ERROR BUDGET OF TERRESTRIAL LASERSCANNING:

INFLUENCE OF THE INTENSITY REMISSION ON THE SCAN QUALITY

Alexander BUCKSCH
Department of Earth Observation and Space Systems,
Delft University of Technology, The Netherlands, e-mail: a.bucksch@tudelft.nl

Roderik LINDENBERGH
Department of Earth Observation and Space Systems,
Delft University of Technology, The Netherlands

Jane *VAN REE*
Department of Earth Observation and Space Systems,
Delft University of Technology, The Netherlands

Key words: Terrestrial Laser Scanning, Error Budget, Surface Reflectivity

SUMMARY (English)
Terrestrial laser scanning (TLS) is a surveying technology to measure distances to surfaces in the spherical surrounding of the scanner instrument. In contrast to pulse, i.e. time of flight scanners, phase based scanners emit a modulated wave signal that allows for determining the object distance from the returned phase pattern. Because of their high scanning speed, phase based instruments are getting more and more popular. It is clear from literature and practice that, because of the interaction between the laser light and the object, the characteristics of the object surface have a large influence on the measurement quality. Still, a quantitative insight in the quality of scanning results is missing.
This publication will compare two phase based scanners, the Imager5003 from Zoller und Fröhlich and the HS880 from Faro. We investigate the scan quality of both scanners for a variety of surfaces with different reflection characteristics. For this purpose scans of an Esser Test Chart TE 109 were made with both scanners. The test chart consists of six different grey patches ranging from 71% remission white to 0.05% remission black. The chart was scanned from a distance of 4 m in a stable environment. In order to compare the scanning results of both scanners a patch wise analysis is made of (i) the number of points scanned, (ii) the intensities values of the scanned points, and (iii) the reliability and precision of a local plane adjustment.
It turns out that for both scanners the measurement noise is significantly increasing with decreasing remission. An insight in the amount of absorbed and reflected energy per grey value patch will be part of the analysis results. An overall conclusion of the presented experiment is that the two scanners differ only in extreme cases from the specifications given by the manufacturers.

SUMMARY (Russian)

Наземное лазерное сканирование - это метод геодезической съемки, суть которого заключается в измерении расстояний, а также углов в горизонтальной и вертикальной плоскостях, при помощи специального сканирующего инструмента (сканера). В отличие от импульсных сканеров, измеряющих время прохождения сигнала до объекта и обратно, фазовые сканеры излучают модулированный волновой пакет, что позволяет определять расстояние до объекта по распределению фазы отраженного сигнала. Благодаря высокой скорости сканирования, фазовые сканеры в настоящее время приобретают все большую популярность. Как известно из литературы и практики, вследствие взаимодействия лазерного луча с поверхностью объекта измерения, отражательные характеристики поверхности оказывают значительное влияние на качество измерений. Вместе с тем, до настоящего момента не проведен всесторонний качественный анализ реэультатов, получаемых на сканерах.

В данной работе демонстрируются результаты сравнения двух фазовых сканеров: Imager5003, компания Zoller und Frohlich, и LS880, компания Faro. Мы исследовали качество сканов получаемых с использованием этих двух сканеров для целого ряда поверхностей с различными отражательными характеристиками. С этой целью при помощи обоих сканеров была просканирована тестовая карта Esser TE 109. Тестовая карта состоит из шести различных серых участков с коэффициентами отражения в диапазоне от 71% для белых поверхностей до 0.05% для черных поверхностей. Карта была просканирована с расстояния 4 м под четырьмя различными углами в стабильных условиях. С целью сравнения результатов сканирования, полученных на обоих сканерах, был проведен поучастковый (patchwise) анализ (i) числа просканированных точек; (ii) интенсивности просканированных точек; (iii) достоверности и точности (precision) приведения к локальной плоскости.

