Airborne or Spaceborne Images for Topographic Mapping?

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Abstract. New airborne optical cameras as well as new very high resolution satellites are available now. With 50cm ground sampling distance (GSD) images from optical satellites are competing with images from airborne digital cameras which may have a GSD of up to approximately 1m GSD. Analog aerial cameras nearly disappeared from the market as it was the case for analog imaging satellites years before. The capacity of large format digital aerial frame cameras has been extended to 250 up to 260 mega pixels as well as the swath width of the very high resolution satellites up to 40 000 pixels. In addition the imaging capacity of the optical satellites strongly improved. The partially very high satellite slewing speed enables now stereo combinations from the same orbit without former restrictions. So the economic conditions and also the availability of actual images are better as before. For special projects of limited size in addition to traditional photo flights unmanned aerial vehicles (UAV) also named unmanned aerial systems (UAS) got a growing share. With the exception of countries or areas where restrictions for the use of aerial images exist, there is the question if airborne or spaceborne imagery should be preferred. Topographic line maps as well as digital elevation models (DEM) are specified by the GSD; the origin of the images – aerial or space - is not important for the quality and accuracy. Aerial image flights for some applications have the advantage of simpler higher overlap by more as two images, but the dominating aspects are the simple access to imagery and the financial conditions.

Keywords. Spaceborne, airborne, optical images, topographic mapping, DEM generation.

1. Introduction

With optical satellite images, now available with up to 0.5m GSD, an overlapping range to digital aerial images exists. The decision for use of aerial or space images for mapping application today is dominated by economic aspects and depends on size and requirements of projects. Because of the increased number of very high resolution satellites and especially the increased imaging capacity today, it is quite simpler to get useful images from the archives or via imaging order. The high imaging capacity as well as the improved slewing speed of the satellites allows the acquisition of stereo pairs which was expensive and time consuming before the launch of WorldView-1 in September 2007. Also digital aerial cameras recently strongly improved the capacity. With mid-format cameras and configurations of such cameras new applications exist. The extended hardware, but also software solutions made the decision for choosing the optimal configuration of projects more difficult.

2. Airborne and spaceborne systems

2.1. Airborne camera systems

Airborne cameras and camera systems are categorised in large format frame cameras, mid-format frame cameras and camera systems, small format cameras and line scan cameras. Analog aerial cameras should not be used any more, their information content corresponds just to the newest digital mid-format cameras, it's geometric accuracy is limited, the spectral range is not well defined, film is not as sensitive as CCD-arrays or CCD-lines, film is expensive and the film development is becoming difficult. Only cameras useful for photogrammetric purposes are respected in following. They must have a fixed focus and a stable camera body to guarantee a stable inner orientation.

Table 1. Specification of large format digital frame cameras.

camera	Pixels (camera)		Pixel size [µm]	f [mm]	Δt [sec]	Image size [mm]		b/h for p=60%	Mega-pixels
	x	y				x	y		
DMC (1st version)	7680	13824	12.0	120	2	49.15	86.02	1:6.1	106
DMCII 140	11200	12096	7.2	92	2	80.64	87.09	1:2.8	135
DMCII 230	**14144**	**15556**	**5.6**	**92**	**1.7**	**79.21**	**87.11**	**1:2.9**	**220**
DMCII 250	**14656**	**17216**	**5.6**	**112**	**2,3**	**82.41**	**96.41**	**1:3.4**	**249**
UC D	7500	11500	9.0	101.4	1	67.50	105.5	1:3.8	86
UC X	9420	14430	7.2	100.5	1.4	67.82	103.9	1:3.7	136
UC Xp	11310	17310	6.0	100	2	67.86	103.9	1:3.7	196
UC Eagle	**13080**	**20010**	**5.2**	**80 / 210**	**1.8**	**68.02**	**104.1**	**1:2.9 1:7.7**	**261**

Large format digital photogrammetric frame cameras are only produced by Z/I Imaging as DMC and by Vexcel Imaging as Ultracam (UC) (Table 1). Both companies recently extended strongly the capacity. Z/I Imaging changed the concept of four slightly convergent sub-cameras for the panchromatic image to one monolithic very large CCD, produced by DALSA, while the pixel size of the UltraCam continuously was reduced now to 5.2µm. This extended the capacity now to nominally 249 respectively 261 megapixels. The reduction of the pixel size caused by the progress of CCD-arrays, used also for mid-format cameras, is not without problems. Smaller pixels are closer to diaphragm limited resolution, requiring good optical systems and longer exposure time. For smaller pixels a difference between nominal and effective resolution may exist.

