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**10 ЛЕТ НАЗЕМНОМУ ЛАЗЕРНОМУ СКАНИРОВАНИЮ – ТЕХНОЛОГИЯ, СИСТЕМЫ И ПРИМЕНЕНИЯ**

## Аннотация

После краткого введения в историю лазерного сканирования, которая является достаточно молодой технологий, особое внимание уделяется определению подземных сооружений. До настоящего времени определение рельефа подземных земляных работ (например, водосточные колодцы, водостоки, коллекторы, и т.д.) считалось дорогостоящим и требующим много времени. Очень часто используются огромные рейки и электронные тахеометры. Разрабатывается новая концепция измерений применительно ко многим стандартным техническим средствам. Главным компонентом является лазерный сканер (в данном случае IMAGER 5006i фирмы ZOLLER +FRÖHLICH, Германия), используемый в перевёрнутом состоянии и прикрепленным на штативе со специальным отвесом. Первые исследования оказались многообещающими. Эту концепция применили ко всем лазерным сканерам, которых можно было использовать в перевернутом состоянии. Главные преимущества такого метода по сравнению с существующими - быстрый сбор данных и наличие большего количества информации. Камеральная обработка данных выполняется после проведения работ и не требует много времени.

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**10 YEARS OF TERRESTRIAL LASER SCANNING - TECHNOLOGY, SYSTEMS AND APPLICATIONS**

**Key words**: Laser scanner, Topography of subterranean excavations, IMAGER 5006, Scanner in Upside-down-mode, Hidden Point poles, special pendulum tripod.

## SUMMARY

After a short introduction into the young history of Laser Scanning special attention will be given the determination of subterranean structures. Until now the determination of the topography of subterranean excavations (like gullies, sinks, sewers, etc.) is costly and time-consuming. Very often huge Hidden-Point-Poles are used in conjunction with Total Stations. A new measurement concept is developed with as much standard products as possible: The main component is a Laser Scanner (here IMAGER 5006i from ZOLLER +FRÖHLICH, Germany) used in an upside-down-mode in combination with a special pendulum-tripod. The first investigations are very promising. The concept can be transformed to all laser scanners which can be used in the upside-down-orientation. The big advantage of this method compared to the existing ones: the data collection on site is faster and there is much more information. The time-consuming data processing is realized later on in the office.

## ZUSAMMENFASSUNG

Nach einem kurzen Überblick über die Entwicklung und Technologie des terrestrischen Laser Scanning wird eine spezielle Anwendung vorgestellt und näher untersucht: Die Erfassung kleinräumiger unterirdischer Hohlräume:

Zur geometrisch gesamthaften Erfassung kleiner unterirdischer Schachtanlagen wurde ein Messsystem, das aus möglichst serienmäßigen Komponenten bestehen soll, bis zur Serien-reife entwickelt. Hauptbestandteil ist ein Panoramascanner im „Überkopfbetrieb“ in Kombination mit einem spez. Pendelstativ. Die Versuche wurden mit einem Z+F IMAGER® 5006i von Zoller + Fröhlich durchgeführt. Das Messkonzept ist jedoch grundsätzlich auf alle Scanner dieses Typs übertragbar, sofern ein Überkopfbetrieb möglich ist. Nach der Beschreibung der grundsätzlichen Ausgangssituation, werden das Messkonzept sowie die Ergebnisse erster Testmessungen vorgestellt.

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## 1. TERRESTRIAL LASER SCANNER – HISTORY, TYPES AND METHODS

The first Laser Scanners appeared on the market about 15 years ago. The company who was first on the market cannot be determined exactly. RIEGL (Austria) and CYRAX (USA) were certainly two pioneers in the field of terrestrial Laser Scanning.


Cyrax time-of-flight range scanner

**Fig. 1a**: The first CYRAX-Scanner

**Fig. 1b**: The first RIEGL Scanner LMS Z 210

### 1.1 Classification of Terrestrial Laser Scanner

Until now Laser Scanner are classified in two different ways:

a. The Distance Measurement Technique. Very similar to Total Stations the Scanners are using phase based methods and pulse based methods in order to determine the distance to the object without an artificial reflector. Pulse based systems assure a wide measurement range, but they are compared to phase based instruments much slower. In contradiction the phase based techniques do allow a high measurement frequency but are limited in the range (distance to object).

b. The Type of Beam Deflection. Each laser Scanner has an individual Beam deflection system. There are three different types, leading to Camera, Hybrid- and Panorama-Scanners (Fig. 2). The Panorama-Type has the biggest Field-of-View (FOV) which is especially useful for indoor situations.