Наши исследования показали, что сканер FARO LS880 позволяет получить большее, чем сканер Imager5003, количество точек на более темных участках, тогда как сканер Imager5003 дает менее зашумленные данные. Объяснение этого феномена, так же как и сведения о количестве энергии поглощенного и отраженного излучения, приходящемся на каждый серый участок карты, будут даны в ходе анализа результатов. Основное заключение, сделанное нами по результатам представленных экспериментов, состоит в том, что оба рассмотренных нами сканера демонстрируют характеристики, отличные от заданных производителем, лишь в экстремальных случаях.

1 Introduction

The principle of distance measurement with a laser and the generation of many measurements in one scan procedure is known since the 80's [1]. Most laser scanners determine a panoramic scan of the 3D surrounding of the scanner. Scan points are stored in a spherical coordinate system, centered at the scanner. For each single scan point, a vertical angle ϕ , a horizontal angle ϑ and a range R between scanner and object is stored. A relative intensity of the signal as captured by the scanner is stored as well. The (ϕ, ϑ, R) -coordinates are generally transformed into a Cartesian (x,y,z)-coordinate system. Instead of measuring the time of flight, like pulse based scanners, phase based systems rely on a bi- and tri-phase modulation of the laser light frequency. The range is determined from differences in phase between the emitted and received laser signal. The wave length of the largest or carrier wave is around 80 meters, depending on the manufacturer.
Because the phase angle of both the emitted and received signal differ continuously, a phase based scanner can measure the distance continuously as well, which results in a scanning speed of approximately 125.000 points per second.

The accuracy of time of flight scanners and phase based scanners is comparable. The manufacturers give out range accuracies at millimeter level at a scanning distance of 10m. The positional accuracy of a scan point is reported to be in the order of a few millimeters as well. The values as given by the manufacturers should be interpreted as average accuracies. The reason for this is the dependence of the accuracy on the mechanics of the laser scanner, the environmental conditions at the time of scanning and on the specific surface characteristics of the object.

Experience has shown that scanning surfaces of different reflectivity characteristics results in systematic biases. This can lead to serious data jumps, if objects consisting of differently reflecting materials are scanned. The only way to avoid these problems is to coat the object with a unique material, but this is almost never possible. An insight in the performance of different laser scanners on different materials with known reflectivity can be used to determine the expected errors.

In this publication we analyze the influence of the intensity remission on the scan quality. For this purpose an Esser Test Chart TE 109 (Fig. 1) consisting of grey patches ranging from a highly reflective white patch to a strongly absorptive black patch is scanned under the same conditions by two different scanners, the Z&F Imager 5003 and the Faro HS880. For every patch in the test chart the scan points returned from that patch are isolated, counted and adjusted to a plane. The number of returned points and the planar parameters give insight in the relative quality of the scan points for that particular patch.

In Section 2 the physics of scattering and absorption is discussed and the measurement setup is described, while in Section 3 the results of the test scans are given and discussed. Conclusions and an outlook to further experiments are given in Section 4.

Figure 1: The Esser Test chart TE 109

2 Scatter theory and experiment set up

When the monochromatic laser light of about 780 nm frequency hits the object surface, it is redistributed in a way dependent on the surface characteristics. In order to understand this interaction insight in the theory of scattering and absorption is needed, [10]. Specular scattering occurs, when the surface of an object is sufficiently smooth. According to the law of reflection, a light ray will be bounced by a shiny surface like water, glass or mirrors under an angle of reflection that is equal to the angle of incidence. As a result no signal will return to the scanner, if the object is not scanned perpendicular to the object surface. In the other extreme case of an ideally rough surface, so-called Lambertian scattering occurs. Incoming light is reflected equally in all directions. If the amount of scattering is made one-parameter dependent on the surface normal, one obtains the Minnaert model. In this sense, Lambertian scattering is just a special case of Minnaert scattering. The Minnaert model can be extended by a specular dependency by incorporating a Henvey-Greenstein term [10], parameterized by an anisotropy parameter.
Scattering describes the redistribution of the laser light when it hits the object surface. The transition of laser light into heat on an object is called absorption. Remission quantifies the amount of absorption. If the remission

is 100%, all incoming light is scattered and no light is absorbed. Typically white surfaces have a high remission in contrast to black surfaces.

