

# **Adaptive Extended Kalman Filter for Geo-Referencing of a TLS-Based Multi-Sensor-System**

**Jens-André PAFFENHOLZ, Hamza ALKHATIB and Hansjörg KUTTERER, Germany**

**Key words:** terrestrial laser scanning, geo-referencing, extended Kalman filter

## **SUMMARY**

This paper works on an adaptive extended Kalman filter (AEKF) approach for geo-referencing tasks for a multi-sensor system (MSS). The MSS is built up by a sensor fusion of a phase-based terrestrial laser scanner (TLS) with navigation sensors such as, e.g., Global Navigation Satellite System (GNSS) equipment and inclinometers. The position and orientation of the MSS are the main parameters which are constant per station and will be derived by a Kalman filtering process. However, by inclinometer measurements the spatial rotation angles about the X- and Y-axis of the fixed MSS station can be respected in the AEKF. This makes it possible to respect all 6 degrees of freedom of the transformation from a sensor-defined to a global coordinate system. The paper gives a detailed discussion of the strategy for the direct geo-referencing. The AEKF for the transformation parameters estimation is presented with the focus on the modeling of the MSS motion. The potential of the strategy will be shown by practical investigations as well as an overview about the observation and GNSS analysis strategy will be given.

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## 1. INTRODUCTION

The characteristic of the terrestrial laser scanning technique established nowadays in the engineering geodesy is the immediate data acquisition in 3D space. This is realized with a high spatial resolution as well as with a very high frequency in a relative or local sensor-defined coordinate system, respectively. The terrestrial laser scanning technique can be divided into static and kinematic scanning. The static scanning is characterized by one single fixed translation and orientation of the terrestrial laser scanner (TLS) in relation to an absolute or global coordinate system. For the kinematic scanning, where the data acquisition is commonly reduced to 2D profiles, the translation and orientation is time-dependent. Hence the transformation parameters for each profile are different in relation to each other as well as to an absolute or global coordinate system. Typically the transformation parameters are observed by navigation sensors and are estimated in a Kalman filtering process [Vennegeerts et al., 2008].

These properties –the observation of transformation parameters and the Kalman filtering process– will be transferred to the static scanning domain for registration and geo-referencing tasks of 3D laser scans. Whenever a combination of several scans from different stations into one coordinate system (registration) is required, the transformation parameters for each scan have to be estimated. These parameters can be estimated by iterative algorithms, e.g., the Iterative Closest Point (ICP) algorithm [Besl & McKay, 1992], or by identifying several artificial control points in each scan. For an additional link to an absolute or global coordinate system (geo-referencing), control points with a known geodetic datum are indispensable. In case of the geodetic datum of the control points has also to be determined, the procedure would be complex and time-consuming due to an extra and independent surveying.

It is possible, however, to transfer the above mentioned properties from the kinematic scanning domain to the static scanning. First there is the direct observation of the position and orientation, which can be derived by the orbital motion of the fixed laser scanner station. Therefore a multi-sensor system (MSS) is created by a laser scanner and navigation sensors, which is comparable to the setup of a MSS for kinematic scanning applications, called mobile mapping system [Vennegeerts et al., 2008]. Afterwards a Kalman filtering process is initiated for the estimation of the transformation parameters, which are constant for the whole 3D laser scan. These parameters may also be used as appropriate start values with variance information for iterative algorithms for registration tasks without the need of any control points.

This short introduction shows already that the direct geo-referencing of static 3D laser scans offers a number of great advantages over the traditional way by using control points.

The paper is organized as follows. Section 2 describes the strategy for the direct geo-referencing of a TLS-based MSS as well as the anew developed algorithm for estimation of the transformation parameters. Section 3 briefly introduces the adaptive extended Kalman filter (AEKF) for direct geo-referencing with its two main components: the kinematic equation of the state and the measurements equation. Practical investigations of the anew algorithm are presented in Section 4. Finally, Section 5 summarizes the results and gives an outlook for future work.

