

MAPPING WITH SKYSAT IMAGES

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ABSTRACT:

The very high-resolution space imagery now competes with some functions that were previously solved with aerial images. Several very high-resolution optical satellites with a ground sampling distance (GSD) of 1 m and smaller are currently active. Not all of these satellites take images worldwide. Nevertheless, it is not a problem to obtain up-to-date satellite images with a very high resolution. Mapping projects not only need to consider access and quality, but also cost-effectiveness. Of course, the economic framework conditions are decisive for the decision as to whether space images or very high-resolution satellite images should be used. With a total 21 SkySat satellites, low-cost satellites with very high resolution have changed the economic conditions. To keep costs and weights down, the Skysat satellites were not designed to offer the best direct geo-referencing performance, but this problem can be solved by automatic orientation in relation to existing orthoimages.

In North Rhine-Westphalia, the cadastral maps must be checked at regular intervals to ensure that the buildings are complete. A test project examined whether this is possible with SkySat images. The geometric conditions and the image quality with the effective ground resolutions are investigated. Experiences from earlier publications could not be used. First the specific problem had to be solved, the resolution of the SkySat images was improved by lowering the satellite orbit altitude from 500km to 450km and by a better super resolution with 0.50m ground sampling distance for the SkySat Collect orthoimages and in addition Planet improved their generation of Collect images. The required standard deviation of the object details of 4 m was achieved clearly as the effective ground resolution of 0.5 m if the angle of incidence is below 20°.

1. INTRODUCTION

1.1 General

With SkySat, BlackSky and Nu-Sat very high resolution optical imagery is available through constellations of inexpensive micro-satellites which like to capture a share of the market of the large satellite systems such as from MAXAR and Airbus DS.

This is not the first publication of using SkySat images for mapping. Nevertheless, several publications are based on SkySat-1 and -2. With the launch of the SkySat C-series, starting in September 2016, the ground resolution and also some technical components changed and with the lowering of the orbit of SkySat-3 up to -15 from 500 km to 450km and the even lower orbit of SkySat-16 up to -21 of 400 km and changing the orbit inclination to 53°, the conditions are no longer the same as before. These changes are at least partially ignored in the current internet information. With the better ground resolution and also some improved data handling by Planet, we now have slightly better conditions than before.

1.2 Project information

In North Rhine-Westphalia, the cadastral maps have to be checked at regular intervals to ensure that the buildings are complete. Previously, this was based on aerial images. The suitability of Skysat images for this topic was checked in a cooperation project together with EFTAS and Planet. The swath width of SkySat imagery is still limited, but this is compensated by the higher number of SkySat satellites. SkySat Basic and Collect images have been tested. For the necessary improvement of the geo-referencing of SkySat Collect

orthoimages as well as for the orientation of SkySat Basic images, existing orthoimages of North Rhine-Westphalia based on aerial images were used. Using the SkySat Collect orthoimages, EFTAS checked the automatic recognition of buildings. The standard deviation of 4m was specified as a requirement for the building identification.

This paper mainly is limited to the geometric behaviour and the image quality of SkySat imagery.

1.3 SkySat Satellites

Skybox Imaging was founded in 2012 and acquired by Google in 2014 under the name Terra Bella. In 2017, Google sold it to Planet Labs, now called Planet. The basic idea behind Skybox Imaging was to build low-cost optical satellites to enable a larger constellation of satellites that can provide very high-resolution imagery in a short period of time. A key factor of the SkySat-1 mission was the simplification of the spacecraft design and the use of ground-based image processing to achieve high system accuracy (Murthy et al. 2014).

With 83kg for SkySat-1 and -2 or 110kg for SkySat-3 up to -21, the satellites belong to the group of micro satellites (11 kg up to 200 kg) or SmallSats (under 600kg) (EOPortal Directory).

SkySat-1 and -2 launched in 2013 and 2014 had no propulsion system, as the following SkySat-3 to SkySat-21 launched from 2016 to 2020. Skysat-3 is also called SkySat-C1, as the others up to SkySat-21, identical to SkySat-C19. SkySat-1 and -2 have an orbit altitude of 600km, while SkySat-3 up to SkySat-15 had 500km orbit altitude, which was lowered to 450km in June 2020 to improve the ground resolution. These satellites have an earth-synchronous orbit with an inclination of about 97°. SkySat-16

to SkySat-21 (C14 up to C19) have an orbital altitude of 400km and an orbital inclination of 53°, which limits data acquisition to the region between 54.3° northern and southern latitude with an acceptable incidence angle of 20°. At the inclination of 53°, the imaging time of day is not fixed. The satellites are flexible due to four reaction wheels, which also allow for in-orbit stereo image coverage.

1.4 SkySat Images

SkySat Satellites have a camera and within the focal plane three staggered arranged CMOS frames with panchromatic and multispectral halves. The three frames capture overlapping strips per satellite (ESA EDAP, 2021) (Figures 1 and 2). The footprints shown in figure 2 are based on the JASON-files that accompany each Basic image. The numbers in Figure 1 contain the focal plane number as first number, followed by the scene number of the data acquisition. As shown, the images from the three frame sensors do not line up in orbit direction. First of all, the focal plane numbers 12 and 15 differ due to the staggered arrangement of the frame sensors in the focal plane and due to the change of the orbit altitude from 500 km to 450 km, the relation of the imaged footprints also changed.