The process of scattering and absorption is illustrated in Fig. 2. A light and smooth object, Fig. 2a, will behave dominantly specular. A darker object, Fig. 2b, will absorb more laser light. Rough surfaces, Fig. 2c and Fig 2d, will behave more Lambertian.

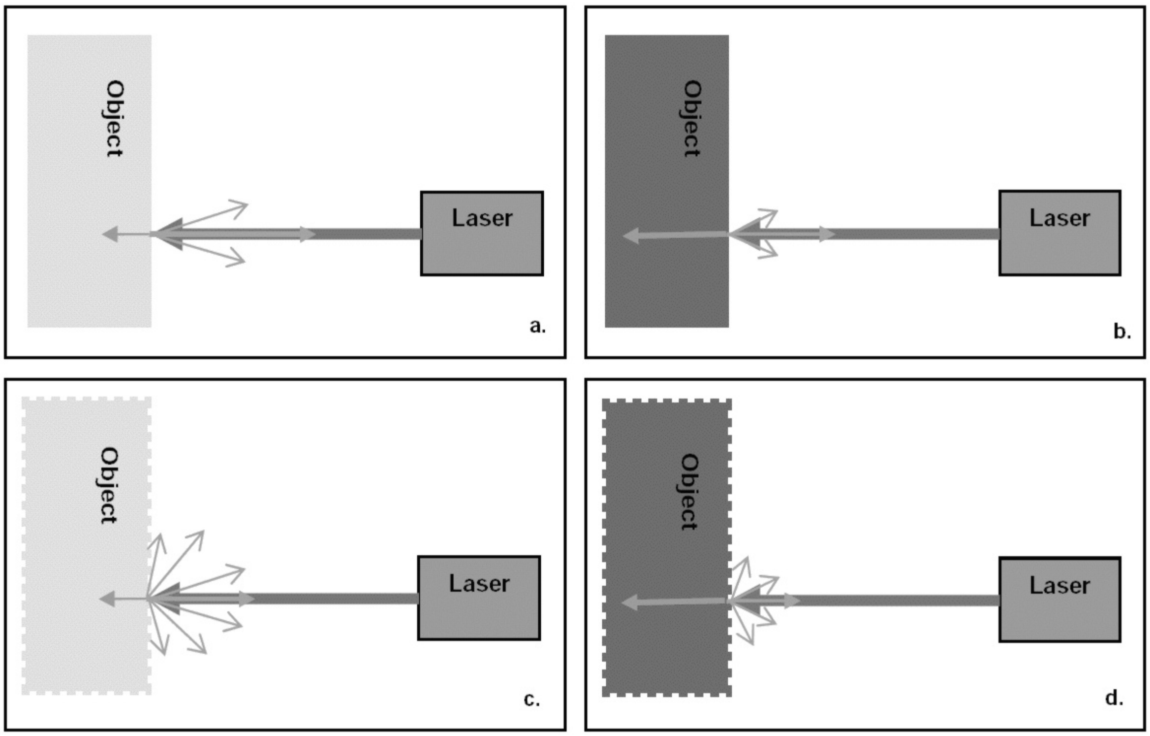

Figure 2: Scattering and absorption of laser light

In the described experiment scans of object patches with known remission are compared. For this purpose an Esser test chart TE 109 is used, see Fig. 1. This plate consists of two 5-graduated counter current grey scales that are arranged on a grey background. In between the two rows of grey value patches, a field of black velvet is located. The remission values of the patches are given in Table 1. It is expected that the black velvet will absorb most of the incoming laser light, which results in a remission close to 0. Table 1 also gives the relative brightness and the output voltage of the different patches. The relative brightness values refer to differences in luminance as observed by a standardized human eye model [8]. The brightness values are determined relative to Barium Sulfate (BaO4S), which is set to 0. BaO4S has a total reflection and is used in mirrors. The output voltage gives the amount of energy reflected, relative to the white patch.