## **2. STRATEGY FOR THE DIRECT GEO-REFERENCING OF A TLS-BASED MSS**

In Section 1 the idea of a TLS-based MSS for direct geo-referencing purposes was briefly outlined. The main aim of the direct geo-referencing strategy is the direct observation of the required transformation parameters from the local sensor-defined coordinate system, given by the MSS, to a global coordinate system. This 3D transformation is defined by a translation vector, which is equal to the position of the MSS, and a rotation matrix, which contains the orientation of the three axes of the MSS, comparable to roll, pitch and yaw angle known from aeronautics. One can sum up that this transformation has at least 6 degrees of freedom (dof) which have to be observed and estimated, respectively. However, 4 of the 6 dof, the position vector as well as the azimuthal orientation (yaw), are essential. Because of the fixed terrestrial MSS, which can be orientated to the center of gravity, the spatial rotations (roll and pitch) about the X- and Y-axis of the MSS can be minimized.

In the following the strategy for the direct geo-referencing of a TLS-based MSS, which is realized as an adapted sensor-driven method at the Geodetic Institute of the Leibniz Universität Hannover (GIH), will be described. The strategy can be divided into a sensor fusion part and a part which deals with the algorithm for the estimation of the transformation parameters.

### **2.1 Sensor fusion in the MSS**

As already mentioned, the MSS is established by a sensor fusion of a phase-based TLS, which is the main sensor, and other additional navigation sensors to observe the transformation parameters. While creating the MSS, several terms have to be considered. So the operation of the laser scanner should neither be restricted nor disturbed by any of the enlisted additional sensors. Hence, one should take advantage of the individual characteristic of any sensor. Here one can point out the usage of the constant rotation of the laser scanner about its vertical axis as time and orientation reference. Due to the TLS characteristic of a high frequency data acquisition rate with in general more than 10 Hz for the used phase-based TLS as well as to get reliable transformation parameters, the availability of data rates of at least 10 Hz for the additional sensors is required. Indispensable in the MSS is the synchronization of all different sensors so that the individual measurements could be set in a temporal relationship to each other. Therefore it is useful to introduce one unique time reference in the MSS. The most suitable way in this MSS is to use the GPS time as reference because it is instantaneously available due to the GNSS observations.

The minimum number for additional sensors is one GNSS equipment. The case of mounting two GNSS antennas on top of the laser scanner leads to different approaches within the scope of the GNSS analysis which will be discussed later on. Nevertheless, if one or two GNSS antennas are used, the trajectory of an antenna reference point (ARP) is a space curve which is described by the orbital motion of the laser scanner. For the first realization of a MSS for direct geo-referencing at the GIH only GNSS equipment was used. This leads to the fact that only 4 of the 6 dof are determinable. Additionally, a horizontally mounted MSS is assumed and any residual divergence of the orientation to the center of gravity will be neglected. For further details, especially about the time synchronization in the MSS, please refer to [Paffenholz & Kutterer, 2008].

In order to optimize the direct geo-referencing strategy, some sensor modifications in the MSS were carried out. In a first step the MSS is extended with additional navigation sensors – inclinometers– to estimate the remaining 2 dof (the spatial rotations about the X- and Y-axis of the MSS). Therefore two single axis inclinometers were mounted next to the GNSS antenna on top of the laser scanner, each of them observing one spatial rotation about the X- and Y- axis, respectively (see Figure 1). For synchronization purposes an external process computer with integrated analogous-digital (A/D) converter is used. The topic of ongoing investigations is to use the integrated inclinometer in the new laser scanner series. The challenge of using the integrated inclinometers is the synchronization of the data because a parallel way of synchronization to the external sensors is not possible at the moment.

Another modification of the MSS, unlike the strategy described in [Paffenholz et al., 2009], was performed to the used data sources for the estimation of the transformation parameters. As new input data the horizontal motor steps of the laser scanner were introduced to the algorithm to get measured information about the orbital motion of the laser scanner. The synchronization of this new data source is straightly available by the general synchronization pulse of the laser scanner which corresponds to the progress in the horizontal rotation of the laser scanner about its vertical axis.

The described sensor modification and additionally available data source lead to significant modifications of the algorithm for the estimation of the transformation parameters. In addition, and due to the consideration of all dof of the transformation from the local to the global coordinate system, a more accurate estimation of the unknown parameters is expected.