The effective resolution can be determined by edge analysis, leading to the point spread function [1]. The width of the point spread function gives the factor for effective resolution which multiplied with the pixel size or GSD leads to the effective resolution in the image or object. An edge analysis was leading to following factors: DMC II 230: 0.98, DMC II 250: 0.87 and UC Eagle: 1.02. That means that the effective capacity for the UC Eagle is 250 megapixels instead of the nominal 261 megapixels. For the DMC II 230 and 250 it is even extending the effective capacity against the nominal.

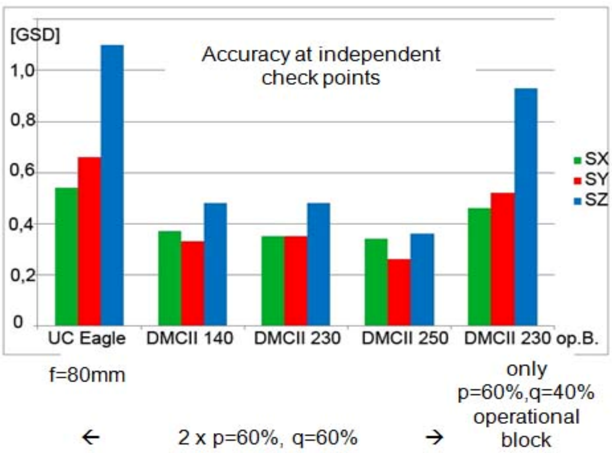


Figure 1: Accuracy at independent check points of block adjustments.

An accuracy analysis of images taken with the UC Eagle and the three DMC II-versions is shown in Figure 1. With the three test blocks taken with the DMC II-versions, having 60% end lap and 60% side lap together with crossing flight lines the accuracy at independent check points is below 0.5 GSD for all coordinate components. For the UC Eagle the root mean square differences are a little larger, which may be caused in X and Y also by the limited accuracy of the check points in the used test area. The accuracy of the operational block flown with the DMC II 230 with just 60% end lap and 40% side lap even under the non optimal conditions of an operational block is below 1.0 GSD for Z and below 0.5 GSD for X and Y. This confirms the good accuracy of the large format frame cameras.

Instead of digital frame cameras, also digital line scan cameras as the Leica ADS 80, the Jena-Optronik JAS 150s and the Wehrli 3-DAS-1 and 3DAS-2 can be used. Within the German camera test [2] these cameras were resulting in the same accuracy as the frame cameras, but operationally the line scan cameras are usually used only for the generation of ortho images and they are not really accepted for topographic mapping.

Several photogrammetric mid-format cameras are on the market. They are not system cameras as the large format cameras, they are just single lens cameras equipped with one CCD-array. All mid-format cameras are using similar or the same CCD-arrays. With the development of the CCD-arrays the pixel size has been reduced as shown also for the UltraCam in table 1 from 9µm over 7.2 and 6.0 to now to 5.2µm, corresponding to 26, 41, 60 respectively 80 megapixels. Most mid-format cameras are available with a sequence of focal lengths from wide angle up to small angle. The colour information is from a Bayer pattern, a regular filter matrix in front of the individual pixels. 50% of the pixels have a filter not eliminating the green band, 25% for the blue band and 25% for the red band. Based on the colour pattern, the grey values are interpolated for all three bands for all pixels. The Bayer pattern has the disadvantage that a forward motion compensation (FMC) is only possible with a mechanical movement of the CCD and not as for the system cameras with a transfer (or time) delay and integration (TDI), moving the charge in the CCD with the speed of the forward motion. On the internet, one mid format camera producer talks about a “FMC by BCM, Blur Control Management: a high shutter speed plus extended radiometric CCD range is operated to compensate motion blur” – this is just the information, that the camera has no FMC. The forward motion is not so much dependent upon the shutter speed as from the exposure time. An extended radiometric range is nonsense for a colour camera, where the three bands are limited by the physics and finally no FMC is possible by a short exposure time, only the influence of the forward motion can be limited. So BCM is misleading information. With reduced pixel size, the FMC became more important because smaller pixels cannot collect so much energy.