With the current generation of Laser Scanners the difference in "measurement frequency versus range" between the two types (a) are becoming smaller. Pulse based instruments are nowadays fast (100 kHz), while the achievable range of phase based systems is close to 200m.

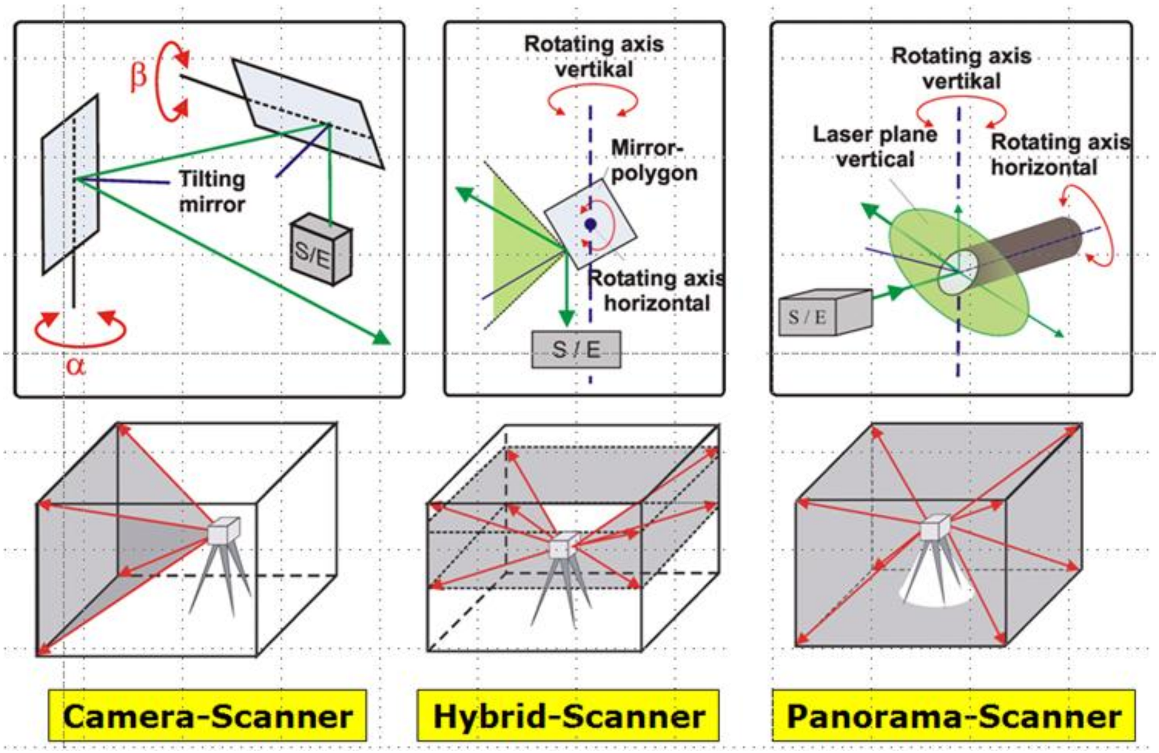


**Fig. 2**: Classification of Terrestrial Laser Scanner by the type of beam deflection

## 1.2 Historical Development of Terrestrial Laser Scanner (TLS)

Since the appearance of the first Laser scanners on the market, dramatic improvements in terms of measurement speed, accuracy and general usability can be observed during the last 10 years. This process of technical progress will certainly continue during the upcoming years. At the same time all systems became smaller, easier to handle and less expensive. Although the existing systems are already very well engineered and real world solutions, the technical progress will nevertheless be continued. The development as such can be roughly categorized into 4 phases or generations:

- 1st generation (from 1997): The instruments are bulky, look like prototypes and the data storage and the power supply were external. The measurement frequency is between 1 and 5 kHz within a range of 50 to 200m. All systems are pulse based. Typical representatives are: CYRAX 2200, RIEGL LMS Z210.

- 2nd generation (from 2002): The data storage and the power supply are still outside of the instrument, but the systems become faster. The first phase based systems appear on the market. Typical representatives are: CALLIDUS, CYRAX 2500, ZOLLER + FRÖHLICH IMAGER 5003.

