

DEVELOPMENT OF 3D TECHNIQUES

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ABSTRACT

Digital Elevation models (DEM) may be based on ground survey, matching of optical images, InSAR or LIDAR. Ground survey only for very small areas is economic. The characteristics of height models based on aerial and space images, InSAR and LIDAR are shown. The selection of the method depends upon the required information including accuracy, point spacing and the requested height – height of the bare ground or height of the visible surface. Also close to world wide covering height models as the SRTM height model or ASTER GDEM are available free of charge via internet. Of course these height models have a limited point spacing and limited accuracy, but they are useful for several applications. An overview about their characteristics and accuracy is included.

Keywords: DEM, Image matching, optical images, InSAR, LIDAR, DSM, filtering

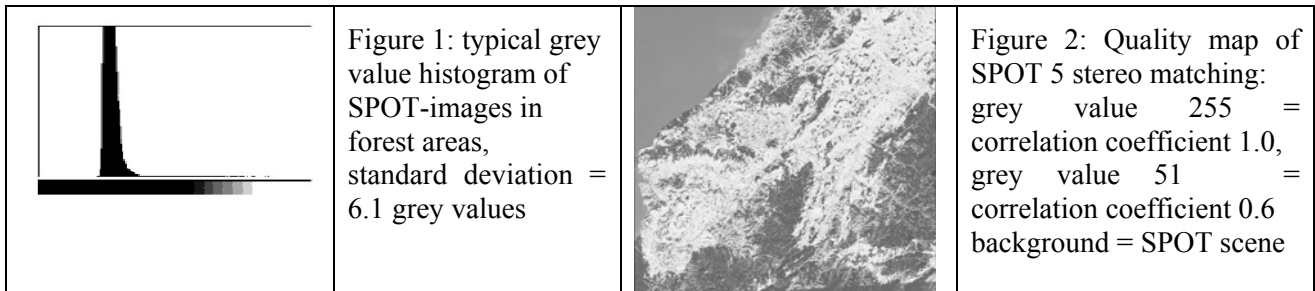
INTRODUCTION

Digital elevation models (DEM) are a basic requirement for several applications. The classical determination by ground survey is time consuming and too expensive. It has been replaced by photogrammetric 3D-techniques at first based on aerial images, later also space images. In the last years in addition interferometric synthetic aperture radar (InSAR or IFSAR) and laser scanning, also named LIDAR, came in addition. All these techniques have some advantages and disadvantages in relation to the details, accuracy and economic aspects. Today also close to world wide covering height models are available free of charge via internet, as the InSAR-based height model from the Shuttle Radar Topography Mission (SRTM) and the optical stereo satellite ASTER, the ASTER GDEM. Height models from X-band InSAR and image matching are at first digital surface models (DSM) including the height of the visible surface or in the case of InSAR based on short wavelength the height is close to a DSM, but in several cases DEMs, including the height of the bare ground, are required. A DSM containing a mixture of points located on ground and vegetation or buildings can be changed by filtering to a DEM, but if no points located on the bare ground are included, a filtering is not possible, only a correction using height information about the vegetation can be made. Another possibility for the direct determination of a DEM is InSAR based on long wavelength as the P- and L-band, which can penetrate the vegetation or LIDAR, which can find small gaps in the tree crown to reach the ground if the forest is not too dense.

HEIGHT DETERMINATION WITH OPTICAL IMAGES

Optical images may be taken from space or air. The major difference between them is the ground sampling distance (GSD), the distance of the projected pixel center to the neighbored projected pixel center, and of course the accuracy depending upon the GSD. But today the GSD has an overlapping range between airborne and spaceborne images; it goes down to 0.5m for images taken by WorldView-1 and -2 as well as GeoEye-1, while depending upon the flying height above ground and the camera, the aerial images can go up to 1m GSD. Another difference is the time interval between the images of a stereo pair. Images from stereo satellites as Cartosat-1, ALOS, ASTER and SPOT HRS, are taken by 2 cameras of the satellite, having different nadir angles in the flight direction with approximate 1 minute time interval of imaging. It is similar for flexible satellites as WorldView, GeoEye, IKONOS and QuickBird, changing their view direction fast during the pass of the object. During the negligible time interval the illumination and the object itself is not changing. This may be different for satellites generating stereo pairs by changing their view direction to the side. So for SPOT-images at least one day of time interval will be between the images of a stereo pair. In case of changing cloud condition, the time interval may be quite larger, causing sometimes problems of image matching caused by changed sun elevation and changes of the vegetation.

