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# 3D remote sensing. Status report

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ABSTRACT: With the fast development and growing number of high resolution satellite sensors and raising application of digital airborne cameras, the field of 3D remote sensing has new challenges and opportunities. The number of optical space sensors even will grow in near future, improving also the ground resolution up to 41cm. With the stereo sensors Cartosat-1 and ALOS/PRISM high quality DEMs can be generated, allowing an improvement of the nearly worldwide available SRTM height model. The very high resolution optical space sensors enable topographic mapping in the scale up to 1: 5000. The limitation of the map scale is not caused by the accuracy, it is caused by the semantic information – what details can be identified.

Large format digital airborne cameras have a quite better colour representation, allowing now also object classification based on the spectral information - this was not possible with analogue photos. The information content of the digital cameras is better than standard analogue photos scanned with 20 µm pixel size.

For the generation of digital elevation models (DEM), the images of the stereo models should be taken with a short time interval. From very high resolution space sensors only a limited number of stereo models taken from the same orbit are available. With unchanged atmospheric conditions images with 10 days difference in imaging usually can be used as a stereo model for DEM generation. For larger difference in time changed shadows and vegetation are causing problems. By this reason the stereo sensors ASTER, SPOT-HRS, Cartosat-1 and ALOS/PRISM have improved the situation of 3D mapping. Cartosat-1 and ALOS/PRISM show promising results of detailed DEMs.

Precise height information can be generated by laser scanning (LIDAR). With medium accuracy, covering large errors interferometric synthetic aperture radar (InSAR) can be used from air and space.

## 1 INTRODUCTION

Geometric correct mapping requires stereo combination of images, a pair of synthetic aperture radar (SAR) images or distance and attitude determination together like in the case of laser scanning. If only one image is available, height information is required for the correct geo-reference like in the case of orthoimages. The accuracy and resolution of the product as well as the imaging conditions and roughness of the area determines the necessary spacing of the used digital elevation model (DEM) as well as the required point accuracy. In general mathematical strict solutions should be preferred for the orientation;

approximations of image orientation and geo-reference like rubber sheeting should be avoided because of not controllable results.

## 2 SENSORS

The dominating changes of three dimensional remote sensing are based on the sensor development. In all fields we can see strong changes, partially leading to new applications of the used technology and products. The aerial imaging is changing from analogue photos to direct digital images with the possibility of close to online results. With the combination of inclined and vertical photos total new applications came. The use of laser scanning, named also LIDAR, is growing, supported by the improved sensor technology. The number and specification of optical satellites is improving permanently. With the coming very high resolution SAR-sensors in space, weather and day time independent mapping will be possible. The combination to interferometric SAR (InSAR) offers new possibilities for more precise and detailed DEM generation. In the field of aerial InSAR whole countries are covered by high resolution DEMs with accuracy in the range of 0.5 m up to 1m and more will be covered in the near future, causing economic competition to traditional methods.

### 2.1 *Optical imaging sensors*

#### 2.1.1 *Aerial cameras*

Aerial film cameras are well established since long time. The handling of the generated photos has changed from analogue photogrammetric devices over analytical plotters to digital photogrammetric workstations; that means the analogue photos have to be scanned to get digital images. The film development and the quality reducing scanning process are not required, if digital images can be taken directly. In addition the expensive film must not be bought, so extended end laps are used, supporting the image block stability. The large frame digital cameras Z/I-Imaging DMC and Vexcel Ultra-Cam as well as the line sensors Leica ADS40 and Jenoptik JAS150 offer the possibility of true colour and false colour infrared band combination without additional cost. It is estimated that world wide approximately 2000 analogue aerial cameras are usable, but only approximately 500 are in use. In spring 2007 approximately 170 large frame digital cameras and 3-line scanners are in operation with rapid growing number. The first countries are not accepting anymore analogue aerial cameras for national mapping projects. In the frame of the National Agriculture Imagery Program of the USA, covering annually the largest part of the USA with 1m or 2m ground sampling distance (GSD), in 2006 54% of the images have been taken by digital systems and it is expected, that in 3 years it will switch totally to digital cameras.