Also combinations of two, three, four and five mid-format cameras are available. These combinations are not on the same accuracy level as large format digital cameras – the cameras partially have some problems with systematic image errors and the cameras are not so rigid fixed together as in the case of the DMC and UC. Partially, no virtual images are generated from the combination of single images, so the user has to handle quite more images. An exception is the combination of five cameras which is in use, for example by Pictometry. In this case, a vertical and four oblique images are generated. In systems as from Pictometry such images are handled separately, but the object geometry has a limited accuracy.

Photogrammetric applications based on unmanned aerial vehicles (UAV), also named–systems (UAS), are booming caused by the reduced price of small UAVs. In several countries the total weight of UAVs is limited to 5kg and usually limited to a flying height of 300m above ground. The small size makes it sensitive to wind, so larger crab angles cannot be avoided, requiring a high overlap to cover the whole project area without gaps. Because of small size and weight partially mobile phone cameras are used with just 1.5µm pixel size. This is below the diaphragm limited resolution, so the factor for the effective resolution may be in the range of 2.3 corresponding to effective pixel size of 1.5µm * 2.3 = 3.4µm – even if the image may have a size of 10 megapixels this corresponds just to the information contents of 10 megapixels / 2.3^2 = 1.9 megapixels because of the limited image quality. If possible, cameras with larger pixels should be preferred.

2.2. Spaceborne imaging systems

For mapping applications, high and very high resolution optical satellite images are useful. As the rule of thumb for 0.1mm GSD in the map scale is required for topographic mapping corresponding to 1m GSD for 1:10000 or 0.5m GSD for 1:5000 map scales. At least 5m GSD is required to identify objects which have to be shown also in smaller map scale. Of course today topographic mapping is a data acquisition for a digital database and the map scale is the presentation scale. The real breakthrough for topographic mapping came with the 1m GSD of IKONOS. Now with the higher number of very high resolution optical satellite systems, with strongly improved imaging capacity (Table 2) and better slewing speed, the conditions for getting actual space images are quite better as before.

Table 2. Existing and **planned** very high resolution optical satellite sensors (≤ 1m GSD for pan).

Sensor	launch	Altitude [km]	GSD pan [m]	Swath in nadir view	Pan/ms channels	Imaging capacity [km²/day]
IKONOS 2	1999	681	0.82	11.3 km	Pan, 4ms	150 000
QuickBird	2001	450	0.61	16.5 km	Pan, 4ms	135 000
EROS B	2006	508	0.7	7 km	Pan	
KOMPSAT-2	2006	685	1.0	15 km	Pan, 4ms	
WorldView-1	2007	494	0.45	17.6 km	Pan	750 000
WorldView-2	2009	770	0.46	16.4 km	Pan, 8ms	975 000
GeoEye 1	2008	681	0.41	15.2 km	Pan, 4ms	700 000
Cartosat-2, 2A, 2B	2007-10	631	0.82	9.6 km	Pan	528 000
Pleiades 1	2011	694	0.50	20 km	Pan, 4ms	1000 000
Kompsat-3	***2012***	***670***	***0.70***	***16.8km***	***Pan, 4ms***	
Pleiades 2	***2012***	***694***	***0.50***	***20 km***	***Pan, 4ms***	***1000 000***
Cartosat-2C,2D	***2012***	***630***	***<1.0***	***10 km***	***Pan, 3ms***	
GeoEye-2	***2013***	***670***	***0.34***	***14.3 km***	***Pan, 4ms***	
WorldView-3	***2014***	***620***	***0.31***	***13.2 km***	***Pan, 8ms***	***676 000***
Cartosat-3A,3B	***2014***	***450***	***0.25***	***16 km***	***Pan, 4ms***	
DMC-3 (3 satellites)	***2014***	***630***	***1.0***	***22.6 km***	***Pan, 4ms***	***100 000***