With the exception of different image orientation the handling of aerial or space stereo pairs is the same. Manual height measurements is the rare exception, the standard method of height determination is the automatic image matching. The image matching is based on the variation of the grey values in object space and this may be quite different depending upon the object and spectral range. So in images covering just the visual range, forest may be very dark with just a small variation of the grey values, as it can be seen in figures 1 and 2. The panchromatic SPOT-images, covering only the visible spectral range, in most cases have a very narrow histogram in forest areas (figure 1) and corresponding to this, poor correlation as it can be seen in the quality map (figure 2). In the quality map the dark parts (low correlation coefficient) are nearly identical to the forest areas. In the same area an image matching with ASTER-images, based on near infrared, did not have any problems in matching the forest areas.



$$SZ = \frac{h}{b} \cdot Spx$$

Formula 1: standard deviation of height

h/b = height to base relation Spx = standard deviation of x-parallax [GSD]

The standard deviation of height determination with optical images is described by formula 1. For space and aerial images it depends upon the height to base relation (h/b) and the standard deviation of the x-parallax, which should be expressed in fractions of the GSD. So it depends also upon the GSD directly. In practice the situation is a little more complicate because the standard deviation of the x-parallax is also depending upon h/b . If the angle of convergence is smaller (larger h/b), the images of a stereo pair are getting more similar, leading to a smaller value of Spx . That means the standard deviation of height is less dependent upon h/b . Of course in addition it is also dependent upon the local contrast and the area itself and the roughness of the terrain. In addition the type of image matching is important.

The traditional method of image matching is the image cross correlation – a small pattern sub-matrix of one image is compared with a larger search sub-matrix of the other image of the stereo pair. The pattern matrix is moved pixel by pixel in x- and y-direction over the search matrix and for any position the correlation coefficient is computed. The position leading to the largest correlation coefficient gives the position of best fitting of both sub-matrices that means the corresponding image positions. This image correlation is based on the hypothesis of local flat terrain as it can be seen in figure 3, left hand side – in this case the size of the corresponding sub-matrices is the same. If the object is not a horizontal plane as shown in figure 3, right hand side, the corresponding sub-matrices of an object part have different size and the image correlation is limited in the accuracy.

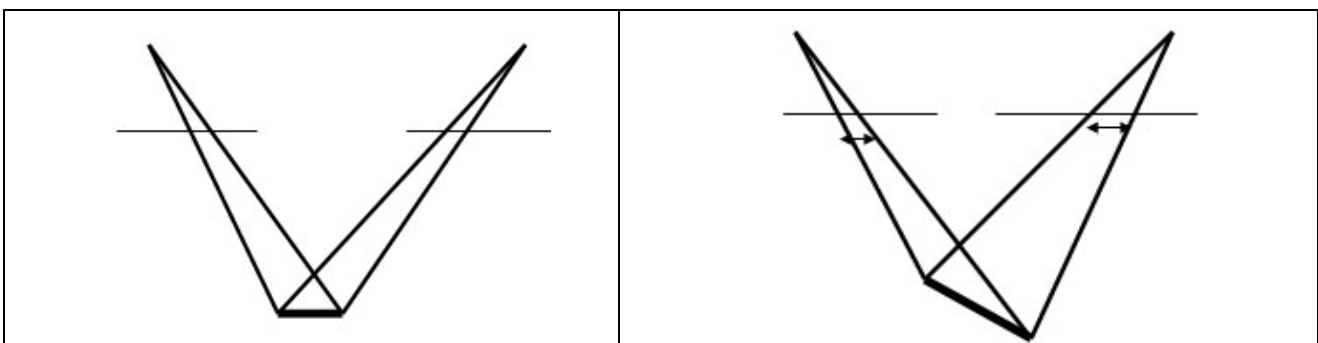


Figure 3: situation of image matching left: horizontal object plane right: inclined object plane

By least squares matching the sub-matrix of one image is fitted to the other image by affine transformation, respecting the different size of the corresponding, enabling also correct matching of inclined objects and convergent imaging solutions. In addition to the area based matching also feature based is possible e.g. based on Foerstner- or similar operators. These operators are searching image positions with clear object elements as corners of objects or well defined points. By feature based matching only few object points can be determined, not sufficient for a height model. Nevertheless feature based matching can be used as start information for area based matching. Another new development is pixel-based matching as semi-global matching (Alobeid et al. 2009), matching single pixels based on the information around. By pixel based matching also discontinuities, available for example at buildings, can be respected, leading to sharp building shapes, but it is not useful for forest areas.