Digital aerial cameras are subdivided into 2 classes – the digital frame and the 3-line or even multiple line sensors. The size of CCD-arrays usable for aerial application is not sufficient for having the same information contents like analogue aerial photos. The required image quality and fast read out time limits the array size. So the Z/I-Imaging

DMC is combining 4, the Vexcel UltraCam 9 and the DIMAC 2 CCD-arrays to one virtual perspective image (Jacobsen 2007b). The information contents, that means the details which can be extracted from the images, of digital images can be compared to analogue photos scanned with 20 μm pixel size and having by the factor 1.5 smaller GSD e.g. 10cm GSD from analogue photo corresponds to 15cm digital image. Several different single frame cameras are in use. Their limited size is complicating the sensor orientation, so for larger projects in an economic manner they have to be combined with direct sensor orientation. The direct sensor orientation is based on relative kinematic GPS-positioning together with an inertial measurement unit (IMU), a combination of gyros and accelerometer, in an incorrect manner also named INS. By the direct sensor orientation the imaging position and the attitudes can be determined. Applanix is using such a combination for the DSS and IGI for the DIGICAM, but also several user made combinations between smaller digital cameras and direct sensor orientation exist. Three or multiple CCD-line sensors require the direct sensor orientation because the orientation is changing from line to line. The correct geometric use of CCD-line sensor images requires special software, but this is available from the mayor photogrammetric software companies. In principle the 3 or multiple CCD-line sensor images can be used like the digital frame images, but the CCD-line sensors are mainly used for the generation of orthoimages covering large areas, while the frame cameras are dominating the mapping application.

Oblique images are getting more popular supported by systems from Pictometry and Multivision, using a combination of a vertical and 4 oblique medium size images to all sides for the generation of overview. For not trained persons oblique images are simpler to be interpreted. Also Microsoft Virtual Earth includes oblique views.

### 2.1.2 *Optical satellites*

A break through in mapping from space came with the very high resolution satellites, especially with IKONOS. The very high resolution satellites are now a direct competition to aerial cameras, the economic conditions and in some projects just the availability are determining the use. In several countries we still have restrictions for the use of aerial images even if their GSD is not better than the resolution of space images, while the space images usually are not restricted. As a rule of thumb for mapping 0.1 mm GSD in the map scale is required. So with 1 m GSD mapping in 1:10 000 is possible, QuickBird images even can be used for mapping in 1:5000.

In Figure 1 the growing number and timely more dense launches of high resolution optical space images can be seen. It will continue with similar frequency–only the most important proposed launches are shown and with RapidEye a system of 5 satellites will be launched at the same time. With 6.5 m GSD and 80km swath width RapidEye is planned for precision farming, but it can be used also for mapping application.

The optical satellites show a clear tendency to higher resolution; this will be continued with WorldView, the successor of QuickBird from Digital Globe and GeoEye. Both systems will be available with 50cm ground resolution of the panchromatic band. World View-1, scheduled for 2007 will have only a panchromatic camera while WorldView-2,

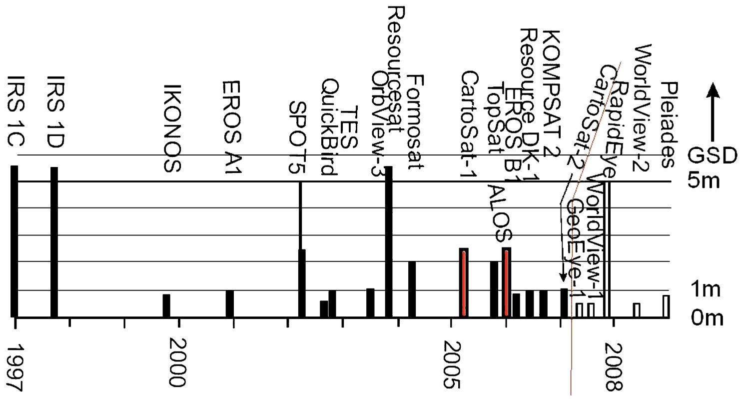


Figure 1. High and very high resolution optical satellites in sequence of launch with their highest GSD. Cartosat-1 and ALOS/PRISM are stereo systems with 2 and 3 cameras. SPOT-5 includes with HRS in addition to the main sensor also a stereo system with 2 cameras.

scheduled for 2008, will have 8 spectral bands – in addition to the usual red, green, blue and near infrared also a coastal channel for better water penetration, yellow, red edge and a second near infrared channel. Pleiades, the successor of SPOT, will follow in 2009 with 70cm GSD.

All newer sensors are equipped with reaction wheels or control moment gyros, enabling a fast and precise change of the view direction also during imaging. So these sensors can generate stereo combinations from one orbit, avoiding the negative influence of the changes in the object space caused by a time delay. The agility of the sensors is setting some limitations for stereo combinations from the same orbit. So for QuickBird the stereo imaging takes 9 times the imaging capacity like a single image, but the price for a stereo combination is only 2.3 times the price of a single scene, so it is not economic for the satellite image vendors. Corresponding to this, the order conditions for stereo combinations are difficult. This will change with the very agile WorldView.

