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Comparison of DEM generation by very high resolution optical satellites

G. Büyüksalih
Zonguldak Karelmas University

K. Jacobsen
University of Hannover, Germany

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ABSTRACT: The very high resolution optical satellites IKONOS, QuickBird and OrbView-3 do have a high potential for generating detailed digital surface models (DSMs). DSMs can be filtered to digital elevation models (DEMs), containing only points on the bare ground. By simple theory the accuracy of the determined point heights is linear depending upon the height-to-base relation, but in reality the dependency is not so strongly caused by better matching results for a small convergence angle.

With spacing the ground sampling distance (GSD) 3 times, the results of matching neighboured points is sufficiently independent, so a grid spacing of 2 m is possible for QuickBird and 3 m for IKONOS and OrbView. DEMs with such details are only available for very limited areas of the world. It opens the possibility for 3D-city models.

The two corresponding images, required for the DEM generation, should be taken under similar conditions. The generation of images from the same orbit is optimal, but this has the disadvantage of larger rotation of the satellite, leading to a loss of imaging capacity. This is also depending upon the agility of the satellite, different for the three mentioned systems. By this reason not all used image combinations have been taken from the same orbit. If the imaging conditions have not been changed too much, the automatic matching is more or less not influenced, but for larger difference in time, problems are caused.

With 0.62 m, QuickBird has the smallest GSD. IKONOS and OrbView-3 are available with 1 m GSD, but OrbView-3 is working with staggered pixels having a projected pixel size on the ground of 2 m causing a low pass effect.

The generation of height models based on the three very high resolution satellites has been analysed.

1 INTRODUCTION

DEMs are a basic component of a Geo Information System (GIS); they are required for the geo-reference of single images like for the generation of orthoimages. DEMs based on aerial images are not available in all parts of the world and sometimes they are classified. For several applications SRTM height models do lead to satisfying results, but with just 3 arcsec point spacing their resolution is far away from the details which can be reached with very high resolution space image pairs.

Automatic image matching with very high resolution space images is more difficult than with images having a larger ground sampling distance (GSD). A larger GSD corresponds to a low pass filter, eliminating the local differences caused by vertical elements, which are represented differently in both images of a stereo combination. These vertical elements and the shadows shown differently depending upon the view direction are causing problems especially for a large convergence angles between both view directions or a low height to base relation. In aerial applications, in city areas usually normal angle cameras are used having a height to base relation of 3.2 because automatic image matching of wide angle images with a height to base relation of 1.6 or even manual measurements are difficult in city areas.

2 USED IMAGES

IKONOS launched in 1999 provides images with 0.82 m GSD for nadir views. Usually images down-sampled to 1 m GSD are distributed. QuickBird followed in 2002 with improved resolution of 0.62 m GSD for nadir view. OrbView-3 was launched in 2003 and provides 1 m GSD. There are more differences between the sensors than just the GSD – IKONOS and QuickBird are equipped with transfer delay and integration (TDI) sensors, accumulating the energy like an electronic forward motion compensation over several pixels. OrbView-3 is using instead of this staggered CCD-lines – 2 CCD-lines are used with elements shifted by half a pixel. So the projected pixel size on the ground is 2 m × 2 m with 50% over-sampling leading to 1 m GSD (Figure 2). Of course the image quality is not the same as with 1 m projected pixel size on the ground, but for automatic image matching the low pass effect may have also an advantage. The sampling rate of OrbView-3 is limited to 2500 lines/sec corresponding to 5km/sec, but the footprint speed is 7.1km/sec. This has to be compensated by a permanent rotation of the view direction, the so called slow down mode (Figure 1) with a factor of at least 7.1/5 = 1.42. Also QuickBird has to use the slow down mode because the sampling rate of 6900 lines/sec together with the GSD of 0.62 m requires a slow down factor of 1.66. The slow down mode has no negative influence to the image quality and geometry. IKONOS even can scan against the moving direction not causing a loss in geometric and radiometric quality. The slow down mode is only reducing the imaging capacity of the sensors.

The images of a stereo combination should be taken under similar conditions. A larger difference in the imaging time may cause changes in the object space like different colour or harvest situations of vegetation and shadow length or the change of located cars in parking places and leads to problems of automatic image matching or even in extreme case to a loss of stereo impression by human operators. Stereo pairs from the same orbit are optimal; they can be taken by the agile very high resolution satellites like shown in Figure 3. But stereo imaging is reducing the imaging capacity. For example for QuickBird the price for a stereo scene is 2.3 times the price for a single scene, but the imaging takes approximately 9 times the capacity in relation to a single image because no other images can be taken during turning around to the other view direction. This fact is depending upon the agility of the satellites.