Image matching as image correlation and least squares matching can be used for the determination of the upper level of a forest. With smaller GSD the details are improving, but with too small GSD matching of forest areas becomes more complicate up to failing in parts, mainly caused by occlusions and shadows on one side of the trees.

HEIGHT DETERMINATION BASED ON INSAR

By Synthetic Aperture Radar (SAR) imaging is possible based on the intensity of reflected radar pulses. SAR has the advantage against optical images of being nearly weather independent – it can penetrate clouds and is only influenced by heavy rain. SAR images are not including the same information contents as optical images with the same GSD and the interpretation is more difficult. Nevertheless the combination of 2 SAR-images taken with a small base enables the possibility of interferometric matching of the SAR-images, the so called Interferometric SAR (InSAR, partially also named IFSAR). InSAR can be used from air and space. For 3D-applications only the following radar-bands are used: P-band (1m wavelength and longer), L-band (15cm – 30cm), C-band (3.75cm – 7.5cm) and X-band (2.5cm – 3.75cm). The longer wavelength radar P- and L-band can penetrate the vegetation, leading nearly to the height of the bare ground, while the shorter wavelength radar C- and X-band are leading more to the top of the vegetation, a little (up to 25% of the tree height) below the tree tops.

Simultaneous InSAR is based on the overlay of 2 SAR-images, based on one active antenna (sending and receiving) and an additional passive antenna (only receiving). The interferogram shows fringes similar to contour lines, which finally after geometric processing are leading to object heights. Shorter wavelength give fringes with a smaller height interval as longer wavelength – see formula 2. Reverse shorter wavelength may cause more problems with phase unwrapping – the process of adding the correct integer multiple of 2π to the interferometric fringes.

$h_a = \frac{\lambda R \sin \theta}{2B}$	<p>Formula 2: height interval of InSAR fringes λ = wavelength R = flying height θ = incidence angle B=base length</p>
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With longer base length the phase unwrapping becomes more difficult up to impossible. So from aircraft a satisfying simultaneous InSAR mapping is not possible with P-band. For InSAR elevation models based on P-band two parallel flight lines (repeat pass) are required, guaranteeing a satisfying base length, but may cause problems with the decorrelation.

On own cost the company Intermap generated based on airborne X-band a digital surface model (DSM) with the height of the visible surface covering whole Western Europe with 5m point spacing and 1.0m standard deviation of the height. This so named NEXTMAP competes with the DEMs of the national mapping authorities.

In a test Intermap made some flights with simultaneous full polarimetric L-band (Mercer et al. 2010). The canopy phase is polarization independent (the polarization is not changed); while the ground phase is polarization dependent (the polarization is changed). So the canopy as well as the ground height could be determined. Based on the so reached information about tree height, the biomass was extracted with the relation $B = a \cdot h^b$ (B =biomass, h =tree height, a and b = factors depending the tree species). In Canadian forest with the relation $B = 0.8 \cdot h^{1.75}$ the biomass of the forest was determined with an accuracy of 20%.

InSAR also is in use from space; with the Shuttle Radar Topography Mission (SRTM) a DSM has been generated which is available free of charge in the Internet with a spacing of 3 arcsec, corresponding to approximately 90m at the equator. Just recently, in June 2010 the second German radar-satellite TerraSAR-X has been placed in the orbit, which shall work together with the first TerraSAR-X as TanDEM-X in a