11 very high resolution optical satellites, available for the commercial market, are currently active. In addition, there are several military satellites from which the images are restricted to military use. Up to 2014, eleven more systems are announced. GeoEye-2, WorldView-3 and Cartosat-3 at first have been specified with 0.25m GSD, but it seems that they will now fly on higher orbits, reducing the GSD to approximately 0.32m and extending the swath width. USA currently has a legal restriction for US companies to deliver just satellite images with 0.5m GSD; if this will not be changed, 0.25m GSD for GeoEye-2 and WorldView-3 would not have advantages for civilian applications against GeoEye-2 respectively WorldView-3.

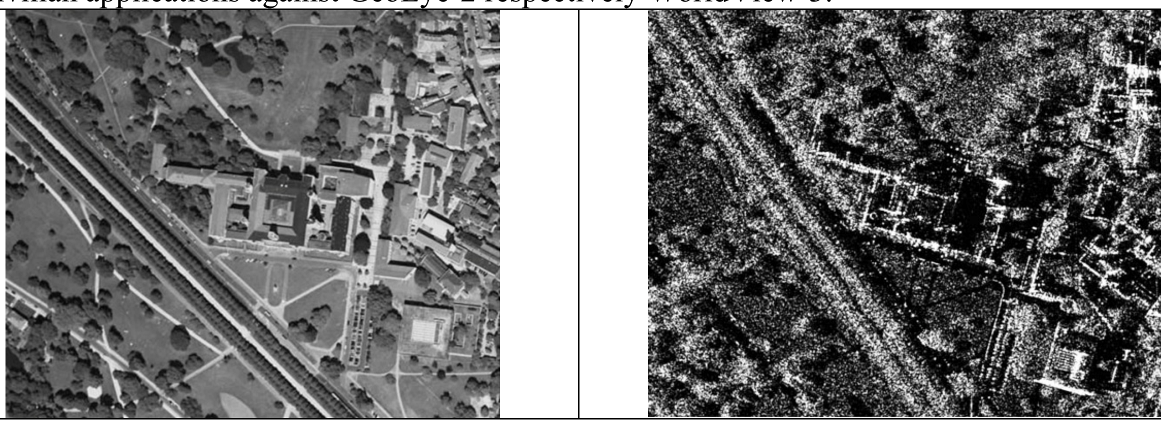


Figure 2: left: Optical image with 1m GSD, right: TerraSAR-X-image with 1m GSD (main building of Leibniz University Hannover).

In addition to optical satellites, there are also Synthetic Aperture Radar (SAR) satellites with up to 1m GSD available for civilian application as TerraSAR-X, TanDEM-X and CosmoSkymed. SAR is not restricted by cloud coverage, but the information content of SAR images is not the same as for optical images as obvious in Figure 2. Nevertheless, a trained operator is able to identify in SAR-images approximately 80% of the elements as in optical images with same GSD [3].

3. Comparison of airborne and spaceborne topographic mapping

Images taken by UAV –cameras cannot be compared with satellite images– caused by the limited range of civilian UAVs, they can be used apart from very small projects which cannot be compared with the size covered by a space image. In addition, the chosen GSD in most cases is quite smaller.

Mid-format cameras can be used for smaller projects. Very often, the camera geometry is not on a comparable level to large format aerial cameras. The generation of accurate height models with mid-format cameras cannot be recommended, so finally only digital large format aerial cameras can be compared with the use of space images for topographic mapping.