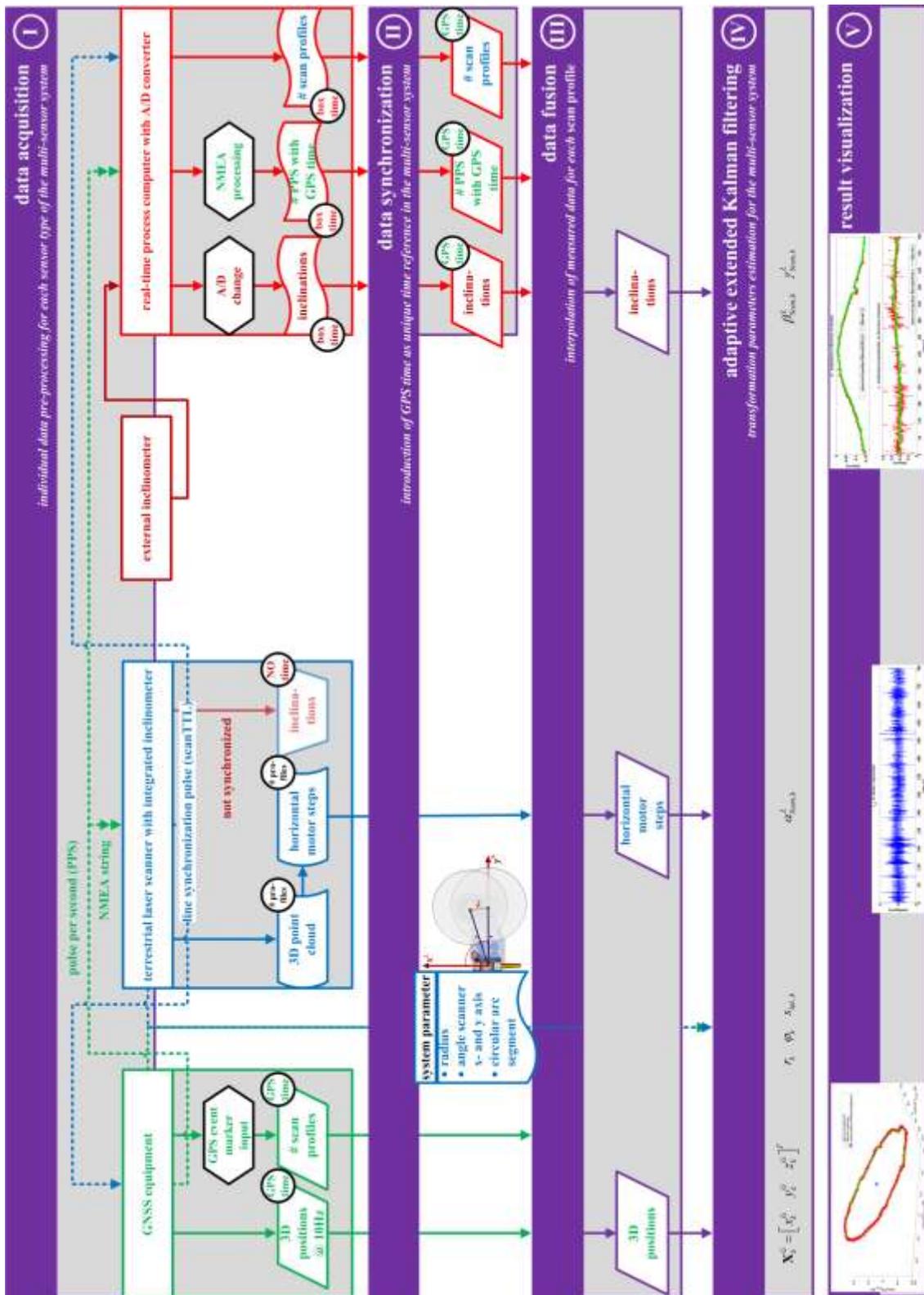
**Figure 1:** Actual setup of the MSS equipped with one GNSS antenna and two external inclinometers on top of a phase-based TLS

## 2.2 Algorithm for estimation of the transformation parameters

The estimation of the transformation parameters according to the first realization of the MSS, which was described in Section 2.1, is done in a two step model. First the 3D positions are projected onto a best-fitting plane and second a best-fitting circle is estimated through the projected positions. These two parameters estimations are computed by means of a least-squares adjustment. Furthermore, in both steps an outlier detection algorithm is performed. In order to derive an azimuthal orientation for each scan line of the 3D laser scan as well as to estimate the position of the MSS, respectively, the space curve parameters (center point and radius), and the adjusted observations are required. For further details please refer to [Paffenholtz & Kutterer, 2008]. The main disadvantage of the above described two step model is that the data acquisition must be finished before the processing steps can be performed. In addition a setup of two separated adjustments with extra outlier detection is needed.