Table 1: The remission table for all grey patches on the Esser Test Chart TE 109

Patch	Relative Brightness	Remission [%]	Output voltage [%]
1 white	0.15	71	100
2	0.37	43	77.5
3	0.65	22	55
4	1.05	09	32.5
5 black	1.75	02	10
6 velvet	0	<0.05	0

The test chart is placed in front of a white plate at a distance of approximately 4 m. The chart is positioned facing the scanner which implies that scanning angles are never larger than about 3 degrees. The chart is scanned by both the Z&F Imager 5003 and the Faro LS880 scanner. It should be noted, that the scan resolution for the Faro LS880 is about two times as high in this experiment. For both scanners we determine and analyze the following parameter values for all seven patches.

1. Amount of points measured by the scanner
2. Average point intensity per patch
3. Precision and reliability of a patch wise planar adjustment.

If all scan points are ideally recorded, the points form a regular raster in the (ϕ, ϑ)-plane. $\Delta\phi$ and $\Delta\vartheta$ between two neighboring points are the vertical and horizontal angle increments of the scanner. In case of strong specular reflection or small remission it is expected however that points are lost in the scan process. The point intensity at the scanner receiver unit depends on the absorption and scattering behavior of the patch because the laser energy is either absorbed by the patch or scattered in different directions. The patch wise adjustment to a plane gives insight in how the individual quality of the scan points and their total number propagates into the parameter values describing the quality of the planar fit. For this purpose the bias with respect to the values obtained from a planar adjustment of the large background gray patch is determined together with the spread or Root Mean Square Error (RMSE) of the patch wise adjustments.

3 Results

The resulting scans of the test chart from both scanners are visualized in Fig. 3 and 4. The individual scan points as returned from the different patches are clearly visible. The points are colored by intensity. Clearly the intensities differ strongly per patch. Also one can observe that in some patches points are missing.

Table 2: Performance statistics per gray value patch of the Z&F Imager 5003 and the Faro LS880 scanners.

Patch	**Imager 5003**				**Faro LS880**			
	Points in %	**Intensity**	**σ in mm**	**Bias in mm**	**Points in %**	**Intensity**	**σ in mm**	**Bias in mm**
1 white	100.0	0.60	0.90	1.04	100.0	0.62	2.34	-3.45
2	100.0	0.38	1.03	0.95	99.0	0.38	2.81	-0.47
3	97.5	0.34	1.33	0.78	92.5	0.34	2.42	-0.48
4	100.0	0.08	3.27	0.80	91.5	0.07	5.76	-1.36
5 black	100.0	0.04	7.07	-2.60	85.1	0.05	7.85	2.50
6 velvet	85.5	0.05	9.85	-6.26	82.6	0.05	10.20	0.94

3.1 The number of points scanned

In Table 2 the percentages of outgoing vs. returning points are given for all seven patches and for both scanners. It can be seen that for both scanners most intended measurements were received, even for the black velvet patch. For both scanners about 15%-20% of the points are missing for this patch. This negative result on the black velvet is still better as expected however, because of the low remission characteristic of this patch of only 0.05 %. The exact numbers in Table 2 are maybe influenced by the different scan resolutions for the two scanners.

3.2 Intensity values of the scanned points

Intensity values represent the strength of the returning signal. In Table 2 mean normalized patch wise intensity values are given with values between 0 and 1. Recall that the white patch has the highest remission value, which means that it reflects more energy of the incoming signal than the other patches. As expected the measured intensity values are highest for this patch, while the average intensity decreases with decreasing remission until the fifth patch. The black and the black velvet patch show comparable results. It was expected that the black velvet would perform even worse, because complete absorption is expected with a remission value of close to 0%, compare Table 1.