Table 3. GSD by large format aerial cameras from 10 000m flying height.

camera	DMC	DMCII 140	DMCII 230	DMCII 250	UC D	UC X	UC Xp	UC Eagle	UC Eagle
f [mm]	120	92	92	112	100	100	100	80	210
GSD	1.0m	0.78m	0.61m	0.50m	0.90m	0.72m	0.60m	0.65m	0.25m

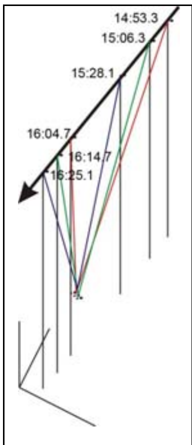
Only few civilian aircrafts can operate in a flying elevation of 10 000m – this is usually approximately the limit. The GSD of images taken from this height are shown in Table 3. The older digital aerial frame cameras are reaching up to 1.0m GSD – the same as IKONOS and KOMPSAT-2. The newer cameras are in the range of 0.50m up to 0.60m GSD as GeoEye-1, WorldView and Pleiades. The smaller GSD of the newer cameras is mainly caused by smaller pixels (Table 1), keeping the footprint from the same flying height constant.

The information content of optical airborne and spaceborne images is just depending upon the ground resolution. The rule of thumb of required 0.1mm GSD in the map scale has been confirmed for both image types [4]. The image quality of original digital aerial images is the same as for space images. Only analog aerial images are not as good [1]. So the determination of a 3D-building model was possible by semi global matching with IKONOS and GeoEye-1 images, but it failed with the limited quality of analog images scanned with 16µm pixel size, corresponding to 0.7m GSD [5], [6].

The orientation of optical satellite images can be done without any problem by bias corrected RPC-solution or geometric reconstruction with a standard deviation determined at independent check points of 1 GSD and better. The accuracy limit is dominated by the identification of the points in the images and not by the scene geometry. Of course the bundle block adjustment with aerial images even can reach 0.25 GSD in X and Y at independent check points [2] but only if they are targeted and available in several images. For single models, as for the space images and not targeted control and check points, the standard deviation is also in the range of 1.0 GSD. That means the orientation accuracy for aerial and space images are on a similar level.

For the standard deviation of the height component we have the relation: $SZ = h/_b * Spx$ (Formula 1) with h as flying height, b as base (distance of projection centers) and Spx as standard deviation of the x-parallax (image coordinates x" – x' in the base direction). The height to base ratio h/b for aerial images is determined by the field of view and the end lap. For the standard end lap of 60% it is as shown in Table 1. With the DMC II 230 and the UC Eagle it is 2.9, a value quite larger as the 1.6 dominantly used for satellite stereo pairs. That means the angle of convergence for space images is usually larger as for digital aerial large format images. Under the condition of the same standard deviation of the x-parallax, satellite images should have an advantage for point height determination, but for automatic image matching the situation is more complex – Spx itself depends upon the height to base ration. With a small angle of convergence, images for matching are more similar as for a large angle of convergence, leading to the fact, that the vertical accuracy of digital height models is not so much dependent upon the height to base ratio.

A configuration of three WorldView-2 stereo scenes taken from the same orbit (Figure 3) has been analysed for its potential of digital height model determination by automatic image matching. The 50cm GSD of WorldView-2 corresponds to small scale aerial images as well as the height to base ratio in the average of 1:1.6 to analog wide angle images. Wide angle digital images as DMCII 230 and UC Eagle have with 1:2.9 a smaller angle of convergence.



imaging configuration of the used WorldView-2 stereo models with minutes and seconds of first scene line take

Red = stereo scene 2
Green = stereo scene 4
Bue = stereo scene 3
b/h=1:1.26
b/h=1:1.73
b/h=1:1.80

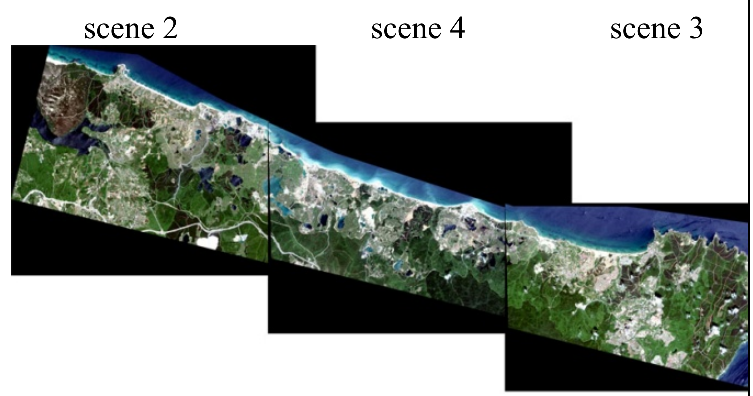


Figure 3: left: Imaging configuration of 3 WorldView-2 stereo scenes, right: Layover of the scenes.