With SPOT-5 HRS a stereo sensor is available since 2002 beside the lower resolution ASTER, but the SPOT-5 HRS images are not distributed, only the generated height models. This is different for the stereo sensors Cartosat-1 and ALOS / PRISM from which images can be ordered.

## 2.2 *Laser scanning*

Airborne laser scanner, named also LIDAR, determine the three-dimensional structure of the visible surface by laser distance measurement from aircraft. The orientation of the laser scanner is determined by direct sensor orientation; together with the beam direction in the scanner, the direction of the individual beam is known. The laser beam has a small divergence angle causing a sufficient spot on the ground. In vegetation areas parts of the laser beam are reflected at the upper vegetation level, parts somewhere within the vegetation and parts may reach the ground. The today sensors can register not only the first pulse, which may come from the upper part of the vegetation, and the last pulse, which may come from the ground, they can register also additional pulses. The Optech ALTM Gemini and the Leica ALS50 (Figure 2) can register 4 returns of a beam.

The swath width of laser scanners is limited by the object. In build up areas larger nadir angles are causing occlusions, but also in a forest the probability that the last pulse is presenting the bare ground is depending upon the nadir angle. So in most applications the nadir angle is limited to 10° in maximum, reducing the swath width. The swath width can be enlarged only with a higher flying altitude, by this reason the new Leica ALS50-II can be used up to 6000 m and the Optech Gemini up to 4000 m height above ground. The laser repetition rate is depending upon the slant range, which for 10° nadir angle is in maximum just 1.5% larger than the height above ground. The repetition rate is determining the point spacing on ground that means the details in the generated height model.

Under operational conditions the height determined by laser scanner has a standard deviation of not better than 15 cm. Only with control areas this may be improved to 10cm. The accuracy also depends upon the flying height above ground; especially the horizontal accuracy is nearly a linear function of this.

Also the last pulse not in any case presents the bare ground, requiring a filtering of the height models if DEMs are required. In build up areas buildings are shown, enabling also a generation of 3D-city models. But even in build up areas the points not located on the ground can be eliminated. In most cases this will be done by a combination of automatic filtering and manual improvement. If artificial objects like dams shall not be excluded, break lines are required for the support of the filtering. In some countries, like for example Germany, the precise height determination switched from photogrammetric survey totally to laser scanning.

## 2.3 *Synthetic Aperture Radar*

Synthetic Apertur Radar (SAR) is imaging the earth independent upon the weather conditions. SAR can be used from aircraft, but also from space. Radarsat-1, ERS-1, ERS-2


Optech ALTM Gemini laser principle

Leica ALS50

possible pulse rate of Lei ALS50

Figure 2. Airborne laser scanner (LIDAR).

and Envisat are active since longer time, but their ground resolution is not sufficient for mapping purposes. 8m GSD, like possible with Radarsat-1, cannot be compared with the information contents of optical images having the same ground resolution. Especially in build up areas SAR-images have some problems caused by double bounds, sending a too strong signal back to the radar antenna and by layover – the top of a building usually is mapped in front of the basement. In addition for a correct georeferencing more precise height information is required for SAR-images like for optical images. Nevertheless in areas with permanent cloud coverage like the Amazon region, southern part of Venezuela and Borneo, a mapping based on SAR-images has been made.

More important for 3D-application than the SAR images is the interferometric SAR (InSAR) generating height models. The most important recent project was the Shuttle Radar Topography Mission (SRTM), generating a nearly worldwide height model from 56° southern up to 61.25° northern latitude. This height model with a spacing of 3" (92 m at the equator) is available free of charge in the internet (Seferkik, Jacobsen 2007). The X-band and the C-band used by SRTM cannot penetrate the vegetation; they are showing the top of the vegetation. Such a digital surface model (DSM) has to be filtered to a DEM. The SRTM height models usually are effected by systematic errors (bias) caused by the sensor orientation and elements on top of the bare soil. In addition the accuracy is depending upon the terrain inclination (Table 2).

InSAR can be used from space and from air. Most often the short wavelength X-band (2.4 cm–3.75 cm wavelength) or C-band (3.75 cm–7.5 cm) and not so often the longer L-band (15 cm–30 cm) or P-band (77 cm–136 cm wavelength) are used. Opposite to X-band and C-band, the longer P-band and L-band can penetrate the vegetation, so InSAR based on P- or L-band are more close to the bare ground. In the case of dense conifers

Table 1. High resolution optical satellites available for civilian use.