According to the sensor modifications in the MSS and the additionally available data sources, the estimation of all 6 dof of the transformation is possible. This leads to an anew developed analysis strategy with vital modifications of the parameters estimation algorithm. The new algorithm was developed in a closed form on basis of a Kalman filter (KF), which determines the required transformation parameters as an output. This algorithm based on KF resolved the above mentioned drawbacks. On the one side the KF allows a real-time processing. On the other side the parameter estimation will be more robust against outlier. The main aim of a KF is the optimal combination of a given physical information for a system and external observations of its state. In comparison with the algorithm described in [Paffenholtz et al., 2009], the filter setup was modified and optimized on the basis of the first experiences with the anew analysis strategy. This will be discussed in detail in Section 4.

The modeling of trajectories of moving vehicles –the static MSS can be understood as moving vehicle due to the orbital motion of the TLS– often leads to nonlinearities in the system equations of the KF. For example, [Aussems, 1999] describes the trajectory of a vehicle with a refined model of consecutive arcs. This model is comparable to the model for the orbital motion of the TLS, refer to Section 3.1. In both cases the functional relationship between the vehicle as well as the MSS coordinates and the other state parameters is nonlinear [Simon, 2006]. However, the state estimation within a KF is optimal only in case of linear state space systems. The extended Kalman filter (EKF) has a reputation for solving nonlinearities in the system and measurement equations. Further details about the EKF, which is based on an approximation of the nonlinear functions by a Taylor series expansion, can be found in, e.g., [Simon, 2006]. The EKF to estimate the transformation parameters of the MSS is additionally supplemented with adaptive parameters. These parameters are time invariant, system specific parameters with well known initial values. The adaption with additional parameters in the dynamic model might improve the filtering and brings the model closer to reality [Eichhorn, 2007]. However, the EKF with adaptive parameters (AEKF) is well known in common literature as dual estimation, e.g., [Nelson, 2000].



**Figure 2:** Schematic overview of the present strategy from the data acquisition to the estimation of the transformation parameters

### 2.3 Schematic overview of the present strategy

In Figure 2 a schematic overview of the present strategy from the data acquisition to the estimation of the transformation parameters is given. In order to simplify the complex strategy the whole procedure is structured into five parts:

In part I the data acquisition of the MSS is summarized. The four sensor types are the GNSS equipment in green, the terrestrial laser scanner with integrated inclinometer in blue, the external inclinometer in red, and the real-time process computer with A/D converter also in red. For each sensor type an individual pre-processing is performed. For the GNSS equipment the analysis is performed by commercial software, e.g., Wai by Lambert Wanninger or Geonap by Geo++<sup>®</sup>. The line synchronization pulses of the laser scanner, registered with the event marker input, are analyzed with respect to data gaps. The time stamp of the data is already the MSS unique GPS time reference. For the TLS the raw values of the horizontal motor steps are extracted from the stored 3D point cloud. They correspond to the number of 2D profiles within the 3D point cloud as well as to the number of line synchronization pulses. It is also possible to get an on-the-fly access to the horizontal motor steps, which will be realized in the ongoing work. The registered inclinations from the integrated sensor are not processed because of the missing synchronization possibility as already described before. The analogous data stream of the external inclinometers adapted on the laser scanner is processed by the A/D converter of the real-time process computer. All incoming data streams to the real-time process computer are marked with an internal time stamp of the process computer. Besides the inclinations the pulse per second (PPS) signal and a National Marine Electronics Association (NMEA) string, containing the UTC time information of the GNSS receiver, as well as the line synchronization pulses are the input data of the real-time process computer. The data delivered by the GNSS receiver is pre-processed in a way that for each PPS the corresponding GPS time stamp is generated by the UTC information extracted from the NMEA string. The line synchronization pulses are registered twice, once by the GNSS receiver (event marker input) and once by the real-time process computer. The data stored by the GNSS receiver is used for the further data processing and the other data source is used as backup.

In part II the required data synchronization of the MSS is described. As unique time reference for the MSS the GPS time is set. Therefore, the data which is not related to the time reference by a GPS time stamp has to be synchronized. This fact is true for all data streams of the real-time process computer, which are marked with an internal time stamp. The connection between the internal time stamp and the GPS time is established by the data stream of the GNSS receiver. Hence the introduction of the required GPS time stamp for the inclinations as well as for the registered line synchronization pulses (# of scan profiles) is possible.