As shown in Table 1 (McGill 2005), the agility of the satellites is quite different. Of course the time for slewing over a distance of 300 km is not the same as the change of

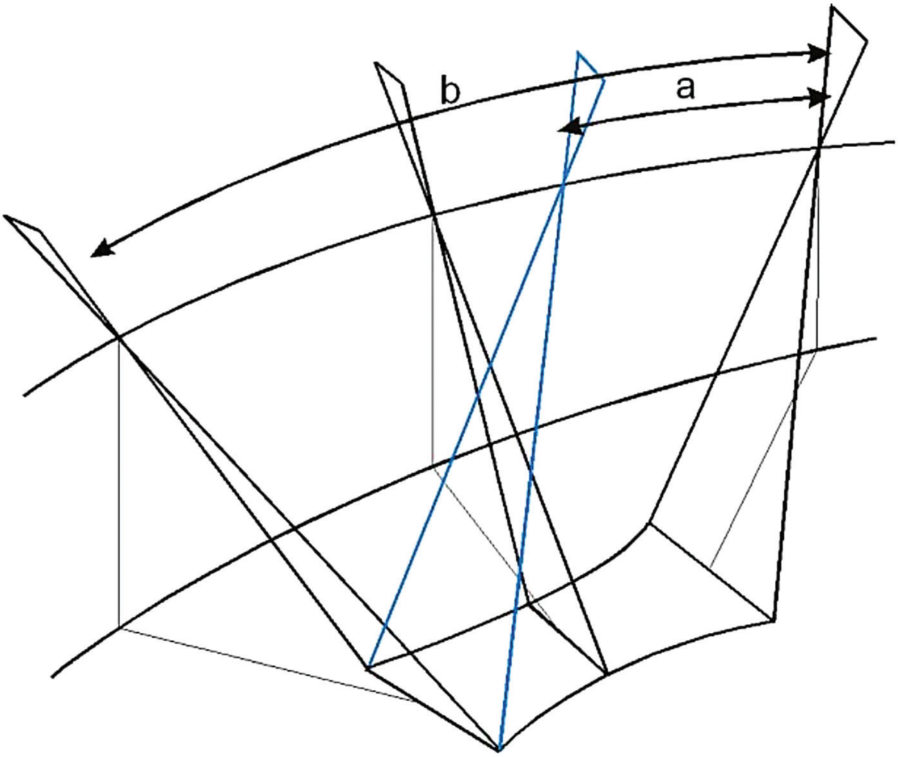


Figure 1. Slow down of imaging by permanent rotation of view direction slow down factor = b/a.

the view direction which is independent upon the flying height. So for getting the same angle of convergence between IKONOS and QuickBird there is only the relation of 1.6 while for the slewing there is the relation of 2.5. The coming WorldView satellites will have a quite higher agility by using control moment gyros instead of reaction wheels for

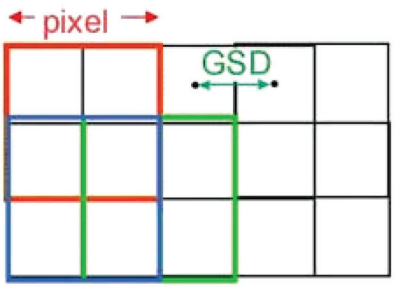


Figure 2. Over-sampling – projected pixel size = 2 m, GSD = 1 m for OrbView-3.

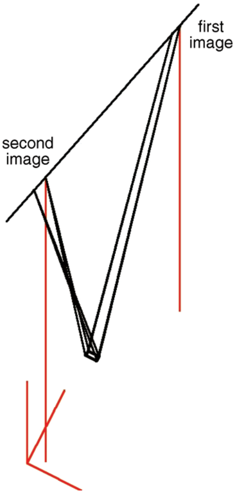


Figure 3. Imaging configuration of Orbview-3 Zonguldak.

a faster rotation. So in the near future the conditions for taking stereo scenes will be improved.