- 3rd generation (from 2007): The manufacturers start integrating the data storage and the power supply into the instrument. The range and the measurement speed are improved. Digital images are more and more combined with point clouds. Forced centering systems and reflectors or GNSS-antennas on top of the instruments show a closer cooperation with traditional surveying methods. Typical representatives are: FARO PHOTON, ISITE 4400, LEICA SCAN STATION, RIEGL LMS Z-420i, ZOLLER + FRÖHLICH IMAGER 5006.

- 4th generation (from 2009): The data storage and the power are fully integrated. The camera is also part of the acquisition and data treatment process. RIEGL introduced the Full-Wave-Form-Analysis, allowing the detection of multiple echoes in one measurement. In addition the performance in terms of measurement speed and range is again improved. Typical representatives are: FARO FOCUS, RIEGL, VZ 400, ZOLLER + FRÖHLICH IMAGER 5010.

## 2. THE DETERMINATION OF SUBTERRANEAN STRUCTURES

In Germany there are millions of small sized sewers, embedded in the urban road system, mainly for waste and rain water purposes. There is an increasing demand for geometrical information about these buildings, because of their age there is a general need for refurbishment. Until now the geometry of these excavations are measured from inside or from outside with a Total Station and a huge hidden point bar. The effort is big and the final results are just some representative points with mediocre accuracy.

In this publication we will develop a new method, which is replacing the existing one with a surface sweeping method. Instead of some representative points we obtain by the data acquisition with a Laser Scanner a huge amount of geometrical information..

### 2.1 What is needed?

Description of the Measurement Task: sewers typical for roads and canals (horizontal dimensions: 10 x 10m, depth 5 to 10 m). The sewer is accessible very often by a hole, which is typically round with a diameter of about 60-80 cm. The general requirements are:

1. The measurement should be executed from “above” or in other words: the personnel should not climb into the cavern.
2. The time for data acquisition should be not longer than 30 Minutes per hole.
3. The equipment should be robust, easy to transport and not expensive.
4. The data acquisition should be done by 1 person

Such a system would have several advantages compared to the existing method

1. The risk of personal damages (pit falls, poisoning gas, …) is small.
2. There is no need for special security personnel when there is no need to climb into the building.
3. The information we can acquire is much more detailed.
4. The data processing can be realized later in the office in a save and more comfortable environment.
5. The data processing can be performed in different steps of density (scalable effort) without any loss of information.

## 3. THE CONCEPT OF THE MEASUREMENT SYSTEM

The sewer will be digitized with a Laser Scanner. The resulting point cloud should be transformed afterwards into the known reference coordinate system from over ground. There-fore the position and orientation of the laser scanner is needed for the measurement time. Analyzing the entire task it becomes clear, that this process of Georeferencing (= transformation into the given coordinate system) is the most critical part of the entire task.

### 3.1 Georeferencing of the Scanner in the manhole

The Swiss Federal Institute of Zurich (Switzerland) developed a special Scanner (KMS) for the acquisition of sewers (manholes, shafts,… ). The main components are a line scanner LMS 200 (SICK, Germany) combined with a rotating module, which was designed and built by the Institute itself. This prototype allows the generation of 3D point clouds. In conjunction with this measurement system two different strategies for the Georeferencing were followed.

1. The scanner hangs under a rigid pendulum tripod, which is on the upper side attached to a horizontal bar, which is equipped with two reflectors (comparable to a subtense bar). The 3D position of the two reflectors is known relative to the position and orientation of the scanner. This means: If the positions of the reflectors are determined with a Total Station, the position and orientation of the scanner in the given coordinate system is also known.

2. If there are prior information about the horizontal orientation of parts of the sewer (like the horizontal orientation of a drain or sluice, the Georeferencing of the point cloud can be realized without additional measurements.