The three frame sensors have a size of 2560 x 2160 pixels, divided into 1080 pixels for the panchromatic channel and four times 250 pixels for the blue channel (450-515 nm), the green channel (515-595 nm), the red channel (605-695 nm) and the near infrared channel (740-900 nm). 20 pixels are required to separate the adjacent channels.



Figure 1: Overlay of corresponding SkySat Basic images captured by the SkySat SSC12's three CMOS-frame sensors



Figure 2: Footprints of Skysat Basic images of the above constellation in Google Earth based on JASON-files

The focal length of the camera is 3.6m. The pixel size is not published by Planet, but the published footprint size of the multispectral pixels corresponds to a pixel size of 6.5µm. Reverse the flying height, determined by resection based on ground control points (GCPs) and controlled by the orbit altitude results in a pixel size of 6.35µm. Rational polynomial coefficients (RPCs) are distributed together with the images. For the orientation, this does not require the knowledge of the pixel size. For control reasons, the orientations were also determined by resection, but for the very narrow field of view of 0.26° x 0.11°, the 2.4% difference in pixel size does not affect the horizontal coordinates determined by resection.

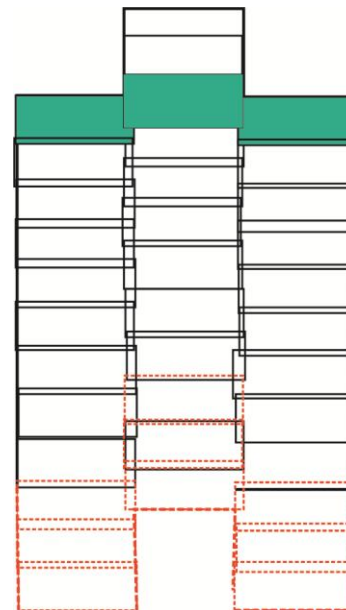


Figure 3: Arrangement of the Basic images in a data set for SkySat Collect, taken by SkySat SSC12

The maximum strip length of SkySat data collection is limited to 200km (ESA Earth Online: <https://earth.esa.int/eogateway/missions/skysat>).

SkySat has the ability to produce videos at 30 Hz for 90 to 120 seconds. This high frame rate is also used to improve the quality of standard images. While each individually captured raw image frame is of moderate quality, ground-based image processing algorithms enhance the raw data by combining data from multiple frames to increase the image's signal-to-noise ratio and decrease the ground sample distance (GSD) in a process Skybox calls "digital TDI" (Murthy et al. 2014). This is not the same as the classic TDI, where the energy for a ground element is summed by shifting the generated free photons to the next pixels in a CCD array according to forward motion. However, SkySat 30 Hz imaging shows the same ground element multiple times, which is used for image sharpening.

D'Angelo et al. 2014 shows the image of a flying aircraft demonstrating the effect of SkySat's "digital TDI". The panchromatic image of the aircraft is shown 18 times, followed by blue, green, red and NIR blobs. To lesser extent, this effect can be seen in trucks driving on freeways (Figure 4). The repeated imaging can also be seen in SkySat Basic Panchromatic images (Figure 5). A similar effect exists for very high resolution satellite images with real TDI sensors such as IKONOS (Jacobsen 2005).



Figure 4: Moving cars and trucks on a highway in SkySat Basic Analytic image

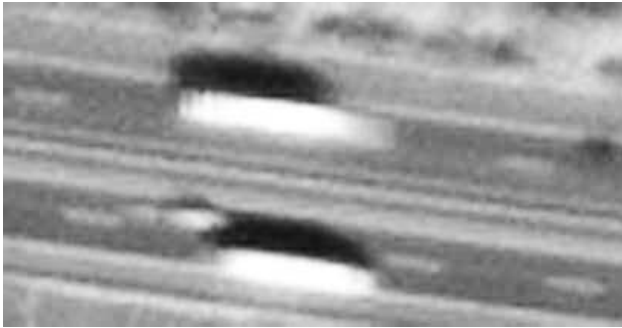


Figure 5: Moving car and trucks in SkySat Basic Panchromatic

SkySat satellite	Orbit height	Geometric GSD	Covered area by Basic imagery
1 - 2	600 km	1.08 m	2765 m x 1166 m
3 - 15 (C1-C13)	500 km	0.90 m	2304 m x 972 m
3 - 15 (C1-C13)	450 km	0.81 m	2074 m x 875 m
16 - 21 (C14-C19)	400 km	0.72 m	1843 m x 778 m

Table 1: Geometric ground sampling distance and area covered by SkySat Basic imagery as a function of flight altitude for the nadir view direction

Table 1 is based on a pixel size of 6.5 μm and 2560 x 2160 pixels. The GSD and the area covered are confirmed by the data sets used. As previously mentioned, in June 2020, SkySat-3 to -13 reduced the orbital altitude from 500 km to 450 km.

The image sharpening by the digital TDI is used for a so-called super-resolution, which reduces the GSD of the generated SkySat Basic Panchromatic.

SkySat satellite	Basic Panchromatic image	Basic Analytic (Multispectral image)
1 - 2	0.86 m	1.0 m
3 - 15	0.65 m	0.81 m
16 - 21	0.58 m	0.72 m

Table 2: GSD of the Planet supplied images in nadir view

The GSD of the panchromatic images supplied by Planet (Planet Imagery Product Specification 2021) corresponds to a pixel size of 5.2 μm , i.e. the GSD is reduced by the factor 1.25 due to the super-resolution. The corresponding images have 3199 x 1349 pixels. Image sharpening is a common technique used also by other satellite image distributors. The GSD of the orthoimages as the SkySat Collect (Figure 3) is reduced to 0.50 m.