By area based matching of the WV-2 stereo scenes with least squares, usual results have been reached. The matching failed in water bodies and some problems also exist in forest areas. The frequency distribution of the correlation coefficients (Figure 4) has a clear maximum at the highest correlation coefficients which are concentrated to the open areas (Figure 5 - red colour), but smaller values occur in forest areas.

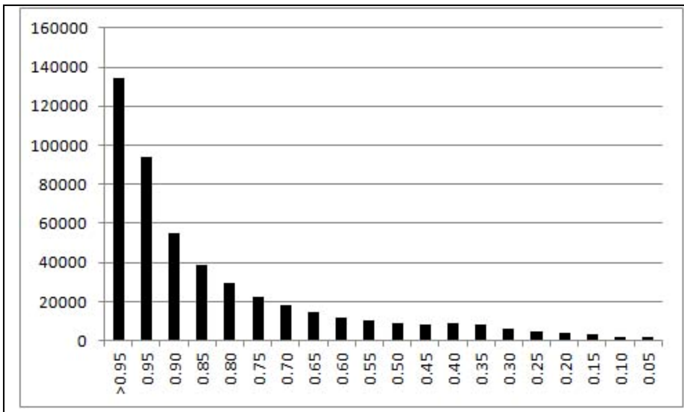


Figure 4: Frequency distribution of correlation coefficient.

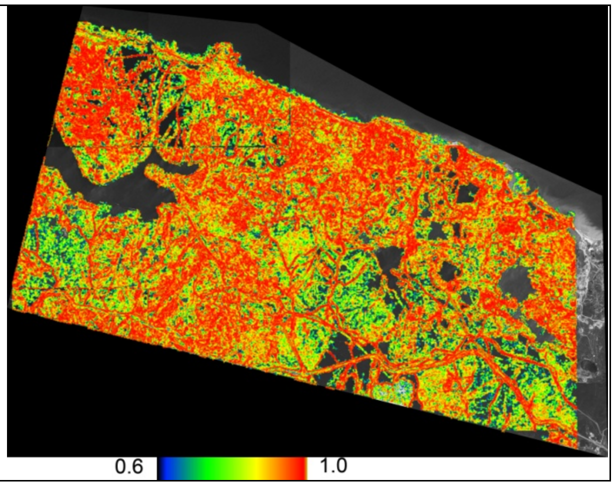


Figure 5: Colour coded correlation coefficient.

For the area of the stereo model scene 2, a reference height model exists determined by large scale aerial photogrammetry with a vertical accuracy between 10cm and 1.0m. The WorldView-2 height model has been compared with this one. The height model determined by area based image matching is a digital surface model (DSM) with the height of the visible vegetation and buildings. A comparison with a DEM including the height of the bare ground shows the influence of the vegetation and building height. A part of this can be removed by a filtering of elements not belonging to the bare ground. This is possible if some points of the bare ground are included, but it has some limitation in closed forest areas. In addition, not the same accuracy can be expected for all land cover types. A special problem in this area is caused by quarries and sandpits with large size because of the closely located city of Istanbul. Here the reference DEM does not include actual height data.

Table 4. Accuracy analysis of the WorldView-2 height model against reference DEM.