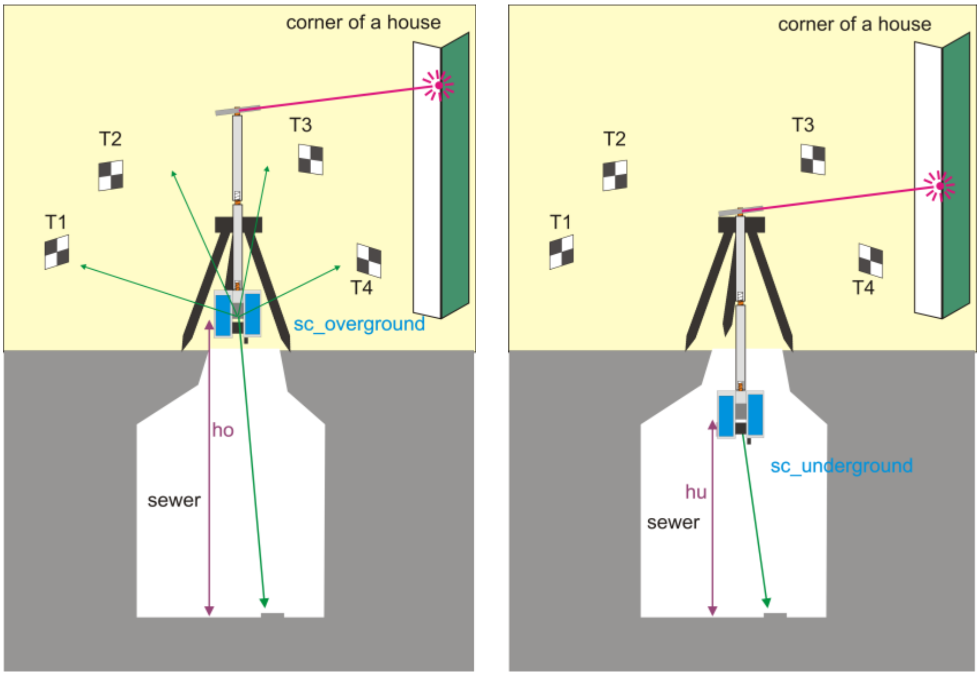


**Fig. 3a**: Scan position over ground

**Fig. 3b**: Scan position underground

Here a third method is suggested and proposed:

3. The scanner hangs in a „upside-down position" under a free pendulum which is fixed by a traditional tripod (Fig. 5).
   In a first step a scan over ground is performed. When there known points (targets) in the point cloud (Fig. 3a), the Position and Orientation of the instrument can be determined. In addition the horizontal orientation of the scanner is fixed with the means of a special Laser pointer (Fig. 4). Before the scan the Laser pointer is oriented towards a vertical reference line, like the vertical line defined by the corner of a house.

   After the lowering of the scanner into the sewer, the horizontal orientation is re-established by pointing with the laser pointer to the same vertical line. In this case both scans have the same horizontal orientation and position. The height difference of the two points of views can be detected directly in the corresponding point clouds.

### 3.2 Measurement Equipment

The measurement equipment consists of a simple laser pointer (special construction, Fig. 4), a Laser scanner IMAGER 5006 from ZOLLER + FRÖHLICH and a special pendulum tripod (Fig. 5), which is until now a prototype from Gottlieb NESTLE (Germany).


**Fig. 4a**: Laser pointer on the top of the tube elements


**Fig. 4b:** Laser pointer with a mechanical fixation for the inclination angle

### 3.3 Principal Sequence of a Measurement

In most of the cases the acquired point clouds should be georeferenced. Therefore a scan over ground is necessary, including some known points (targets). After the scan over ground - also executed in the up-side down mode - the scanner is lowered into the underground position (Fig. 7). The lowering itself can be handled with a mechanical or electrical crank.


**Fig. 5a**: Scanner in „upside-down-mode“

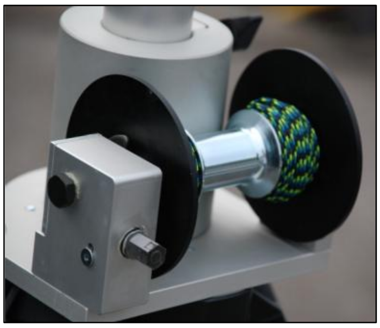
**Fig. 5b**: Elevation component of the tripod

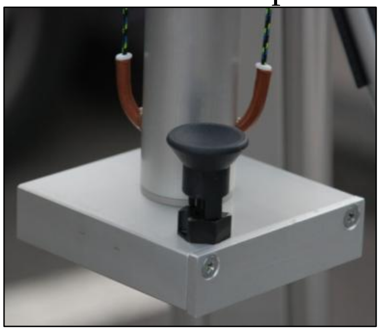
**Fig. 5c:** Adapter plate for the Scanner

The horizontal position and the horizontal orientation of the scanner do not change between the over ground and underground position. The only remaining unknown value is the height difference between both scans: it will be determined later on during the data processing via a direct comparison of the z-component in the two point clouds. The result is a georeferenced point cloud of the sewer.