Up to part III all data sources are marked with the GPS time stamp. In this data fusion step for each 2D profile of the 3D point cloud the corresponding 3D position of the ARP as well as inclination has to be determined. Therefore, the data is interpolated with respect to the time stamp of each 2D profile.

In part IV the core issue of the data analysis is realized. By an AEKF the estimation of the transformation parameters is performed. Besides the already mentioned observations, three system parameters are integrated into the AEKF as adaptive parameters. These time invariant parameters are determined in an independent procedure with high accuracy by a laser tracker. As mentioned before the integration of adaptive parameters in the dynamic model may improve the filtering and brings the model closer to reality. More details about the modeling of the motion of the MSS, the system equations elements, and the measurement model are given in Section 3. The achieved results are discussed in Section 4.

At the current step of the research work part V shows the state parameters estimated by the AEKF as interim result. For the ongoing work in part V the final transformation of the whole 3D point cloud, from the local sensor-defined to a global coordinate system, will be performed.

### 3. AEKF FOR DIRECT GEO-REFERENCING OF A TLS-BASED MSS

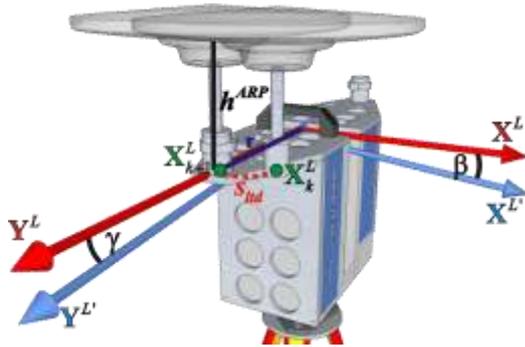
In Section 2 the strategy for the direct geo-referencing of a TLS-based MSS was introduced. This section deals with the algorithm for the estimation of the transformation parameters, which is performed within an AEKF. The idea behind the EKF as well as the background of the integration of adaptive parameters was briefly described in Section 2.2. In the following the modeling of the motion of the MSS and the measurement model will be outlined. The discussion will be focused on the modifications with respect to [Paffenholtz et al., 2009].

#### 3.1 Modeling of the motion of the MSS

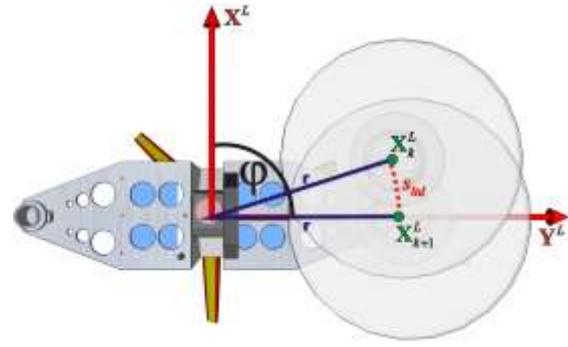
The trajectory of the MSS in 3D space can be parameterized by a circle in 3D space. In comparison to the general trajectory state estimation in engineering geodesy, e.g., [Aussems, 1999], this parameterization is possible due to the orbital motion of the ARP. This orbital motion is caused by the constant rotation of the laser scanner about its vertical axis and the fixed adaption of the GNSS antenna on top of the laser scanner.

The modeling of the motion of the MSS starts with a local sensor-fixed coordinate system with the upper index L (see Figure 3, in red), which is defined by the X- and Y-axis of the laser scanner. In general there will be a residual divergence of the orientation to the center of gravity, which leads to the coordinate system with the upper index L' (see Figure 3, in blue). In order to describe the plane motion of the ARP with respect to the coordinate system L, the residual spatial rotations about the X-axis  $\beta$  –in the scan direction– and about the Y-axis  $\gamma$  -perpendicular to the scan direction– have to be considered. These two residual spatial rotations or inclinations are introduced apart from the global position of the ARP  $\mathbf{X}^G = [x^G \quad y^G \quad z^G]^T$  and the local orientation  $\alpha_{scan}^L$  as state parameters in the AEKF. Figure 4 shows the plane motion of the ARP which is described by the system parameters radius  $r$  and circular arc segment  $s_{td}$ . Next to the radius and circular arc segment the angle between X- and Y-axis  $\varphi$  is introduced as adaptive parameter in the AEKF. These three

system parameters are determined in a system calibration procedure for the MSS by laser tracker measurements.