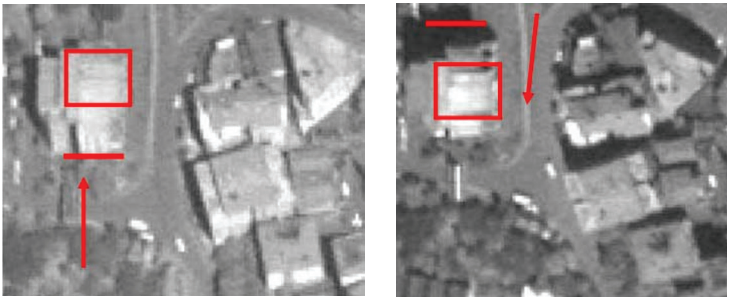
3 EXPERIENCES IN GENERATION HEIGHT MODELS

The height accuracy is linear depending upon the accuracy of the x-parallax and the height to base relation. For digital images and especially for images with unpublished inner orientation geometry the accuracy of the x-parallax should be expressed in units of GSD (Formula 1). In this publication in general the standard deviation is used and not the LE90 or LE95. The standard deviation is based on 68% probability level – that means in the case of normal distributed discrepancies, 68% of the discrepancies are smaller than the standard deviation and 32% are larger. LE90 corresponds to 90% probability level and LE95 to 95%. The relation between LE90 and the standard deviation is 1.65 and for LE95 it is 1.96. LE90 and LE95 are calculated as standard deviations and are multiplied with these values.

$SZ = h/b * Spx$ formula 1: standard deviation of height (SZ)
h = flying height above ground
b = base (distance of projection centres)
Spx = standard deviation of x-parallax [GSD]

Table 1. Required time for slewing 300 km.

satellite	IKONOS	QuickBird	OrbView-3	WorldView-1	OrbView-5	WorldView-2
time	25 sec	62 sec	31 sec	10 sec	42 sec	9 sec



25m high building in OrbView-3 stereo model with height to base relation of 1.4, roof and ground marked

49 m high building in IKONOS stereo model with height to base relation of 7.5

Figure 4. Different presentation of high buildings in stereo models.

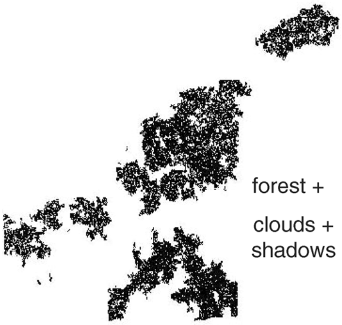
Corresponding to Formula 1 the best vertical accuracy can be reached for a low height to base relation – that means a large base while the flying height is fixed for satellites. A small height to base relation or large convergence angle indeed leads to better height values of well defined points, but it is causing larger Spx-values by automatic image matching because in very high resolution images a three-dimensional (3D) object is presented quite different in the left and the right scene (Figure 4).

The dependency of x-parallax standard deviation from the convergence angle is not the same for different areas. For well defined points used as control points, Spx is in the range of a GSD for IKONOS and QuickBird and 1.6 GSD for OrbView-3 (Jacobsen 2006), so for such points the accuracy is linear dependent upon the height to base relation. Especially for areas with inclined up to vertical elements like especially city areas the optimal height to base relation may be quite different as for flat parts.

The influence of the imaging conditions to the scenes can be seen in Figure 5. In city and forest areas the change of the sun elevation makes the automatic image matching of such an image combination hopeless as it can be seen also at the distribution of the matched points in the IKONOS image combination taken in July and October. Just 33% of the possible points have been matched with a correlation coefficient above the

IKONOS sun elevation 41.5°

IKONOS sun elevation 67.2°



distribution of matched points

Figure 5. Influence of sun elevation to images and image matching.

tolerance limit. On the other hand a matching of QuickBird images with 10 days difference in imaging has not caused any problems. Only in the large including parking lots the matching failed caused by moved cars.

With images taken from the same orbit and a limited convergence angle of the view directions, the matching results of the very high resolution space images can be excellent as visible in Figure 6. The large buildings in the image left hand side easily can be identified in the shaded 3D-view of the generated height model. In this model a vertical accuracy of 1.7 m has been reached for areas with good contrast, this corresponds to a standard deviation $Spx = 0.22$ GSD. It was confirmed by the root mean square y-parallax of the intersections of 0.25 GSD. Not the whole area shows good contrast, so this very good result is not representative for the whole height model. As rule of thumb the general accuracy of a DEM checked with a reference DEM has approximately the double standard deviation as identified at check points.