## 4. PRELIMINARY INVESTIGATIONS

First of all this method was evaluated in terms of functionality and accuracy. Several tests were made at the University of Applied Sciences Bochum, by simulating the manhole-situation.

### 4.1 Feasibility Study - Outdoor

Directly in front of the Laboratory for Laser Scanning a hole was made into the balcony in order to simulate the manhole. This allowed simulations up to a height difference of about 4m (Fig. 6).

**Fig. 6:** Measurement of the rotation of the scanner with auto collimation

The biggest advantage of this simulation is the combination of the over ground and underground scans by identical targets. This is in the real situation not possible. Here it is the key element for an independent evaluation of the real budget of measurement uncertainties.
Scans in three different depths were performed. During the scans the scanner position was continuously determined with a Laser Tracker (T3 from API, USA). The accuracy of the determination was better than 0.1mm (1 $\sigma$).

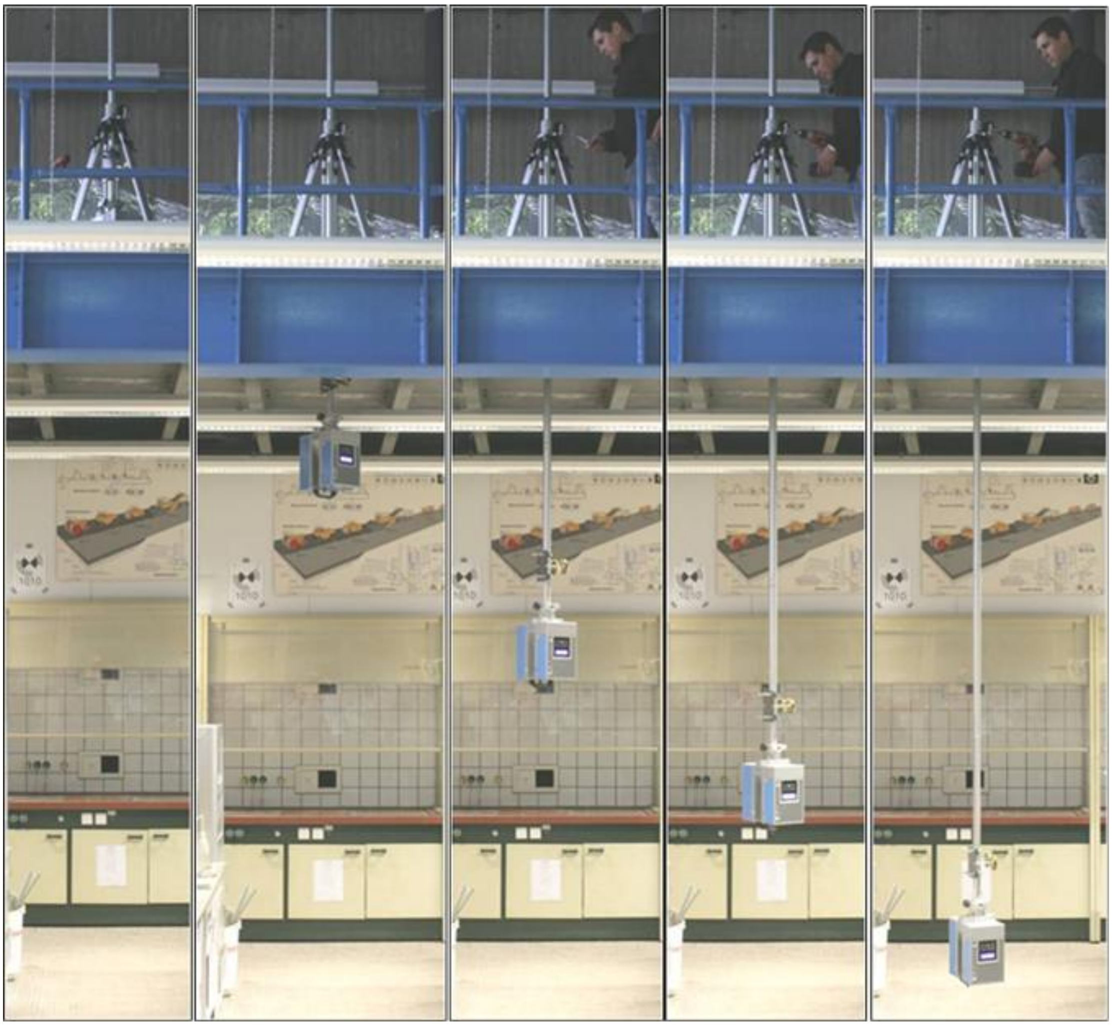

**Fig. 7**: Sequence of a measurement – the sewer is simulated by a hole in the balcony

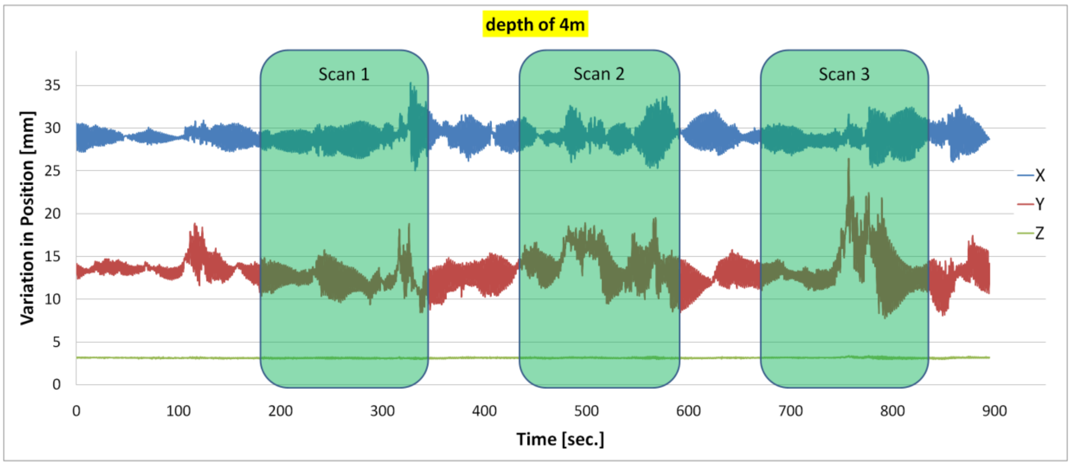


**Fig. 8**: Stability of the position of the Laser Scanner during the scans

The changes in position show a magnitude of 10 millimeters. For the height there are nearly no variations.

The horizontal (X) and vertical (Y) rotations were additionally observed during the scans with an auto collimator (ELCOMAT 2000, MÖLLER-WEDEL, Germany). The results are displayed in Fig. 9.

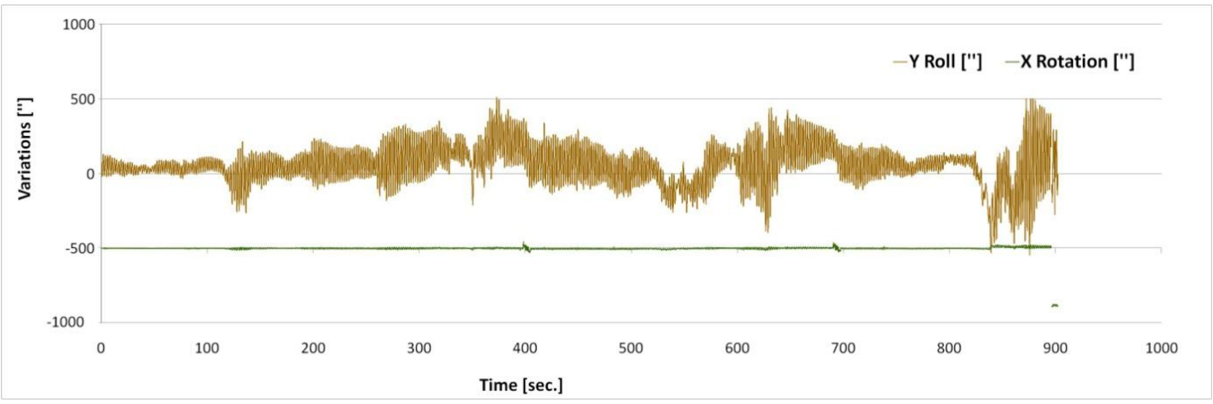


**Fig. 9**: Rotation angles during 1 Scan – observed with autocollimator ELCOMAT 2000.

The rotations about the vertical axis (horizontal changes) were very small, compared to the rotations about the horizontal axes.

