10061235-P2AS-011789242010_01_P001	Incidence Angle (Across Track): -9.70° Incidence Angle (Along Track): 23.2° Sun azimuth: 168.2° Sun elevation: 40.1°
	19OCT10061333-P2AS-011789242010_01_P001	Incidence Angle (Across Track): -11.2° Incidence Angle (Along Track): -3.9° Sun azimuth: 168.5° Sun elevation: 40.2°

References

- Olofsson, P., Foody, G. M., Herold, M., Stehman, S. V., Woodcock, C. E. & Wulder, M. A. 2014. Good practices for estimating area and assessing accuracy of land change. *Remote Sensing of Environment*, 148, 42-57.
- Olofsson, P., Foody, G. M., Stehman, S. V. & Woodcock, C. E. 2013. Making better use of accuracy data in land change studies: Estimating accuracy and area and quantifying uncertainty using stratified estimation. *Remote Sensing of Environment*, 129, 122-131.