**Figure 3:** Side view of the plane motion of the ARP and residual divergences  $\beta$  and  $\gamma$  of the orientation to the center of gravity



**Figure 4:** Top view of the plane motion of the ARP and system parameters  $\varphi$ ,  $r$ ,  $s_{ltd}$  (adaptive parameters in the AEKF)

The local plane motion of the ARP, modeled by the state parameters  $\beta$  and  $\gamma$  and the adaptive parameters  $r$  and  $s_{ltd}$  for an epoch  $k$ , is described as:

$$\begin{aligned} \mathbf{X}_{k+1}^L &= \begin{bmatrix} x_{k+1}^L & y_{k+1}^L & z_{k+1}^L \end{bmatrix}^T \\ &= \begin{bmatrix} r_k \cdot \cos(\gamma_{Scan,k}^L) \cdot \sin\left(\frac{s_{ltd,k}}{r_k}\right) & r_k \cdot \cos(\gamma_{Scan,k}^L) \cdot \cos\left(\frac{s_{ltd,k}}{r_k}\right) & s_{ltd,k} \cdot \sin(\beta_{Scan,k}^L) \end{bmatrix}^T. \end{aligned} \quad (1)$$

The expression of the orientation change of the ARP between two epochs is expressed by the circular arc segment divided by the radius. This is in contrast to the former approach described in [Paffenholz et al., 2009], where the orientation change was expressed by the velocity  $v$  and the time interval  $\Delta t$  divided by the radius  $r$ . This parameterization is not suitable because the velocity parameter  $v$  is due to the non-accelerated motion of the MSS not reliably measurable. To avoid the use of pseudo-observations for the velocity parameter, like in the former approach, the orientation change will be expressed by the circular arc segment as already mentioned above.

For the description of the local plane motion of the ARP from one epoch to the next epoch the scanner origin has to be taken in account. Therefore the translation between the actual ARP position and the scanner origin is expressed by:

$$\mathbf{X}_{ScanN,k}^{GNSS} = \begin{bmatrix} -r_k \cdot \cos(\varphi_k) & r_k \cdot \sin(\varphi_k) & h^{ARP} \end{bmatrix}^T. \quad (2)$$

These translations in X- and Y-axis are given by the adaptive parameters radius and angle between the X- (scan direction) and Y-axis (in direction to the mounted GNSS antenna) (see Figure 4). The value for the angle  $\varphi$  depends on the antenna position on the scanner –positive Y-axis as shown in Figure 3 or negative Y-axis– and is nearly 100 gon or 300 gon, respectively. The translation in z-axis  $h^{ARP}$  is given by the antenna height which can already be considered in the GNSS analysis and has then to be set to zero.

To finish the local plane motion description of the ARP, the local orientation  $\alpha_{Scan,k+1}^L$ , which is updated by  $\alpha_{Scan,k+1}^L = \alpha_{Scan,k}^L + \frac{S_{ltd,k}}{r_k}$ , has to be regarded:

$$\Delta \mathbf{X}_{k+1}^L = \mathbf{R}_{ScanN}^L \left( \alpha_{Scan,k}^L \right) \left[ \mathbf{X}_{k+1}^L - \mathbf{X}_{ScanN,k}^{GNSS} \right]. \quad (3)$$

The transformation of the local plane motion given in equation (3) is the last step in modeling of the motion of the ARP in the local coordinate system besides the consideration of the ARP position in the epoch  $k$ :

$$\mathbf{X}_{k+1}^G = \mathbf{X}_k^G + \mathbf{R}_{\alpha^G}^L(\lambda, \phi) \cdot \mathbf{R}_L^{\alpha^G}(\alpha^G) \cdot \Delta \mathbf{X}_{k+1}^L, \quad (4)$$

whereby  $\mathbf{R}_L^{\alpha^G}(\alpha^G)$  defines the global azimuthal orientation and  $\mathbf{R}_{\alpha^G}^L(\lambda, \phi)$  describes the transformation from the local to the global coordinate system. The value for the initial global azimuthal orientation  $\alpha^G$ , the longitude  $\lambda$ , and latitude  $\phi$  of the MSS are calculated as mean values of all trajectory points.