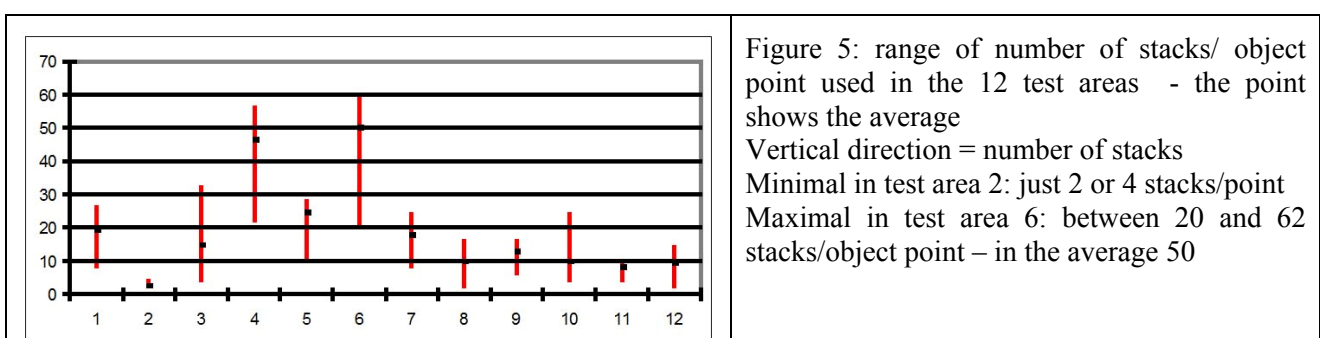
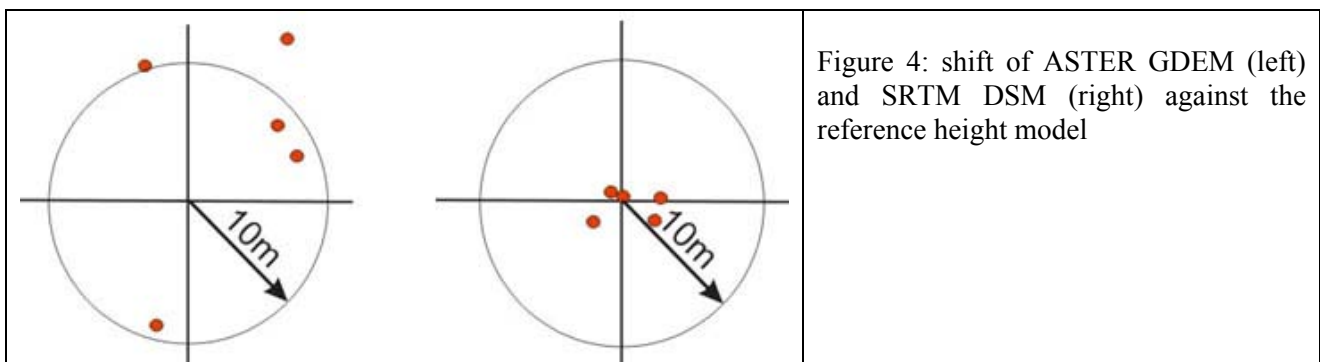
configuration enabling InSAR-DSMs covering the whole world twice within the next two years. With this configuration height models with a spacing of 12m and approximately 2m standard deviation shall be generated, which will be available on commercial base. But also based on multiple imaging of single radar satellites InSAR-DSMs can be generated.

HEIGHT MODELS AVAILABLE FREE OF CHARGE

As first free of charge available, worldwide covering height model GTOPO30 was placed by USGS in the internet. GTOPO30 has a point spacing of 30", corresponding to 925m at the equator. The large spacing and the lower height accuracy limits the use of this height model. This is different for the Shuttle Radar Topography Mission, having in the space shuttle a combination of 2 active radar antennas – the US C-band and the German/Italian X-band and in addition on an 80m long arm 2 corresponding passive antennas. The height model based on the US C-band data are available free of charge in the internet with a point spacing of 3", corresponding to 92m at the equator. Only for the area of the USA this height model has an improved spacing of 1". The corresponding height model generated by the German DLR, using the X-band data can be bought from the DLR with 1" point spacing, but it is not covering the whole area from -56° southern up to 62.5° northern latitude as the C-band DSM.

Since June 2009 in addition the height model ASTER GDEM (global digital elevation model), determined by matching of stereo satellite ASTER images is also available free of charge in the internet. ASTER GDEM is a product of the Japanese METI and the US NASA. The near infrared images of the optical ASTER have a ground spacing of 15m and a height to base relation of 2.0. With own matching of ASTER stereo scenes only a standard deviation of 10m up to 15m has been reached, but the ASTER GDEM is using all stereo scenes available for one ground point. So with a very high number of so called stacks (number of ASTER images used for the computation of a ground point) an improved accuracy has been reached.

On the WEB-page of the ASTER GDEM a validation report is available (see references), but some important details are missing, so I made my own analysis with 12 ASTER GDEM and corresponding SRTM DSM tiles. For all test areas precise reference height models are given. The test areas from 6 countries are covering the whole range of elevation models from flat over rolling to mountainous and steep mountainous areas, open, covered by low forest, high forest and build up including downtown areas. As first step of a digital elevation model analysis, a verification of possible shifts in X and Y is required, so all investigated height models have been shifted by adjustment to the reference height model. Partially problems of the national datum may cause a shift up to 300m, but also without datum problems some shifts in the range of the orientation accuracy of the elevation models occurred (figure 4). The standard deviation of horizontal shifts for the ASTER GDEM is in the range of 8m, while it is in the range of 3m for the SRTM DSMs.