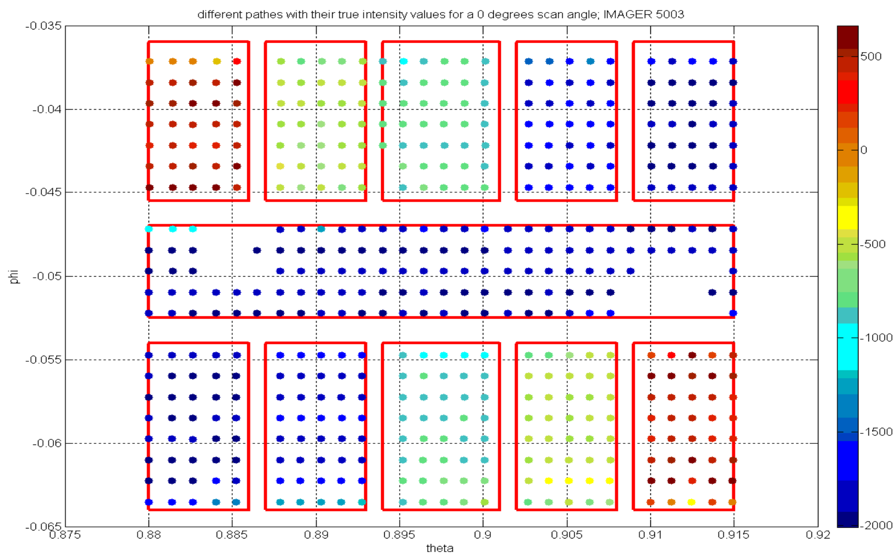

Figure 3: The grey level patches of the Esser Test Chart TE 109 measured with the IMAGER 5003. In the upper row the white patch is on the left ranging to black on the right. The black velvet is located in the middle. The bottom row ranges from black (left) to white (right)

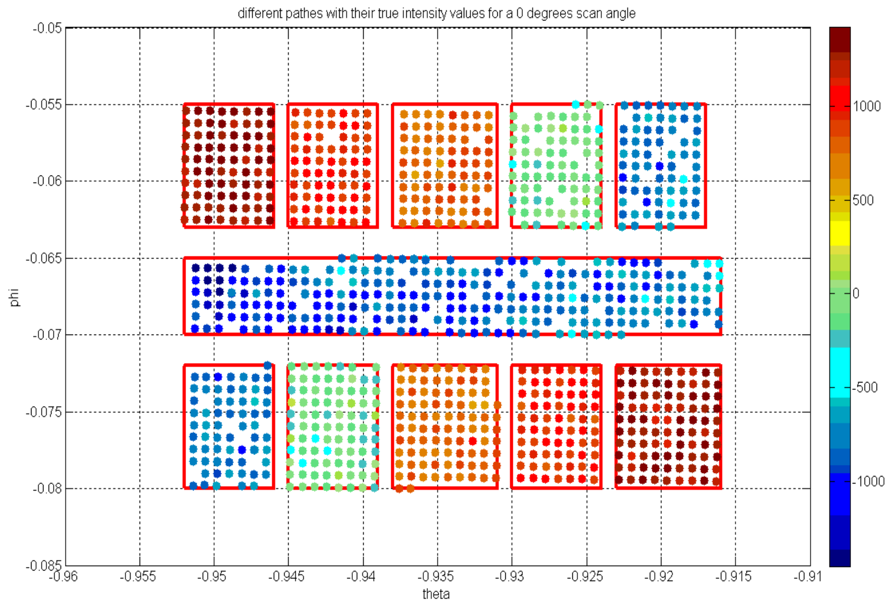

Figure 4: The grey level patches of the Esser Test Chart TE 109 measured with the Faro LS 880. The patch arrangement is the same as in Figure 3.

3.3 Reliability and precision of a local plane adjustment

The reliability and precision is examined by fitting a least squares plane, [9], through the recorded scan points per patch. These planes are visualized in Fig. 5. Clearly the adjusted planes have different positions and orientations with respect to the overall fitted plane. This indicates that the reliability of the planar parameters differs for the different patches. A measure for the reliability is given by the bias. The patch wise bias is defined here as the difference between the range coordinate of the middle of the adjusted plane and the range coordinate of the gray background of the test chart, compare Fig. 1. The biases are also given in Table 2. The spread of the adjustment residuals is a measure for the precision of the scans. In Table 2 the standard deviations, σ, in mm of the residuals give insight in the spreading of the points per patch.

It can be seen for both scanners that basically the precision decreases with decreasing remission value and decreasing intensity value. What is striking is that even for not extreme cases the difference in precision is very significant, e.g. the standard deviation is more than doubled from patch 1 to patch 4 for both scanners. The bias values do not show a clear pattern. Both positive and negative biases of values up to a few mm are detected. In general the middle patches (not white, not black) give the best results.