Normally we don't have nadir images. The GSD across the direction of view is increased by $\text{GSD}/\cos(\text{incidence angle})$ and in the direction of view by $\text{GSD}/\cos^2(\text{incidence angle})$, the corresponding 0.65m GSD in nadir view for an angle of incidence of 20° is increased to 0.69 m x 0.74 m.

1.5 Use of SkySat imagery

SkySat-1 was launched in 2013 and -2 in 2014. Today they do not play an important role due to the lower ground resolution, which cannot be changed to lower orbital altitude due to lack of a propulsion system. The European Space Agency (ESA) Earthnet Data Assessment Pilot (EDAP) has published an intensive quality assessment (ESA EDAP 2021). They mention that the image quality differs strongly, depending on the satellite

involved and capture settings used. Of course, the image quality also depends on the GSD (Table 1) and the actually angle of incidence used.

The angle of incidence is larger than the nadir angle (Figure 6). At an orbit altitude of 450 km for 20° nadir angle, the angle of incidence is 21.3°. For the calculation of the GSD, the angle of incidence must be used (see above). In my own investigation, only images from SkySat-3, SkySat-9 and SkySat-14 (SSC1, SSC7 and SSC12) were used, which showed no differences in image quality.

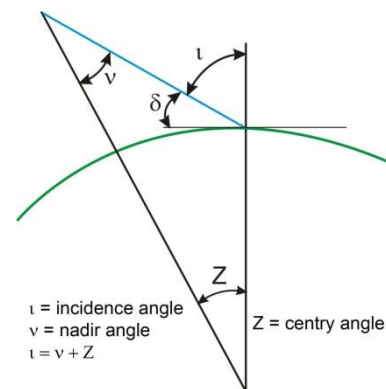


Figure 6: Relation incidence angle ι and nadir angle ν

As already mentioned, SkySat's image sensors are capable of generating video sequences of up to 90 or even 120 seconds. During the data acquisition, the satellite must be continuously rotated to point to the same ground location. For a 90 second video, this requires a change in the angle of incidence from approximately +30° to -30°. For a 120 second video, the angle of incidence must be changed from +45° to -45°. The panchromatic video of 2560 x 1080 pixels is limited to one frame sensor. Video sequences are not examined in this paper.

The individual video images have the original geometry of a Basic image. In theory, the entire video sequence could be used to create a Digital Elevation Model (DEM). Nevertheless, for a satisfying base length only selected images of the sequence can be used. (D'Angelo et al. 2014) used triplets and up to 20 images of a video sequence related to a master scene for DSM generation by Semi Global Matching (SGM) based on a relative block adjustment resulting in a tie point standard deviation of 0.1 pixels. This resulted in very detailed DSMs, but limited to the small area covered by a SkySat Basic scene.

(Aati and Avouac 2020) generated DEMs based on block adjusted neighbored SkySat Basic scenes using tie points with height constraint to a reference DEM. Based on the LiDAR reference, a standard deviation in height of 3.9 m was achieved.

(Bushan et al. 2021) used triplet stereo combinations of Basic imagery with 27° off-nadir, nadir and -27° off-nadir views for DEM generation. Scene orientation was based on bias-corrected RPCs with GCPs from a reference orthoimage base-map, aided by tie points of overlapping scenes and bundle adjustment. Matching for DEM generation used a combination of stereo pairs and a "More Global Matching" technique. The result has been filtered for points that exceed 5 m elevation discrepancies. A DEM covering the range of a SkySat Collect image in mountainous terrain was generated with an NMAD of 2.49 m over static surfaces. In summary, they mention "However, the accuracy of the resulting DEM products is limited by the relatively poor geolocation accuracy of the original Level-1A/1B SkySat camera models and inconsistent orientation of

individual scenes in both the collects and videos. As a result of these limitations, and the absence of robust processing software, SkySat imagery has not yet seen wide-spread use for stereo reconstruction.”

This gives only a brief overview of the possibility of DEM generation through SkySat images, which is not part of this paper. In general it is possible to create DEMs with SkySat imagery, but this can only be economical for small areas and for special subjects. The effort of a precise orientation should not be underestimated.

The main advantage of the SkySat satellites is the fast and not so expensive object information. This can be used for mapping purposes. A typical example is the publication of (Interpine Innovation, 2021) describing the replacement of traditional airborne imagery for forest remapping by SkySat imagery.

2. MAPPING WITH SKYSAT IMAGES

2.1 Scene orientation

To keep costs and weights down, the Skysat satellites were not designed to offer the best direct geo-referencing performance. (Smiley et al. 2014) from SkyBox company mentioned that ground processing is far cheaper than star trackers. Despite this, the SkySat satellites are equipped with two 90 gram ST 15 star trackers and TQ 15 torque rods (Dzamba, 2014), but angular pointing accuracy is still limited. In the (Planet Imagery Product Specification 2021) the geo-location knowledge is given as 30m - 50 m for SkySats-3 up to -21. This is not satisfactory for mapping purposes. In addition, as can be seen below, these figures are overly optimistic.

The SkySat Basic scenes come with orientation information by RPCs that need to be enhanced by GCPs. For this reason, the orientation of the Basic scenes required for the generation of the joint orthoimages SkySat Collect was determined through Planet by automatic matching of Basic scenes with the most recent aerial orthoimages from the North Rhine-Westphalia survey authority. Automatically matching of the single small scenes is a challenge, since the situation that reference orthoimages of the survey authority are based on aerial images of the no foliage period, while the SkySat images are taken during the foliage period. In addition, there were several changes in the agriculture areas; in one subarea it changed completely by land consolidation. For checking purposes the author identified manually GCPs between the reference orthoimages and the SkySat Basic images, which by the same reason was difficult in the footprint area of just 2073 m times 875 m in case of nadir view, but by manual identification only unchanged objects have been used.