From the area of Phoenix, Arizona some QuickBird images have been used for the analysis of automatic matching in the city area. The combination of the used images has been taken with 10 days difference in time causing no problems with changed shadows. The build up area was matched successfully (Figure 7). The height determination in

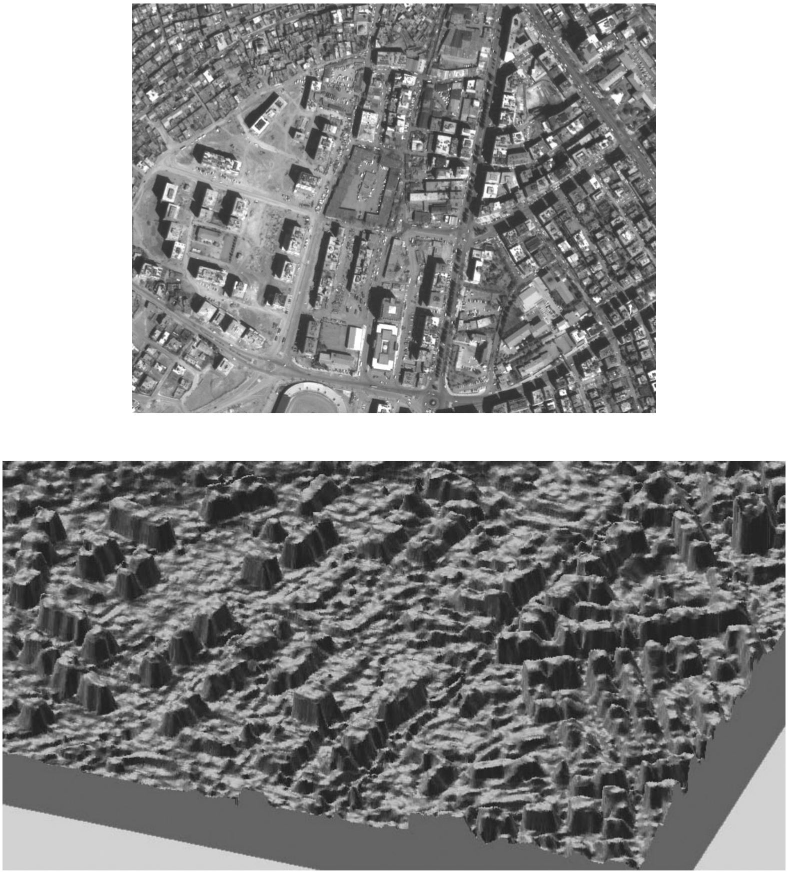


Figure 6. Sub-area of IKONOS scene Maras and generated elevation model – height to base relation = 7.5.

large parking places at shopping centres was difficult – the cars have moved and so the matching failed (Figure 8).

Dark image parts, moved cars and repeated elements, especially on roof tops, caused errors in matching in some areas (peaks in Figure 8). The caused height errors have been eliminated automatically with the Hannover filter program RASCOR (Passini et al 2002). After this, the result was satisfying. The dominating small individual houses with trees and bushes did not lead to clear shapes of buildings. A comparison with a reference DEM was difficult – by filtering not the whole influence of the buildings and the vegetation could be removed. The reached mean square difference of 4 m corresponds with the height to base relation of 11.6 to Spx = 0.6 GSD; under the difficult conditions of the comparison this is a satisfying result. The y-parallax of the intersection was in the same range, confirming this result.

The area of Zonguldak has been imaged by OrbView-3 in the configuration shown in Figure 3 with a height to base relation of 1.4 corresponding to a convergence angle

Figure 7. Overlay of matched points to QuickBird image matched points = whitedark parts = matching failed.

between both view directions of 39°. The city area of Zonguldak is built up densely with high buildings. Also with wide angle aerial images having a standard height to base relation of 1.6, automatic image matching and also manual measurements would be difficult, so problems in the city area have been expected from the beginning.