We can conclude that the state vector  $\mathbf{X}_k$  is given as follows:

$$\mathbf{X}_k = \left[ \mathbf{x}_{g,k} \mid \mathbf{x}_{a,k} \right]^T = \left[ \mathbf{X}_k^G \quad \alpha_{Scan,k}^L \quad \beta_{Scan,k}^L \quad \gamma_{Scan,k}^L \mid r_k \quad \phi_k \quad s_{ltd,k} \right]^T \quad (5)$$

with  $\mathbf{x}_{g,k}$  the general state vector and  $\mathbf{x}_{a,k}$  the adaptive state vector.

### 3.2 Measurement model

Observation data from the GNSS equipment and the inclinometers are instantly available, for each epoch. The horizontal motor steps of the laser scanner are indirectly derivable by an extraction procedure from the 3D point cloud. However, this represents no restriction about the current strategy since in general it is possible to get an on-the-fly access to the current horizontal motor step during the scanning process. The linearized measurement equations are:

$$\begin{bmatrix} \overset{-G}{x}_{k+1} \\ \overset{-G}{y}_{k+1} \\ \overset{-G}{z}_{k+1} \\ \overset{-L}{\alpha}_{Scan,k+1} \\ \overset{-L}{\beta}_{Scan,k+1} \\ \overset{-L}{\gamma}_{Scan,k+1} \end{bmatrix} + \begin{bmatrix} \mathcal{E}_{x_{k+1}^G} \\ \mathcal{E}_{y_{k+1}^G} \\ \mathcal{E}_{z_{k+1}^G} \\ \mathcal{E}_{\alpha_{Scan,k+1}^L} \\ \mathcal{E}_{\beta_{Scan,k+1}^L} \\ \mathcal{E}_{\gamma_{Scan,k+1}^L} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{I}{6 \times 6} & -\frac{S_{ltd,k+1}}{r_{k+1}} & 0 & 1/r_{k+1} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} x_{k+1}^G \\ y_{k+1}^G \\ z_{k+1}^G \\ \alpha_{Scan,k+1}^L \\ \beta_{Scan,k+1}^L \\ \gamma_{Scan,k+1}^L \\ r_{k+1} \\ \phi_{k+1} \\ s_{ltd,k+1} \end{bmatrix}, \quad (6)$$

where  $\bar{\mathbf{X}}^G = \begin{bmatrix} \overset{-G}{x} & \overset{-G}{y} & \overset{-G}{z} \end{bmatrix}^T$  is the observation vector of the GNSS position,  $\bar{\alpha}_{Scan}^L$  is the value of the horizontal motor step of the laser scanner, and  $\bar{\beta}_{Scan}^L$  and  $\bar{\gamma}_{Scan}^L$  are the measurements of the inclination sensors.

## 4. PRACTICAL INVESTIGATIONS OF THE ANEW DEVELOPED ALGORITHM

This section treats the practical investigations of the anew developed algorithm and is structured into three parts. First, the observations strategy of the practical investigations is discussed. Second, a brief overview of the GNSS analysis is given. Third, an example dataset is studied. In contrast to the numerical investigations in [Paffenholtz et al., 2009] the results of the practical measurements with the MSS setup in Figure 1 are discussed here. The measurements were performed in front of the GIH building using only one fixed station. The preliminary results of the TLS-based MSS, such as the state parameters, are discussed.

### 4.1 Observation strategy for the practical investigations

In the present strategy only one GNSS equipment is used to observe the orbital motion of the MSS. The simultaneously captured data of all sensors, which were already described in Section 2.3, is the only environment-specific input data for the AEKF. The adaptive parameters are estimated in a calibration procedure under laboratory conditions with a laser tracker. The required values for the connection of the local and the global coordinate system are calculated by the kinematic GNSS observations. For the longitude and latitude this a feasible solution due to the huge number of 3D positions. The absolute orientation is also determinable in this way but the reliability of the result is not optimal. One can get results for a metric uncertainty caused by the global azimuth in a range of a few centimeters in a distance of about 35 m [Paffenholtz & Kutterer, 2008].

In order to improve the result of the global azimuth, a modified observation strategy will be performed for the upcoming practical investigations. In other words, this means to realize initialization measurements before the further data acquisition will start, and to use two GNSS antennas on top of the laser scanner. Within the initialization measurements, rapid-static GNSS observations should be done only at a minor number of predefined positions. It is expected to derive a more reliable global azimuth information by these positions.