The shift values in Y for data set 3 (Figure 7), which is almost in orbit direction, show larger and more abrupt changes than the X-component. These values are based on bias corrected RPC orientations. The linear mean for the X-direction is 32.1 m and for the Y-direction 51.4 m and the root mean square differences and the root mean square are 35 m and 65 m, respectively. The satellite inclination is continuously corrected, particular in the direction of the orbit. This also affects the relative position of frames 1 and 3 with respect to centre frame 2, which is exposed about 0.28 seconds earlier. The relative standard deviation in Y of the over next image corresponds to 24.9 m or 38 pixels. Also frame 1 compared to frame 3 has a shift in the Y-direction of 94 pixels, corresponding to 0.008 seconds in relation to the footprint velocity for 450 km orbit height of 7130 m/sec.

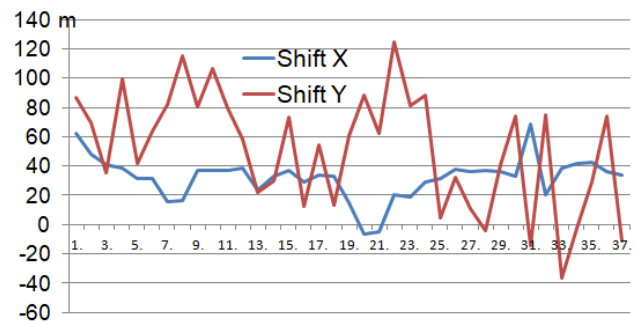


Figure 7: Shifts in the RPC-orientations versus GCPs, frame1 of data set 3, SkySat SSC12, 37 Basic Analytic scenes with 2560 x 1080 pixels of 6.5 μ m

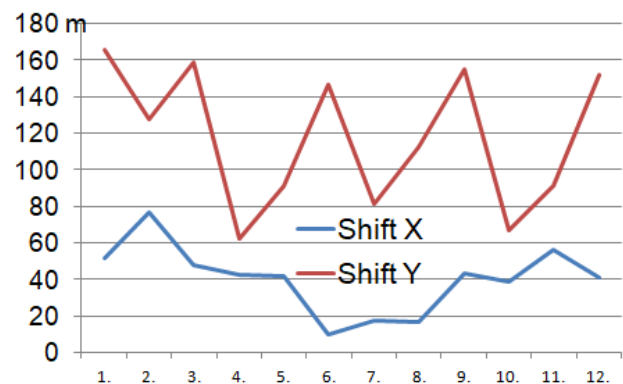


Figure 8: Shifts in RPC-orientations versus GCPs, frame 2 of data set 6, SkySat SSC12, 12 Basic Panchromatic scenes with 3199 x 1349 pixels of 5.2 μ m

This second data set shows a similar behavior. The linear mean for the X-direction is 40.4 m and for the Y-direction 117.6 m and the root mean square differences are 44 m and 123 m, respectively. In the Y-direction it exceeds Planet’s specification in both cases, but this is not important due to the requirement for a bias-corrected RPC-orientation.

The bias correction by affine transformation with the Hannover program RAPORIO often required the 6 unknowns of the transformation. Sometimes one or two affine parameters are not significant, but this is not important. As Figures 7 and 8 shows, the shift parameters are large and absolutely required.

As previously mentioned identifying corresponding points between the survey authority orthoimage and the SkySat images was difficult and also required the use of non-optimal GCPs, as shown in Figure 9. On the left of Figure 9, the GCP is a path junction, where one path is partially obscured by trees. In the centre, the GCP is the middle of a bridge and on right another junction.

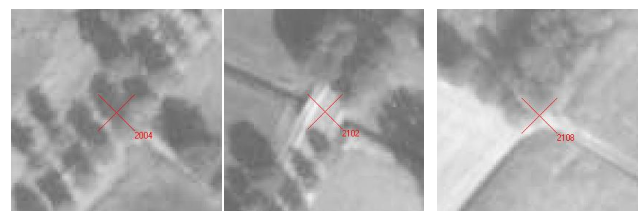


Figure 9: Not optimal ground control points

For 37 Basic Analytic scenes with 0.81m GSD from data set 3, based on angles of incidence of 4° up to 6°, in the average the root mean square error (RMSE) of the orientation in X is 1.16 m and in Y 1.01 m. The standard deviation, which corresponds to 1.3 pixels, is dominated by the uncertainty of the GCPs and not so much by the geometry of the images. Planet did the same by automatic matching to the same reference ortho that I used. Planet achieved an RMSE for X of 1.51 m and for Y 1.02 m based on 2700 to 16800 tie points per Basic image, with images with below 15° nadir angle (incidence < 16.1°).

CMOS- or CCD-sensors have a very high internal accuracy. However, systematic discrepancies can also arise due to the super resolution used in scene reconstruction. Image deformations may be possible due to the optical system. Image distortion is not common with optics with such a small field of view. Nevertheless, the 349 residuals of all 37 orientations were superimposed to verify this.