In Fig. 10 two images of the same target in the object space are shown. Fig. 8a shows a geometrically stable point cloud from the over ground position. In contradiction Fig. 10b: The dark and bright segments of the targets are separated in reality by straight lines. The undulated lines indicate periodic rotations of the scanner during the data acquisition.

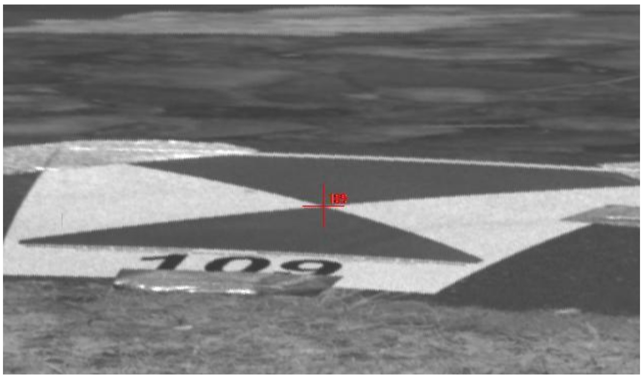

**Fig. 10a**: from over ground position

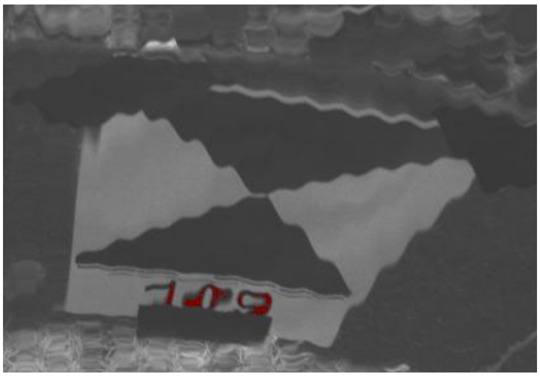

**Fig. 10b**: from lowest underground position

As a first result we can conclude: in principle the scanner is working in the upside-down mode and also in conjunction with the special tripod. The underground positions of the scanner are not stable enough during the scans. As a consequence it was decided to make a second test in an indoor environment.

## 4.2 Feasibility Study - Indoor

The second feasibility study was conducted in an indoor environment. The situation was simulated again with an artificial hole in the balcony of one of our laboratories (Fig. 7). In this environment 25 Auto-targets from ZOLLER + FRÖHLICH were used for the independent accuracy estimation.

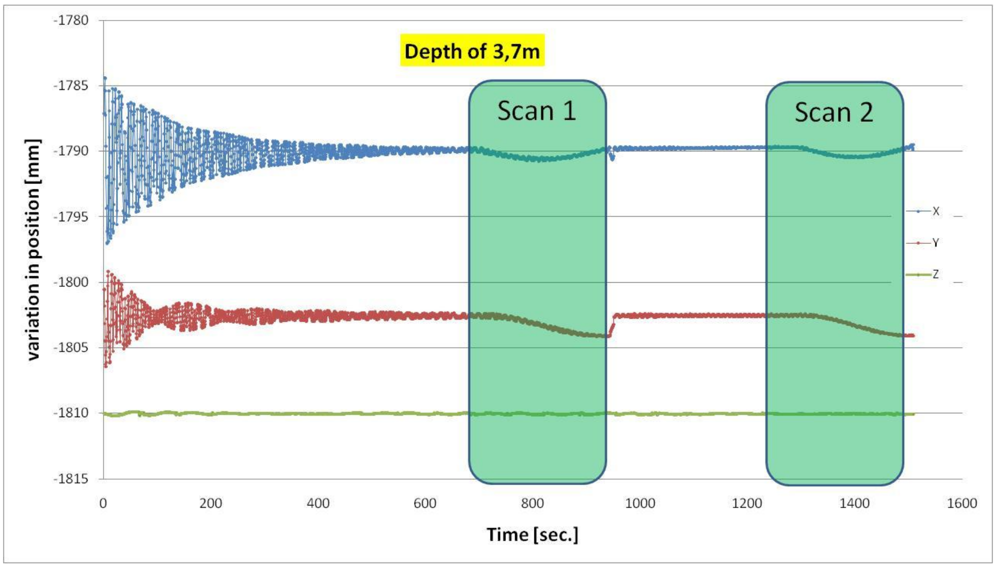


**Fig. 11**: Proper movement of the scanner in a depth of 3.7m

The proper movements of the scanner were much smaller compared to the first outdoor study. Fig. 11 shows the position displacement during several scans. One important result is: The movements in the lowest position show - after a period of initial damping - residuals of some Millimeters. The asymmetric behavior during the real data acquisition can be caused by a slightly asymmetric mass distribution in the scanner itself.