| Sensor | Pixel size (nadir) [m] | Swath [km] | Pointing in-track | Pointing across |
|---|---|---|---|---|
| SPOT 1–4 | 10/20 | 60 | – | ±27° |
| SPOT 5 | 5 (2.5)/10 | 60 | – | ±27° |
| SPOT 5 HRS | 5 × 10 | 120 | +20°, −20° | – |
| MOMS-02 / −P | 5.8/16.5 | 37/78 | −27°,0°,27° | |
| IRS-1C/1D, Resourcesat | 5.8/(23.5) | 70/(142) | – | ±26° |
| KOMPSAT | 6.6 | 17 | – | ±45° |
| Terra ASTER | 15/(30, 90) | 60 | 0°, 27.2° | |
| IKONOS | 0.82/3.2 | 11.3 | free view dir. | |
| EROS A | 1.8 | 12.6 | free view dir. | |
| QuickBird | 0.61/2.44 | 16.4 | free view dir. | |
| OrbView 3 | 1/4 | 8 | free view dir. | |
| EROS B | 0.7 | 14 | free view dir. | |
| FORMOSAT 2 | 2/8 | 24 | free view dir. | |
| IRS-P5 Cartosat-1 | 2.5 | 30 | 26° fore, 5° after | free view to side |
| ALOS | 2.5 | 35 (70) | −24°, 0°, +24° | free view to side |
| KOMPSAT-2 | 1/4 | 15 | free view dir. | |
| Resource DK1 | 1/3 | 28 | free view dir. | |
| IRS Cartosat-2 | 1 | 10 | free view dir. | |

some test showed height values up to 5 m above ground, but in other forest areas the ground has been reached. In the frame of the NextMap project Intermap has completed a DSM over Britain with a standard deviation of 0.5 m up to 1.0 m for the height and will finish 2007 Western Europe and 2008 the USA with 5 m spacing.

With the announced TerraSAR-X, which shall be completed in 2009 with a second system to the TanDEM-X configuration, up to 2012 a world wide DSM shall be generated with 10m spacing and 1 – 2 m vertical accuracy.

## 3 GENERATION OF HEIGHT MODELS BY IMAGE MATCHING

The available SRTM height model is not detailed enough for several applications. So the generation of height models with space images by automatic image matching is often a requirement. The vertical accuracy is depending upon the GSD and the height to base relation (formula 1).

$$SZ = \frac{h}{b} * Spx \tag{1}$$

SZ = standard deviation of height
h = flying height
b = base
Spx = standard deviation of x-parallax [GSD]

The accuracy of the automatic image matching (Spx) is influenced by the imaging conditions. There should be only a short time between both instants of imaging to avoid negative influences by change of the object and the illumination. With optimal configuration this should be made from the same orbit, but only the new flexible sensors and the stereo sensors like ASTER, SPOT-5 HRS, Cartosat-1 and ALOS PRISM are able

Table 2. Root mean square Z-discrepancies of SRTM C-band height models [m].

| | RMSZ | Bias | RMSZ F (terrain inclination) |
|---|---|---|---|
| Arizona, open area (flat up to smooth mountain) | 3.9 | 1.3 | $2.9 + 22.5 * \tan \alpha$ |
| Williamsburg NJ, open area (flat) | 4.7 | −3.2 | $4.7 + 2.4 * \tan \alpha$ |
| Atlantic City NJ, open area (flat) | 4.7 | −3.6 | $4.9 + 7.6 * \tan \alpha$ |
| Bavaria, open area (rolling) | 4.6 | −1.1 | $2.7 + 8.8 * \tan \alpha$ |
| Bavaria, open area (steep mountain) | 8.0 | −2.4 | $4.4 + 33.4 * \tan \alpha$ |
| Zonguldak, open area (rough mountain) | 7.0 | −4.4 | $5.9 + 5.6 * \tan \alpha$ |
| West-Virginia, forest (mountainous) | 11.6 | −7.7 | $7.3 + 7.2 * \tan \alpha$ |
| Atlantic County, open area (flat) | 4.4 | −3.4 | 4.4 |
| Pennsylvania, open area (flat – rolling) | 5.4 | −0.2 | $5.3 + 9.4 * \tan \alpha$ |
| Pennsylvania, forest (mountainous) | 7.9 | −4.3 | $7.0 + 6.4 * \tan \alpha$ |
| Philadelphia, city area, filtered (flat) | 3.2 | −1.3 | 3.2 |
| $\alpha$ = terrain inclination (Passini & Jacobsen 2007) | | | |

Table 3. Accuracy of height models generated by automatic image matching.