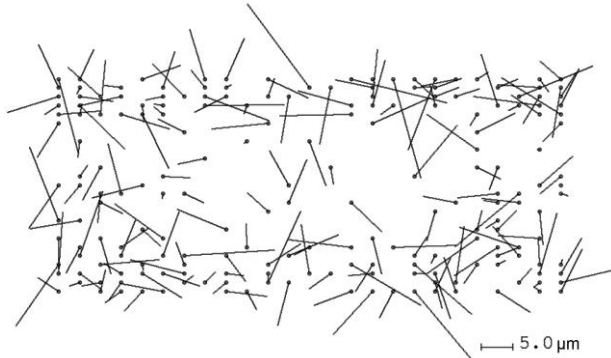


Figure 10: Superimposition of the image residuals of 37 orientations of data set 3, gridded in 25 x 25 cells

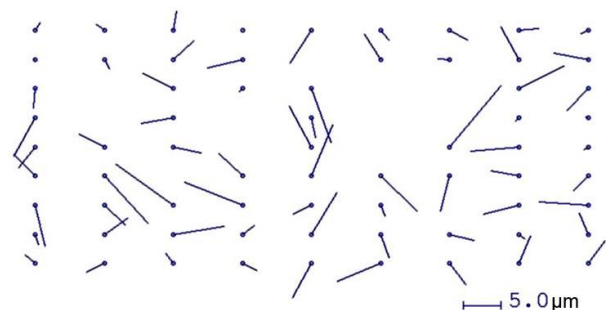


Figure 11: Superimposition of the image residuals of 37 orientations of data set 3, gridded in 9 x 9 cells

Figure 10 and 11 show the superimposed and gridded residuals, averaged in the grid cells, of all orientations. Figure 10 shows the dominating distribution of the points in the outer image area. The random errors dominate. In figure 11, the residuals are averaged in 9 x 9 grid cells, which give a better overview of possible systematic image errors. In the centre right there is a small trend of the vectors showing to the left, but this is far from significant. There is no indication of radial symmetric and tangential distortion.

In 12 Basic Panchromatic scenes with 0.65m GSD of data set 6, based on angles of incidence of also 4° up to 6°, in the average a standard deviation of 1.22 m in X and of 1.10 m in Y was achieved. The ground accuracy is similar to data set 3, due to the smaller GSD of 0.65 m this corresponds to a standard deviation of 1.8 pixels, which is also dominated by the uncertainty of the GCPs and less by the geometry of the images.

	ϕ	ω	κ	X0	Y0	Z0
ϕ	1.00	0.02	0.54	1.00	-0.02	0.95
ω	0.02	1.00	-0.69	0.02	-1.00	-0.17
κ	0.54	-0.69	1.00	0.54	0.69	0.65
X0	1.00	0.02	0.54	1.00	-0.02	0.95
Y0	-0.02	-1.00	0.69	-0.02	1.00	0.17
Z0	0.95	-0.17	0.65	0.95	0.17	1.00

Table 3: Correlation matrix of resection unknowns

SkySat has an array sensor that also allows for orientation through resection. Of course, with such a small field of view, strong correlations are to be expected. As can be seen in Table 3, with the exception of kappa, all other unknowns are extremely correlated. This is not a problem for the resection, only the iteration requires more steps and the unknowns have larger standard deviations.

For the 37 resection orientations of dataset 3, the average standard deviation for the image coordinates in X is 5.3 μm and for Y 5.1 μm and sigma0 6.7 μm. For the pixel size of 6.5 μm, sigma0 corresponds to 1.03 pixels. This is slightly better than the 1.3 pixels for the bias corrected RPCs, which also have 6 unknowns. The situation is similar with data set 6. The average standard deviation for the image coordinates in X is 6.8 μm and for Y also 6.8 μm and sigma0 8.3 μm. For the 5.2 μm pixel size of the Basic Panchromatic images, sigma0 corresponds to 1.6 pixels, which has to be compared to 1.8 pixels for the bias-corrected RPC orientation.

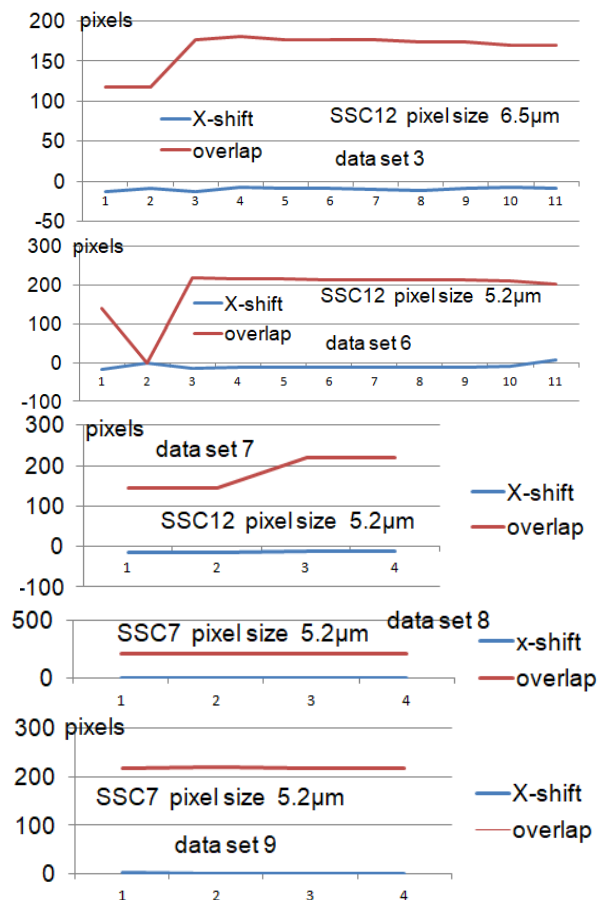


Figure 12: X-shift and overlap of adjacent Basic images in flight direction for the same frame, horizontal = sequence of images in Collect arrangement

The RPC orientations of SkySat SSC7 Basic Analytic images acquired at an incidence angle of 18° resulted in a standard deviation for X of 2.7 m and for Y of 1.3m. The X-direction is roughly in the view direction with a GSD of 0.90 m, the GSD in the Y-direction is 0.85 m. This corresponds to a standard deviation for X of 3 GSD and for Y of 1.5 GSD. No general differences could be determined between the images used from the satellites SSC12, SSC3 and SSC1.