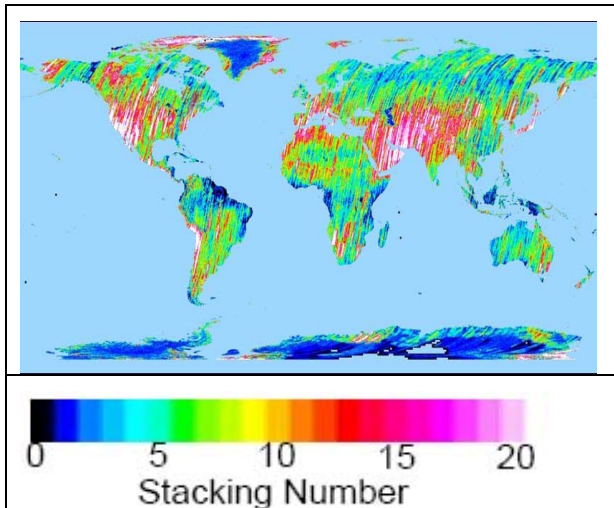


Figure 6: Number of images (=stacks) used for ASTER GDEM (ASTER GDEM evaluation report)

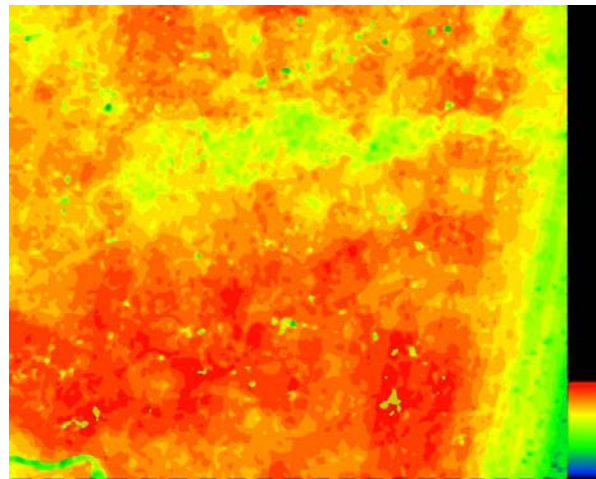


Figure 7: number of stacks/point used for ASTER GDEM in test area Pennsylvania (up to 56 stacks/point)

As shown in figures 5 up to 7, the number of stacks per object point varies strongly from test area to test area. The test area 2 with the smallest number of stacks and the test area 6 with the highest number of stacks/object point are both located in the USA, approximately 500km apart. The accuracy of the height models are depending upon the number of stacks as shown in figure 8.

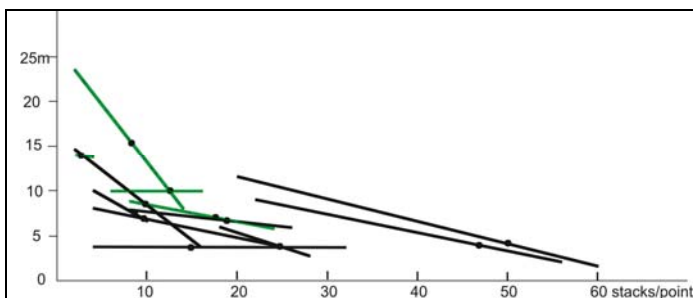


Figure 8: adjusted regression of the relation of the height standard deviation to the number of stacks/object point
Green lines = test areas affected by forest

As all digital elevation models, ASTER GDEM and SRTM DSMs have an accuracy depending upon the terrain inclination following the formula: $SZ = a + b * \tan(\text{slope})$, so the analysis has to respect this. In addition both are DSMs with the height of the visible surface, while the reference height models are containing the height of the bare ground. If in the neighborhood of a point, not located on the bare ground, at least one ground point exists, such points can be excluded by filtering, leading to a DEM. In closed forest areas a filtering is not effective as in more open areas. Nevertheless for analysis both height models have been filtered, improving the result.