| Sensor | Area | SZ [m] | SZ F(inclination) [m] | Spx flat terrain [GSD] |
|---|---|---|---|---|
| ASTER Zonguldak, mountainous | open areas | 25.0 | 21.7 + 14.5∗tan α | 0.7 |
| | forest | 31.2 | 27.9 + 18.5∗tan α | 0.9 |
| | check points | 12.7 | | 0.4 |
| KOMPSAT-1 Zonguldak, mountainous | open areas | 13.6 | 11.3 + 11.5∗tan α | 0.8 |
| | forest | 14.7 | 14.1 + 12.1∗tan α | 1.0 |
| SPOT 5 Zonguldak, mountainous | open areas | 11.9 | 5.3 + 5.9∗tan α | 0.6 |
| | forest | 15.0 | 6.6 + 6.3∗tan α | 0.7 |
| | check points | 3.8 | 3.5 + 0.9∗tan α | 0.4 |
| SPOT 5 HRS, Bavaria, rolling | open areas | 4.7 | 4.3 + 1.0∗tan α | 0.7 |
| | forest | 13.0 | 11.0 + 6.2∗tan α | 1.8 |
| IKONOS, Zonguldak | open areas | 5.8 | | 1.5 |
| IKONOS, Maras, flat | city | 1.4 | | 0.22 |
| OrbView-3, Zonguldak | open areas | 8.5 | 4.4 + 15.7∗tan α | 3.1 |
| Cartosat-1, Warsaw, flat | open areas | 2.5 | 2.4 + 8∗tan α | 0.6 |

to generate the images of a stereo pair within a short time. The stereo imaging by QuickBird is not economic for the vendor, so only few stereo combinations exist.

Table 3 gives an overview about the reached accuracy of height models based on high resolution space images. Only by comparison of a DEM with a reference DEM the correct accuracy information can be achieved. With check points too optimistic results are computed because check points are located usually in a flat area and have good contrast. Promising results have been reached with the stereo sensor Cartosat-1 while ALOS/PRISM needs more time for the sensor calibration (Kocaman & Grün 2007). The reached DEM-accuracy transformed by formula 1 to the standard deviation of the x-parallax (Spx) shows only a limited variation. In all cases where Spx for open and flat areas exceeds 1.0, special conditions are given – in the case if IKONOS in Zonguldak a larger time difference between both images of the stereo pair caused quite different shadows and in the case of OrbView-3 in Zonguldak the height to base relation was not optimal for the build up area and the extremely rough terrain. Optical systems operating in the near infrared or with panchromatic spectral range extended to the near infrared have advantages in vegetation areas including forest. For example DEMs generated with SPOT images, limited mainly to the visible range, have large gaps in forest areas while this problem does not exist for ASTER, operating in the near infrared.

## 4 CONCLUSON

We have a fast change of the analogue aerial cameras to digital cameras. Digital aerial cameras have better geometric and radiometric image quality, the colour comes without additional cost and the images don't have to be developed and scanned. Oblique images are used more often.

More and more high and very high resolution optical space systems are entering the market and this will be continued in the near future. The resolution will be improved to better than 50 cm, additional colour bands will come with WorldView-2 and stereo systems will cover in near future the whole world by stereo models with 2.5 m GSD. By automatic image matching detailed height models can be generated especially with the new high resolution stereo systems.

High and very high SAR images with up to 1m GSD will come this year. The Shuttle Radar Topography Mission generated nearly for the whole world DSMs by InSAR. With TanDEM-X in the future the accuracy and resolution will be quite better. With airborne SAR some areas with permanent cloud coverage have been mapped and with airborne InSAR for large areas accurate and high resolution DSMs have been and will be generated in the Intermap NextMap program. Radar still has some problems in the build up areas, here with laser scanning the most precise and detailed DEMs can be made.

## REFERENCES

Jacobsen, K. 2007a. Orientation of high resolution optical space images, *ASPRS Annual Conference* Tampa.

Jacobsen, K. 2007b. Comparison of Large Size Digital Airborne Frame Cameras with Analogue Film Cameras. *EARSeL Symposium Bolzano*, 2007.

Kocaman, S., Grün, A. 2007. Orientation and Calibration of ALOS/PRISM Imagery. *ISPRS Hannover Workshop 2007*, IntArchPhRS. Vol XXXVI Part I/W51.

Leberl, F., Gruber, M., Ponticelli, M., Bernoegger, S. & Perko, R. 2003. The UltraCam large aerial digital camera system. *ASPRS Annual Conference, Anchorage*, 2003.

Passini, R., Jacobsen, K. 2007. High Resolution SRTM Height Models. *ISPRS Hannover Workshop 2007*, IntArchPhRS. Vol XXXVI Part I/W51.

Sefercik, U., Jacobsen, K. 2007. Quality Assessment of InSAR Digital Elevation Models. *EARSeL Symposium Bolzano 2007*.