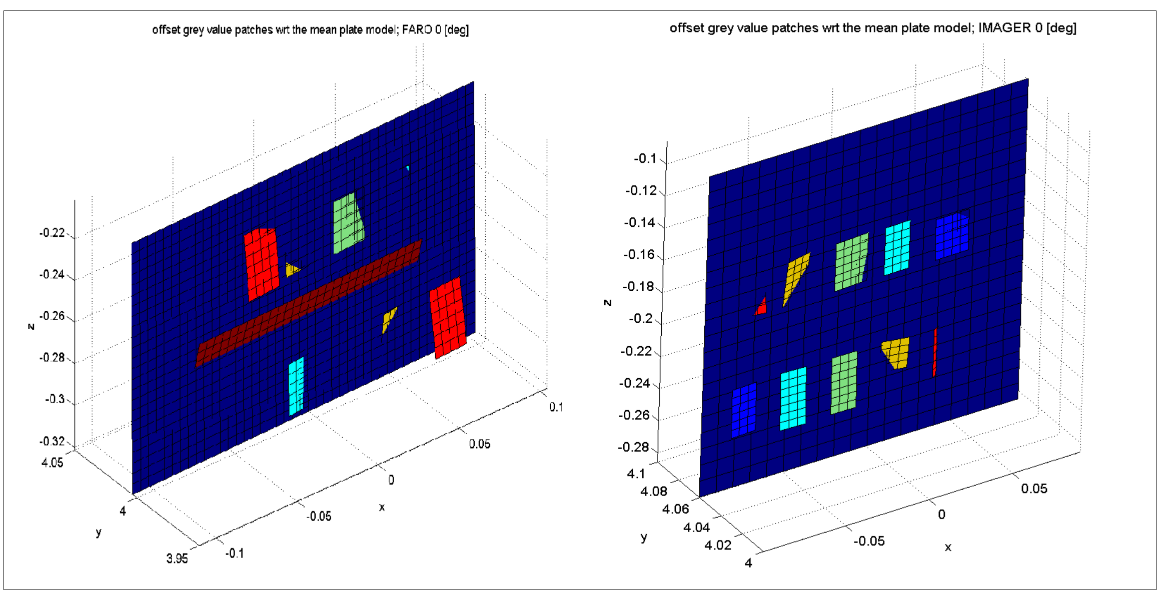

Figure 5: The location of the LSQ-planes of the grey value patches of the test chart wit respect to the average plane through these patches at a scan angle of 0[º]. To remember: the test chart consists of the following grey patches (from bottom left to bottom right): white, light grey, middle grey, dark grey and black. On the top exactly the other way around and they are separated by a large patch of black velvet. **Left:** the patches for the average plane determined for the FARO LS 880. **Right:** the patches for the average plane determined for the IMAGER 5003.

4 Discussion, Conclusion and Further research

The general conclusion is that light surfaces are scanned with a higher accuracy than darker surfaces. This is due to a high remission value of light surfaces, which results in higher intensity values measured. Avoiding scanning black and dark objects with a phase shift laser scanner is the best solution, but for a scan angle of 0 degrees, as used in these experiments, the result is still reasonably reliable on dark surfaces. When comparing the reliability parameters of the two laser scanners it can be said that the output scans obtained with both scanners are evenly reliable with respect to the different reflectivity characteristics. It has to be taken into account that a fair comparison between both scanners is not valid, because the results of the Faro LS880 concerns non-filtered data, while the IMAGER 5003 filters the data directly after scanning. Therefore, the conclusions drawn in this paragraph are only valid for the performances of both scanners with respect to their output scans.