The frequency distribution of the least squares matching correlation coefficients for 3 of the mentioned areas is shown in Figure 9. The IKONOS images of Maras are from the same orbit having a height to base relation of 7.5. Under the conditions of the small convergence angle of just 7.6° the matching was optimal with very high correlation

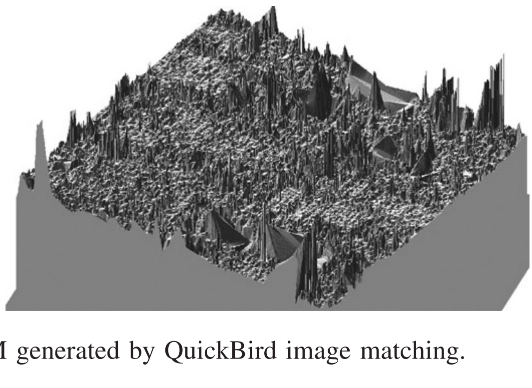
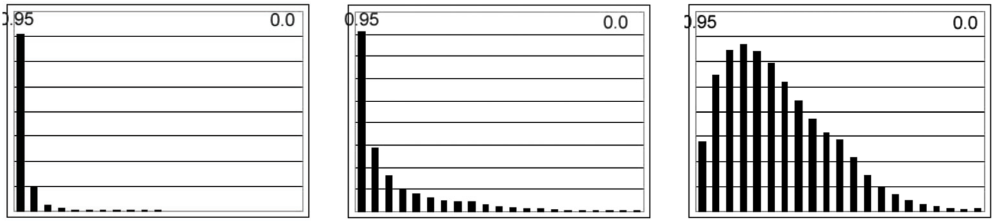


Figure 8. Shaded DSM generated by QuickBird image matching.



IKONOS, Maras QuickBird, Phoenix OrbView-3, Zonguldak

Figure 9. Frequency distribution of correlation coefficients.

coefficients. The used QuickBird stereo model has 10 days difference in time and also a small convergence angle with 5°. The slightly lower result can be explained by the difference in time of imaging – the matching failed over the parking lots with moved cars and also partially in wide roads having no contrast and moving cars. Under such conditions the matching results are better than expected. Quite different results have been achieved with the OrbView-3 stereo model caused by the large convergence angle. Even with the reduced acceptance level 0.5 for the correlation coefficients, just 53% of the possible points have been matched successfully.

The quality image of matching the city area (Figure 10) shows the problems, the brighter parts – that means higher correlation values – are in the open areas while the matching in the densely built up areas was poor or even failed.

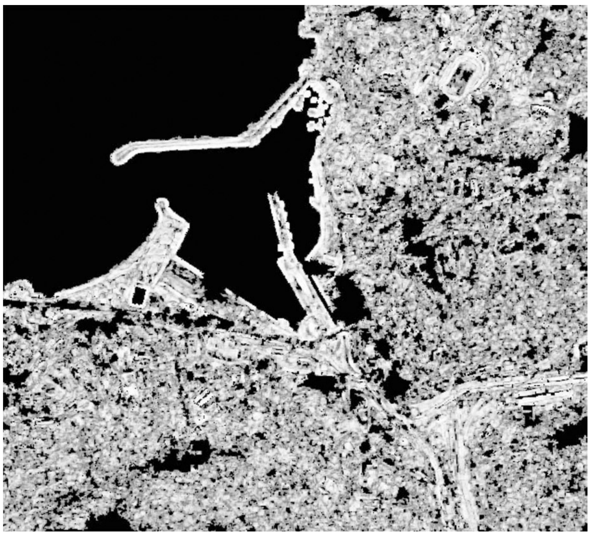


Figure 10. Quality image of OrbView-3 matching grey value 255 = correlation coefficient = 1.0 grey value 127 = correlation coefficient = 0.5 grey value 0 = correlation coefficient =< 0.5.

Figure 11. corresponding sub-area of OrbView-3 scene.

4 CONCLUSION

Automatic image matching with very high resolution space images is more difficult than with lower resolution. Similar problems as with aerial images have been achieved in city areas. It is optimal to use stereo pairs taken from the same orbit just with a limited number of seconds time difference, but it is not a problem to combine images taken with 10 days difference in time. By simple theory the height accuracy is linear depending upon the height to base relation, but vertical elements viewed from different directions are presented quite different causing problems of matching and leading to larger standard deviations of the x-parallax. So the optimal height to base relation for built up and also mountainous areas is more in the range of 3.0. Very good results have been reached also for very mall convergence angles. The standard deviation of the x-parallax is in the range of up to 0.22 GSD for small convergence angles; in any case it was below 1 GSD.

The variation of the reported results are not dependent upon the type of the used image, it is dependent upon the imaging conditions and geometry. Of course the ground sample distance has a linear influence to the reached quality, but no other sensor related influence significantly could be found.

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