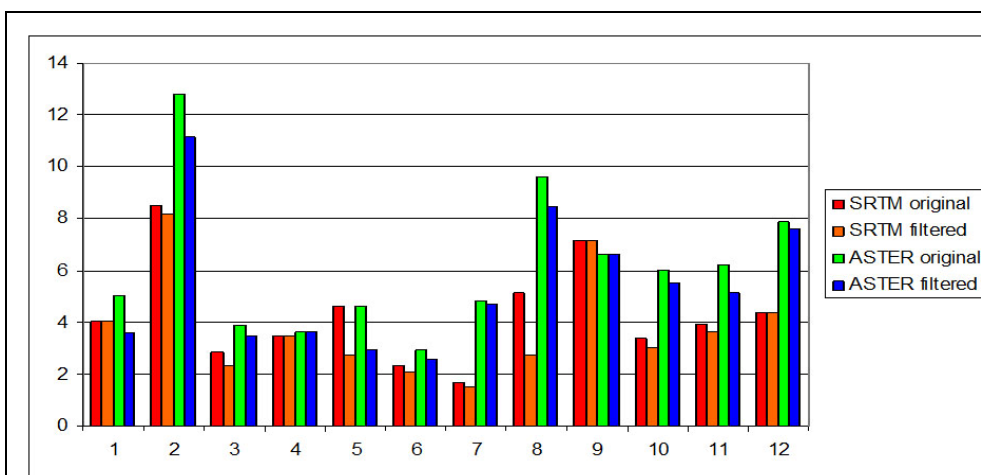


Figure 9: standard deviation of height with and without filtering
– vertical direction = values [m]

As shown in figure 9, the standard deviations of height for SRTM DSMs are smaller and more homogenous as for ASTER GDEM. The test areas 2 and 9 are special, test area 2 is to 95% covered by forest and test area 9 is a very steep mountainous area, partially covered by forest. If these test areas are excluded, in the root mean square the standard deviation of the height in flat areas is $\pm 3.1\text{m}$ for SRTM DSMs and $\pm 5.1\text{m}$ for ASTER GDEM.

Another aspect of the height models are the morphologic details, which directly depend upon the point spacing. Morphologic details are important for the description of details, visible at contour lines or 3D-presentations of the height models. ASTER GDEM has 1" point spacing, while it is 3" for SRTM DSM, so more details should be expected in ASTER GDEM as in SRTM DSMs. Nevertheless if the contour lines in figure 10 are compared for the morphologic details, there is nearly no difference between the details of both height models, while the SRTM X-band DSM, having 1" point spacing, shows quite more details, similar to the reference height model having 10m point spacing. A reason for the loss of morphologic details is the method of combining the ASTER stereo models to the GDEM – the single stereo models are not fitted to each other, they are just averaged, causing a smoothing coming from the geometric shifts of the single stereo models against each other. This is similar for the other test areas, so the morphologic details of ASTER GDEM are not better as corresponding to a point spacing of 2".

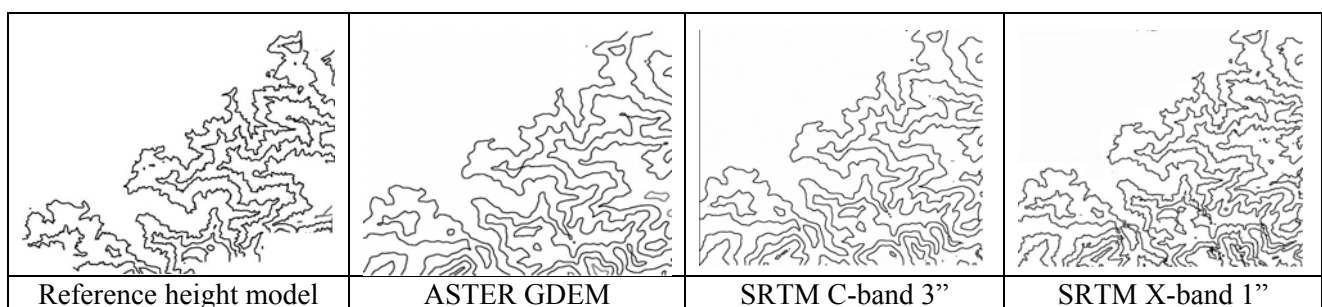


Figure 10: contour lines, test area Zonguldak

Even if the SRTM DSM is more precise as ASTER GDEM, in steep mountainous and dry sand desert areas ASTER GDEM has not the gaps as the original SRTM DSMs and ASTER GDEM is covering the area from -83° southern up to 83° northern latitude, while SRTM DSMs are limited to -56° up to 62.5° latitude.