The patches of the test plate are connected, Fig.1. The non-parallelism of the adjusted patches [Fig.5] with respect to the average plane can therefore most likely be explained by mixed points that influence the plane fitting. This problem is less strong for the IMAGER 5003, but this can be explained by the fact that the IMAGER 5003 filters before the output is created. This leads to more parallel plane fits. Fig 5. shows that the two scanners obtain almost opposite results with respect to the sign of the bias. The models of the darker patches obtained with the IMAGER 5003 are located behind the average plane in general. The brighter patches are located in front of the plane. For the FARO LS 880 this is the other way around. It is not possible to give a general conclusion with respect to the offset features caused by differences in reflectivity characteristics. In order to get this information additional research will be made to understand the behavior of different reflectivity characteristics. Furthermore, it can be seen from Table 2 and Fig. 5 that the biases of the IMAGER 5003 are very small for the brighter patches; on sub-millimeter level in most situations. The biases of the FARO LS 880 vary more for these patches and they are within millimeter level. It can also be seen that the biases for the darker patches are smaller for the FARO LS 880. Further research will be done on the characteristic bias determinations caused by reflectivity. Taking an average plane on which the performances of laser scanners is known will improve the results, because the influence of one grey value can be examined easier and exact. Another future mission to improve the experiments is to examine one grey value per scan to eliminate mixed reflectivity information that can influence the results negatively. In the upcoming experiments we plan to separate the effect of absorption from the effect of reflectivity.

Acknowledgements

Thanks to Maxim Keshin and Pavel Ditmar for the Russian summary. Further we want to thank the companies “Faro” and “Zoller + Fröhlich” for supporting this research.

References

[1] Franois Blais. *Review of 20 years of range sensor development.* Journal of Electronic Imaging, 13(1):231–240, 2004.

[2] Boehler, W. and A. Marbs, 2002. *3D Scanning Instruments,* Proceedings CIPA-ISPRS Workshop on Scanning for Cultural Heritage Recording, Corfu, Greece, pp. 9 – 12.

[3] Boehler, W., et al, 2003. *Investigating Laser Scanner Accuracy,* Proceedings XIXth CIPA Symposium, Antalya, Turkey.

[4] Clark, J., and S. Robson, 2004. *Accuracy of Measurements made with a CYRAX 2500 Laser Scanner.* IAPRS, Vol. XXXV(B5), Istanbul, Turkey.

[5] Lester, P.M., 2005. *Visual Communication, Images with Messages,* 4th Edition, Wadsworth Publishing, Belmont.

[6] Lichti, D.D., and M.G. Licht, 2006. E*xperiences with terrestrial laser scanner modelling and accuracy assessment,* IAPRS, Vol. XXXVI(5), Dresden, Germany.

[7] Lindenbergh, R.C., et al, 2005. *Accuracy analysis of the Leica HDS3000 and Feasibility of Tunnel Deformation Monitoring,* IAPRS, Vol. XXXVI (3/W3), Twente, The Netherlands.

[8] Longhurst, R.S. 1957, *Geometrical and Physical Optics,* 2nd edition, Longmans, London.

[9] Teunissen, P.J.G., 2000a. *Adjustment Theory, an introduction*, Delft University Press, Delft.

[10] Rees, W.G., 2001. *Physical principles of Remote Sensing,* 2nd edition, Cambridge University Press, Cambridge.

[11] Wehr, A. en U. Lohr, 1999. *Airborne laser scanning – an introduction and overview*. ISPRS Journal for Photogrammetry and Remote Sensing, 54 (2-3), p 68-82.

Biographical notes

Alexander BUCKSCH is researcher at the Optical and Laser Remote Sensing Chair (DEOS) at the Delft University of Technology. He obtained his Master degree at the BTU Cottbus on surface reconstruction from point clouds. His main research interest is focused on point cloud processing algorithms, which includes the insight into the instruments.

Roderik LINDENBERGH is one of the most recognized mathematicians in the field of Geodesy. After writing a PhD Thesis on limits of Voronoi Diagrams at Utrecht University he joined DEOS in 2004. His research is focused on deformation analysis and on statistical methods for processing large spatial data sets.

Jane VAN REE is a Master Student at the section Optical and Laser Remote Sensing at the Delft University of Technology. She finished successfully her master Thesis in Geomatic under her Promoter Peter Teunissen at the TU Delft in 2006. She is now employed at a surveying company in the Netherlands, and is still active in the field of Terrestrial Laser Scanning.