Original DSM							
	RMS	bias	SD	NMAD	F(slope) – no bias	relative	Positive part
Whole area	3.80	-3.23	3.08	1.86	2.85+0.26*tan(slope)	1.39	2.06
Open area	2.72	-1.81	2.03	1.70	1.72+0.93*tan(slope)	0.86	2.32
Forest	4.02	-2.82	2.86	2.17	2.37+1.31*tan(slope)	1.26	1.90
quarries	5.80	-2.13	5.39	2.56	4.30+1.70*tan(slope)	2.32	2.95
Filtered DEM							
Whole area	3.43	-1.88	2.87	1.64	2.28+1.48*tan(slope)	0.82	1.92
Open area	2.33	-1.58	1.72	1.60	1.44+0.85*tan(slope)	0.57	1.72
Forest	3.41	-2.14	2.66	1.70	2.12+1.54*tan(slope)	1.17	1.91
quarries	5.71	-2.28	5.28	2.23	3.80+3.00*tan(slope)	1.14	2.70

Table 4 includes the root mean square height differences (RMS), the systematic errors (bias), the standard deviation (SD) the normalized mean absolute deviation (NMAD) which should be close to SD. This is the case only if the height discrepancies are normal distributed, the accuracy as a function of the tangent of the terrain inclination, the relative SD in relation to the directly neighboured points and the standard deviation just computed by the positive part of the frequency distribution which should be independent upon the vegetation and buildings. After filtering the standard deviation of the flat part of the open area is 1.44m, corresponding to a standard deviation of the x-parallax of 1.1m for the base to height relation 1/1.26. Of course this is influenced by the accuracy of the reference DEM, so an additional analysis has been made with the overlapping area of the stereo models 3 and 4. The comparison of the independent determined DSM has the same influence by the land cover to both, so the difference of both DSM should result in the system accuracy.

The comparison of the overlapping height models is based on 411356 points. The root mean square height difference is 1.06m with the same probability for deviations from both DSMs, so for a single DEM the accuracy can be estimated with $\frac{1.06}{\sqrt{2}} = 0.75m$. Corresponding to the average height to base ratio of 1:1.5, a root mean square difference for the x-parallax of 0.5m or 1.0 pixel can be estimated. A small bias of 0.12m between both overlapping DSM has just 1cm influence to the root mean square Z-difference. The discrepancies are not normal distributed as it can be seen at the normalized medium absolute deviation (NMAD) of 0.83m, being clearly below the root mean square differences. The frequency distribution of the height differences is slightly wider as a normal distribution and includes also some larger height differences, influencing the root mean square more as the NMAD.

The standard deviation of 1.0 pixel for the x-parallax is also an operational accuracy for height models determined by digital aerial cameras [7]. Therefore, in general no difference in accuracy and the same information content is available with optical aerial as with space images having similar ground resolution. This means the decision of taking aerial or space images is based on other reasons.

In some countries the use of aerial images is restricted; in such a case, space images have to be used. Reverse Russia has with Resurs-DK1 also a very high resolution optical satellite which is not included in Table 2 because Russia does not like to sell space images with a higher ground resolution as 2m. If no restrictions for the use of aerial and space images exist, the selection is just based on economic conditions. If images from archives are available, it is just a financial question. In Germany, aerial images from archives of the survey administrations are quite less expensive as space images from archives, so in Germany optical space images are not used as standard for topographic mapping. If no aerial images exist or actual images have to be taken, a photo flight for smaller areas is more expensive compared to space images. In reverse, for very large areas the acquisition of optical stereo pairs from space may take more time as a photo flight and the space images may be more expensive. In some developing countries, no aircrafts with aerial cameras are available and the photo flights are slowed down by bureaucratic administrations, leading to the use of space images. The limits between economic use of aerial and space images are different from country to country, so only the general trend can be mentioned. In Europe, price reductions have been made for aerial photo flights over the last years, but with the improved imaging capacity of the satellites too, the conditions have been improved.

4. Conclusions

The conditions for aerial images have been improved by digital cameras and their extended capacity. With the increased number of very high resolution satellites, the improved imaging capacity and slewing speed, the conditions for getting actual stereo pairs are quite better as before. In general, the same accuracy and information content is available for aerial as well as for space images. It is just a question of the ground sampling distance and this overlaps between both. Finally, it is also a question of financial and organizational conditions if optical space or aerial images shall be used. The answer to this question depends upon the size and location of the project area and restrictions which still exist in some countries, even if there is no justification for this to exist anymore.

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