HEIGHT DETERMINATION BASED ON LIDAR

LIDAR, also named laser scanning, determines the object height based on a laser pulse or laser wave reflected from the object. In some countries, as in Germany, it became the standard method of the survey administrations for height determination. The main reason for this application is the possibility of the ground height determination also in areas covered by forest. But it has to be mentioned, that the forest in European countries cannot be compared with the Brazilian forest. In Europe trees have no leaves in winter, so a laser pulse partially can penetrate the trees without leaves down to the ground, enabling the possibility of first and last, or even multiple, return of the reflected laser pulse (figure 12), giving detailed information about the forest.

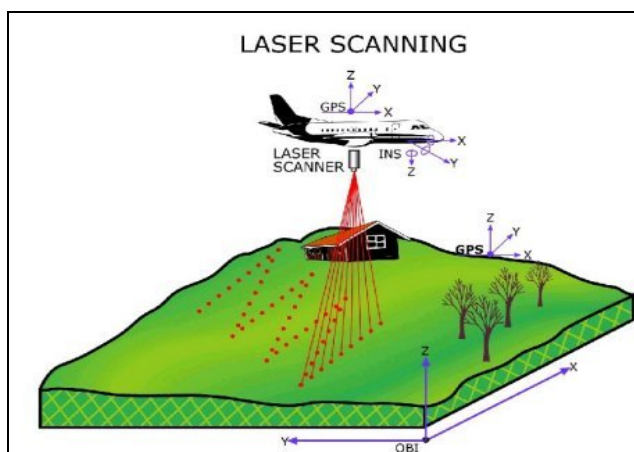


Figure 11: principle of LIDAR flight

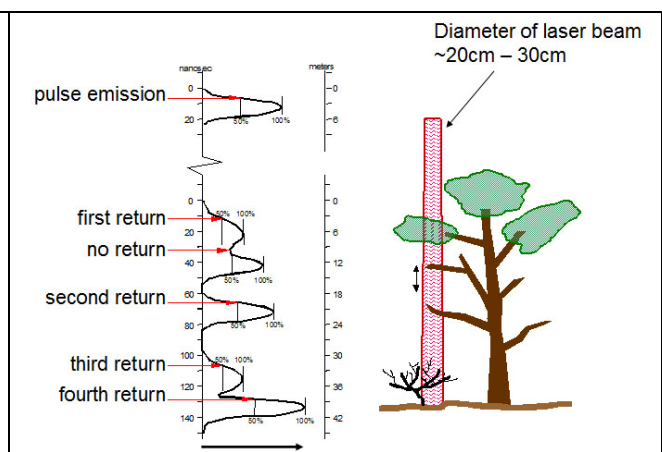


Figure 12: Returns of a laser pulse

The nadir angle of the laser beam should be limited to allow a determination of the ground height – with larger inclination the last return pulse may not come from the ground. By this reason in most cases the nadir angle is limited to 7° up to 14° , reducing the swath width, so several flight lines are required for covering a larger area.

The position and attitude of the laser scanner is determined by relative kinematic GPS positioning and inertial measurement unit (IMU) (figure 11). For the relative GPS-positioning a GPS ground station is required in a distance not exceeding approximately 50km. Based on this, the view direction of the laser beam can be determined, allowing the absolute positioning of the point of reflection. The standard deviation of the object height can be determined up to $\pm 15\text{cm}$ or in the case of an improvement by means of control areas up to $\pm 10\text{cm}$.

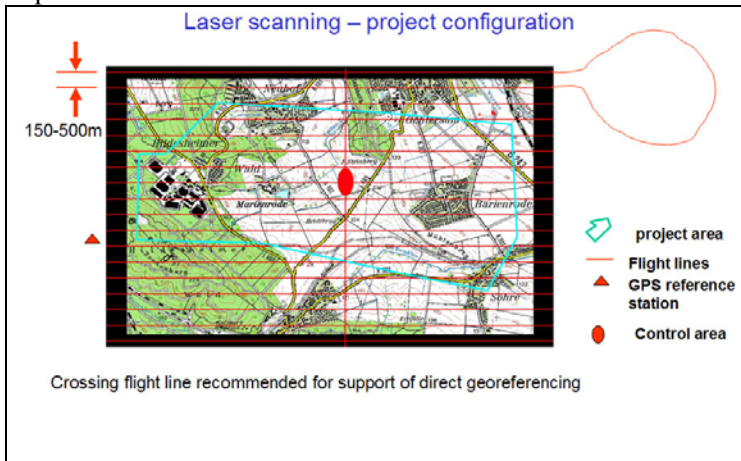


Figure 13: Configuration of laser scan flight with crossing flight line and control area used in Germany