The X-shift and overlap in-flight direction of adjacent Basic images taken with the same frame has been checked (Figure 12). Basic Analytic images correspond to a pixel size of 6.5 µm and Basic Panchromatic to 5.2 µm. The relation of 1.25 : 1 has to be respected.

In particular, the overlap of the first two images of a data set can differ significantly from the overlap of the other scenes, as it is evident for data sets 3, 6 and 7. Other data sets were checked, but they show similar small changes as data sets 8 and 9. Of course, the overlap and the X-shift depend on the ground elevation and the angle of incidence, but the main project area is very flat with an elevation of 22 m up to 47 m and the angle of incidence of the datasets used to verify the overlap is only in the range of 5°. At a 5° incidence angle, the distance from the orbit is 1.7 km longer than in case of a nadir view. With the field of view in orbit direction of 0.11° this causes a change of the overlap by 3.3 m or 5 pixels. The variations of the overlap are quite larger.

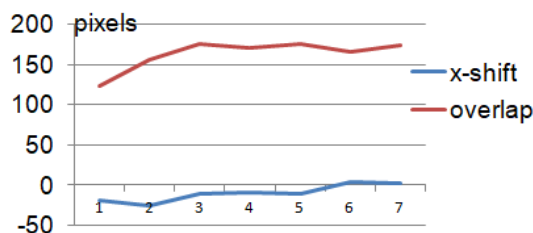


Figure 13: Average X-shift and overlaps without the first two images of the data sets 1 to 7 used, based on a pixel size of 6.5 µm

The average X-shift of the used data sets without the first two images (Figure 13) ranges from -25 up to 4 pixels of 6.5 µm, the overlap changes from 123 up to 176 pixels of 6.5 µm. The x-shift depends on the yaw of the satellite. That is, a calibration as attempted by some authors is not possible due to changes in the satellite's angular orientation, in the short time interval between image acquisitions for the three frame arrays.

The lateral overlap of the three CMOS arrays is in the range of 5% to 7%. At 5% overlap, the total swath of images taken from 450 km orbit altitude is 7223 pixels for 0.81 m GSD, which corresponds to 5780 m for nadir view direction. Due to the situation that the nadir angle is usually across orbit, at 5° angle of incidence the swath is 5820 m, at 10° angle of incidence 5960 m, and at 20° angle of incidence 6550 m. At SkySat-16 to -21, with an orbit height of 400 km, the swath is 11% smaller.

2.2 Accuracy of SkySat Collects

Planet generates SkySat Collects as geo-referenced orthoimages based on the original Basic imagery (Figure 3). Following Collect products are generated:

Visual-pansharpened, as colour corrected RGB images
Pan-sharpened multispectral – as colour corrected NGRN images
Analytic DN – multispectral BGRN
Panchromatic DN – panchromatic

All these products have the same geometry as geo-referenced orthoimages with 0.50 m GSD based on images taken after June 2020. Before the GSD was 0.80 m. The improvement is due to the reduced orbit altitude, more importantly, to the super-resolution scene reconstruction approach based on multiple narrow baseline stereo pairs (Planet Imagery Product Specification Febr. 2021). In the project area, triangulation with tie points between neighbouring SkySat Basic scenes is difficult due to the small overlap and large areas without unchanged texture. Due to this problem, Planet generated in the project area SkySat Collect scenes by individual orientation of Basic Imagery in relation to the reference aerial orthoimage. Planet creates orthoimages of the Basic scenes and merges the orthoimages, also paying attention to misfits of neighbouring orthoimages. Planet improved the technique during the project phase, resulting in a better accuracy than at the beginning.

Some SkySat Collect scenes have been checked against the reference aerial orthoimage by manual identification of check points (Table 4).

scene	Inci- dence	RMSX [m]	RMSY [m]	Bias X [m]	Bias Y [m]	SX [m]	SY [m]
1	3.7°	3.19	1.27	2.48	0.47	2.00	1.18
2	4.3°	2.55	0.90	2.04	-0.31	1.52	0.84
3	9.3°	2.02	1.94	-0.71	0.87	1.89	1.73
4	16.6°	1.81	1.17	1.14	0.53	1.14	1.05
5	16.7°	1.44	1.04	0.81	0.24	1.20	1.02
6	25.2°	4.35	2.73	3.13	-2.02	3.03	1.83
7	30.8°	5.97	3.12	4.31	1.76	4.13	2.51
8	33.6°	5.46	3.25	4.30	1.13	3.36	3.05
9	37.8°	9.92	4.28	-6.28	1.78	7.68	3.89