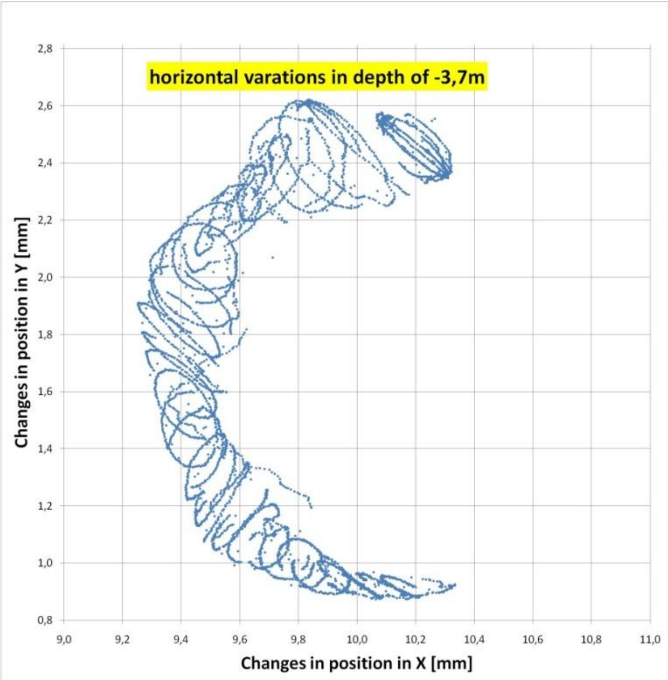


**Fig. 12**: Horizontal displacements of the scanner during 1 scan (3m19s).

Fig. 12 is representing the horizontal displacements during one active scan (3m19s). On a first view the displacements are looking dramatic, but the magnitude of the variations is overall smaller than 2 mm for each direction.

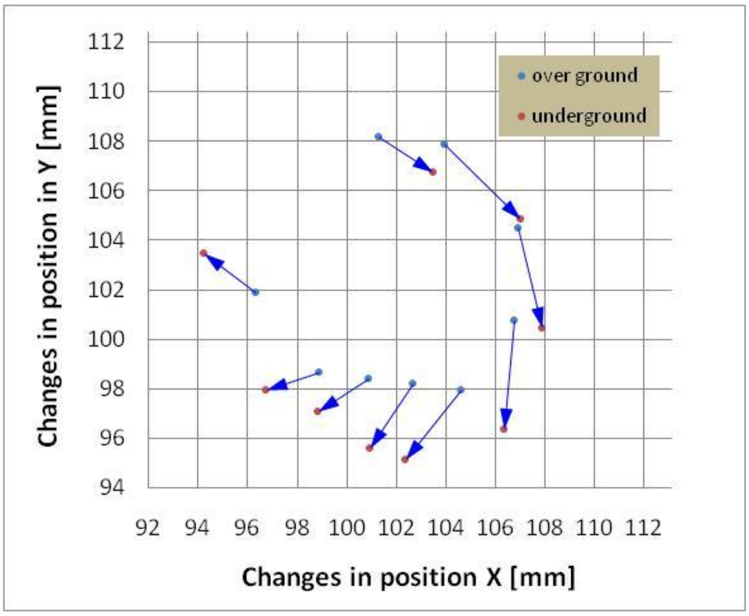


**Fig. 13**: Deviations of the horizontal orientation as vector plot between the 2 scans.

In order to investigate the quality of the horizontal orientation a real registration was compared with the known nominal values. The plot of vectors shows the results (Fig. 13).

## 5. CONCLUSIONS

With this method we can measure and determine the geometry of small sized subterranean structures, like manholes, sewers, shafts, etc. without climbing into the building. An accuracy of 1 to 3cm horizontal and vertical is achievable. The significant differences in the quality and accuracy of the measurements between the indoor and the outdoor study were mainly caused by wind during the outdoor experiments.

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