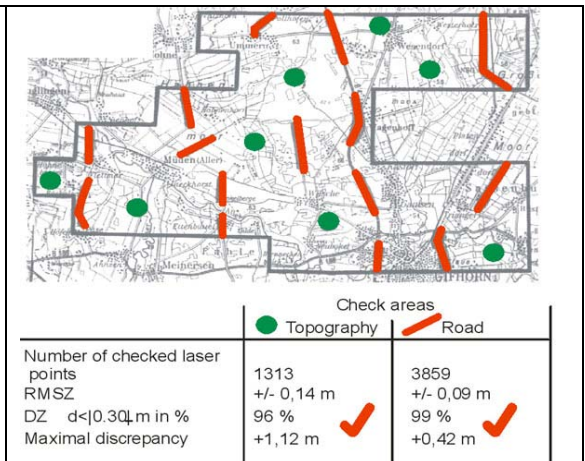


Figure 14: Accuracy evaluation of laser scan flight using a configuration as figure 13

The configuration of a LIDAR flight for precise height determination is shown in figure 13. With a crossing flight line and a control area with known ground height, systematic height errors can be determined and respected. Such a configuration leads to the precision shown in figure 14. Without crossing flight line and control area, the absolute standard deviation of the height is limited to approximately 15cm and below, depending also upon the flying height. Nevertheless the relative height accuracy, important for the determination of tree heights, is not affected.

Today the use of LIDAR is ranging from 50m up to 5000m flying height with point spacing from 25cm up to 10m. There is a clear tendency to use LIDAR in combination with other sensors as mid-format digital cameras. LIDAR has the advantage of being independent upon sun light, allowing also a flight during night if no combination with an imaging sensor is required. LIDAR also has the advantage of delivering accurate height values from areas without contrast. The main disadvantage of LIDAR is the relative high cost. LIDAR is a proven technique for precise height determination with densely located points. The trend goes to higher flying elevation and the use of multiple pulses instead of only first and last pulse. An example of flight parameters of the Optech ALTM 2033 is shown in table 1. Depending upon the flying height, the ground point spacing is increasing and the swath width is getting larger, reducing the cost. Scan angles of $\pm 20^\circ$ are not recommended for forest areas, only for open areas outside cities to enable the measurement of the ground by the last pulse.

	$\pm 7^\circ$ Scan angle (14° Field of View)				$\pm 20^\circ$ Scan angle (40° Field of View)				Table 1: technical parameters of flight with Optech ALTM 2033
Altitude	500m	1000m	2000m	3000m	500m	1000m	2000m	3000m	
Scan Freq.[Hz]	66	47	33	27	29	27	19	16	
Swath Width [m]	115	240	488	735	361	724	1454	2180	
X-spacing [m]	0.48	0.68	0.97	1.19	1.11	1.19	1.69	2.01	
Y-spacing [m]	0.48	0.68	0.97	1.19	0.63	1.18	1.66	2.10	
Pts./m ²	4.3	2.1	1.1	0.7	1.4	0.7	0.4	0.2	

CONCLUSION

The determination of digital elevation models with the height of the bare ground or digital surface models with the height of the visible surface is possible by means of optical images taken from air or space, Interferometric Synthetic Aperture Radar, also from air and space and by LIDAR from air. Of course not only the height is determined, it is a 3D-positioning including the X-Y-coordinates.

DSM determination from optical stereo pairs is a standard procedure, reaching standard deviations in the range up to one GSD with sufficient height to base relation. The use of aerial or space images overlaps today and it is more a question of economy which type shall be used. Of course space images today have up to 0.5m GSD, for more details and higher accuracy aerial images have to be used. Today the positioning of aerial images at least should be supported by relative kinematic GPS-positioning. As new development for automatic image matching semi global matching came, but it is not very successful for forest application.

Depending upon the used wavelength by InSAR a DSM or with P- or L-band radar a DEM can be generated. With a test configuration from Intermap, using simultaneous full polarimetric L-band, the ground height as well as the canopy height of a forest has been determined.

For several purposes free of charge available, nearly worldwide covering height models can be used. The SRTM DSM has some advantages against the ASTER GDEM, even if the point spacing is larger by a factor of 3. Only in mountainous areas there is an advantage of the ASTER GDEM.

By LIDAR very detailed and precise height information can be reached, including the canopy height and the ground if the forest is not too dense. The disadvantage of LIDAR is the high price level.

In summary no special method of height generation can be recommended, it always depends upon the application, what spacing and accuracy is required and what type of height is necessary.

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