Table 4: Accuracy numbers of SkySat Collect images

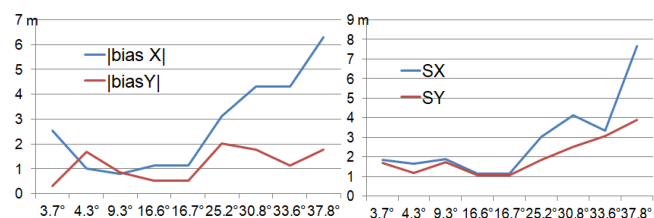


Figure 14: Absolute value of bias and standard deviation of SkySat Collect geo-reference as function of angle of incidence

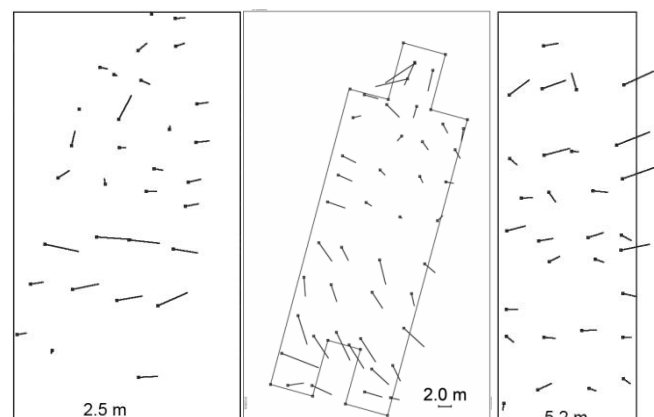


Figure 15: Discrepancies at check points, left: data set 1, centre: data set 5, right: data set 7

The result of the SkySat Collect investigation is unequivocal, above an incidence angle of 20°, the required geo-reference accuracy of 4m is not achieved (Table 4, Figure 14). First, the

GSD is increased by an average of 10% at 20° angle of incidence, but more importantly, data sets 6 through 9 are not in the flat area like the others, they are in the Sauerland, a gentle mountainous area with high proportion of forest. In the forest area, the matched reference points from the reference orthoimage are located on the canopy, which leads to systematic errors (bias) which is the dominant problem, especially in the X-direction. The X-direction is close to the view direction (satellite azimuth). Additionally, Planet used the Intermap NextMap World30 digital surface model, based on SRTM with 3 arcsec (~90 m) point spacing, with a densification to 30 m by ASTER GDEM and enhanced by ICESat elevation points as digital elevation model. This is not an optimal elevation model; the free AW3D30 supported by TDM90 would be better (Jacobsen, Passini 2021). However, systematic errors also play an important role in the areas with angles of incidence below 20° (data set 1 - 5), which can be seen in Figure 15. Nevertheless, for angles of incidence below 20°, the condition is met that the standard deviation should be better as 4 m. In addition, modified and new buildings are to be recorded in the project. The automatic building detection is based on roofs. At an angle of incidence of 20°, the roof of a 5m high building will shift by 1.8 m, which must also be taken into account.

2.3 Image quality

In addition to a simple visual check, the image quality was determined using the point spread function from by edge analysis (Jacobsen 2008). This is expressed as a factor for effective resolution. This factor multiplied by the GSD gives the effective GSD, which is often greater than the nominal GSD. For SkySat Collect super resolution imagery, since June 2020 the imagery has been distributed with 0.50 m GSD. Image quality may not correspond to 0.50 m GSD due to weather conditions and the angle of incidence.

Internal area number	Angle of incidence	Factor for effective resolution	Effective GSD	remarks
1	4.9°	0.90	0.45 m	
2	4.9°	0.87	0.44 m	
3	6.3°	1.17	0.58 m	
4	17.3°	1.02	0.51 m	
5	18.3°	0.88	0.44 m	
6	21.8°	1.14	0.57 m	clouds
7	26.5°	1.34	0.67 m	clouds
8	29.1°	1.30	0.65 m	

Table 5: Effective GSD of SkySat Collect orthoimages

The factor for effective resolution of the SkySat Collect images shows a dependency on the angle of incidence. This is not surprising due to the geometric magnification of the Basic images for inclined view used to generate the Collect images. At an angle of incidence of 29.1°, the GSD of the Basic imagery is magnified by the factor 1.14 across view direction and 1.30 in the view direction. Areas 6 and 7 in Table 5 have some clouds. Usually, the air next to clouds is a bit foggy, resulting in reduced image quality. According to simple theory, the factor for effective resolution should not be less than 1.0, but this is not the case for areas 1, 2 and 5. Planet uses super resolution for generating Collect images therefore Collect images are not original images. In addition, the contrast enhancement can influence the point spread function at edges, which can reduce the factor of effective resolution to values below 1.0. Larger factors can occur due to non-optimal imaging conditions.

The same investigation was carried out for Basic images. Basic Panchromatic images are distributed with a pixel size of 5.2 µm, while Basic Analytic, the colour images, are distributed with the original geometric pixel size of 6.5 µm. For the Basic images, the angle of incidence is not as important due to the original image geometry as it is not projected onto the ground.

Internal area number	Angle of incidence	Factor for effective resolution	Effective pixel size (5.2 µm)
1	4.4°	1.09	5.7 µm
2	4.4°	0.91	4.7 µm
3	6.3°	1.09	5.7 µm
4	17.3°	1.02	5.3 µm
5	18.0°	1.13	5.9 µm
6	18.6°	0.98	5.1 µm
7	29.1°	0.98	5.1 µm
8	29.1°	0.90	4.7 µm
9	29.8°	0.89	4.6 µm
10	30.8°	1.02	5.3 µm
average		1.00	5.2 µm

Table 6: Effective GSD of SkySat Basic Panchromatic images with a distributed pixel size of 5.2 µm

Internal area number	Angle of incidence	Factor for effective resolution	Effective pixel size (6.5 µm)
1	6.3°	1.08	7.02 µm
2	6.3°	0.96	6.24 µm
3	6.3°	1.03	6.70 µm
4	18.0°	1.15	7.47 µm
5	18.1°	1.03	6.70 µm
6	18.5°	1.13	7.34 µm
7	37.7°	1.11	7.21 µm
average		1.07	6.95 µm

Table 6: Effective GSD of SkySat Basic Analytic images with an original pixel size of 6.5 µm

As expected, the Basis images show no dependence on the angle of incidence. For Basic Panchromatic, the average factor for the effective resolution is exactly 1.0; i.e. the effective pixel size is identical to the nominal pixel size. With Basic Analytic it is 1.07, i.e. the effective resolution is slightly below the nominal resolution. A simple visual check confirms this. In general, it can be said that the image quality is good. My experience with other satellite imagery is similar. Images from the SkySat satellites SSC1, SSC7 and SSC12 were used; differences between the various SkySat satellites were not discernible.

3. CONCLUSION

The usability of SkySat images to update building information for German cadastre has been confirmed. Satisfactory results were obtained with SkySat images up to an angle of incidence of 20°. The Basic images are very small, covering only 2074 m x 875 m when viewed vertically from an orbital altitude of 450 km. They can only be recommended for special applications due to the requirement for orientation supported by ground control points. Planet uses automatic orientation with respect to existing high resolution aerial orthoimages and combines orthoimages of Basic images for the three CMOS-sensors and a flexible number of in flight images to generate orthoimages under the name SkySat Collect. These SkySat Collect orthoimages have a satisfactory accuracy for the building update when the Basic images used are taken with an angle of incidence of up to 20°. The geo-referencing of the Collect orthoimages does not need to

be improved, so the smaller area covered compared to the classic very high resolution images does not matter much if the entire project area is covered with Collect images.

The image resolution of the Basic Panchromatic images corresponds to the pixel size of the supplied 5.2µm, while the Basic Analytic images correspond to a pixel size of approximately 7 µm, slightly less than the nominal 6.5 µm. The GSD of the SkySat Collect images corresponds to the delivered super resolution of 0.50 m GSD up to an angle of incidence up to 20°, while at higher angles of incidence the effective GSD is larger.

Finally, the economic conditions show advantages for this project of only horizontal mapping for the use of SkySat Collect imagery over aerial and very high resolution classical satellite imagery.

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REFERENCES

- Aati, S., Avouac J.-P., 2020. Optimization of Optical Image Geometric Modeling. Application to Topography Extraction and Topographic Change Measurements Using PlanetScope and SkySat Imagery, *Remote Sensing* 2020, 12, 3418
- D'Angelo, P., Kusch, G., Reinartz, P., 2014. Evaluation of Skybox video and still image products, *IAPRS*, Vol. XL-1, 2014
- Bushan, S., Shean, D., Alexandrov, O., Henderson, A., 2021. Automated digital elevation model (DEM) generation from very-high-resolution Planet SkySat triplet stereo and video imagery, *ISPRS Journal of Phot. And Remte Sens.*, 173 (2021) 151-165
- eoPortal Directory: <https://directory.eoportal.org/web/eoportal/satellite-missions/s/skysat> (Feb. 2022)
- Dzamba, T. Enright, J., Sinclair, D., Amankwah, K., Votel, R., Jovanovics, I., McVittie, G.R., 2014: Success by 1000 improvements: Flight Qualification of the ST-16 Star Tracker. In: 28th Annual AIAA/USU Conference on Small Satellites.
- ESA EDAP: Technical Note on Quality Assessment for Skysat, 2021, https://earth.esa.int/eogateway/documents/20142/37627/EDAP.REP.015+TN+on+Quality+Assessment+for+SkySat_v1.0.pdf/59a2a91d-eecd-20f1-4a13-e670dad8eed3 (Feb. 2022)
- Interpine Innovation, 2021. Planet SkySat Imagery Replacing Traditional Airborne Imagery for Forest Remapping, <https://interpine.nz/planet-skysat-imagery-replacing-traditional-airborne-imagery-for-forest-remapping/> (Feb. 2022)
- Jacobsen, K., 2005: High resolution Satellite Imaging Systems – Overview, *ISPRS Hannover Workshop 2005, IntArchPhRS Vol. XXXVI/1-W3*
- Jacobsen, K., 2008: Tells the number of pixels the truth? – Effective Resolution of Large Size Digital Frame Cameras, *ASPRS 2008 Annual Convention, Portland*
- Jacobsen, K., Passini, R., 2021: Analysis and Bias Improvement of Height Models based on Satellite Images, *ISPRS Archives, XLIII-B1-2021*, 23–30, 2021
- Murthy, K., Shearn, M., Smiley, B., Chau, A., Levine, J., Robinson, D., 2014. SkySat-1: very high-resolution imagery from a small satellite, *Proc. SPIE 9241, Sensors, Systems, and Next-Generation Satellites XVIII*, 92411E (7 October 2014)
- Planet Imagery Product Specification Febr. 2021. https://assets.planet.com/docs/Planet_Combined_Imagery_Product_Specs_letter_screen.pdf
- Smiley, B., Levine, J., Chau, A., 2014: On-Orbit Calibration Activities and Image Quality of SkySat-1, *JACIE* 2014.