Another modification of the observation strategy affects the inclination information about the X- and Y-axis of the MSS. However, it could be an alternative way to get reliable inclinations to carry out also measurements with the inclinometers at a minor number of predefined positions. Afterwards a representative function for the inclination plane of the MSS can be derived, which can be used instead or parallel to the inclinometer measurements during the scanning process.

### 4.2 GNSS analysis strategy

The kinematic GNSS analysis strategy depends on the number of used GNSS equipments (receiver and antenna) in the MSS. Each ARP describes a space curve due to the orbital motion of the laser scanner. The current setup of the MSS consists of one GNSS equipment which operates with a data acquisition rate of 10 Hz. If two GNSS equipments are used in the MSS, the GNSS analysis can be done in two different ways. One way is the calculation of one single baseline for each equipment. The combination of the two ARP trajectories has then to

be realized in the subsequent filter algorithm. The other way is the calculation of a relative baseline between the two GNSS antennas installed on top of the laser scanner. Within the filter algorithm there is no combination step necessary. Apart from the 3D positions of the ARP trajectory the corresponding variance-covariance matrices are regarded within the filter algorithm to derive the position and especially the orientation of the MSS.

For the kinematic GNSS data processing several approaches are possible. The common characteristic of all three approaches is the data post-processing. In addition a GNSS reference station is required to obtain precise 3D positions for the orbital motion of the ARP as well as for an additional transformation to a global coordinate system. Also a real-time processing would be possible. The consequence will be higher variances for the 3D positions. The three post-processing approaches differ with regard to the used GNSS reference station which could be: a) a commercially running reference station, e.g., of the *German reference station network SAPOS*, b) an own temporal reference station positioned on a physical point with known coordinates nearby the scanning scene, and c) a virtual reference station close to the scanning scene calculated by at least three reference stations of approach a).

#### 4.2.1 Brief discussion of the error budget of the GNSS component

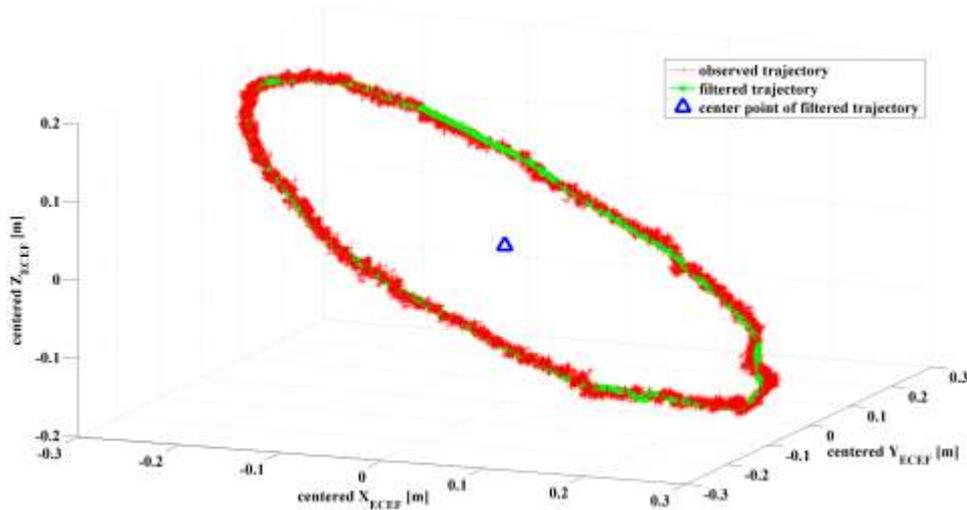
The 3D positions and their variances are of great importance for the quality of the position and orientation information of the MSS. On the one hand the error budget of the GNSS components in combination with the environment has to be considered. These are errors like near-field effects caused by the antenna adaption made of aluminum on the laser scanner or possibly multipath effects. Also the data acquisition principle within the MSS has to be considered with respect to the orbital motion of the laser scanner. This could affect another error caused by the alternating antenna orientation. Here a solution may be reached by the introduction of azimuthal dependent phase center variations. On the other hand the kinematic GNSS data processing itself has an effect on the quality of the 3D positions and on the derived position and orientation for the MSS.

### 4.3 Example dataset

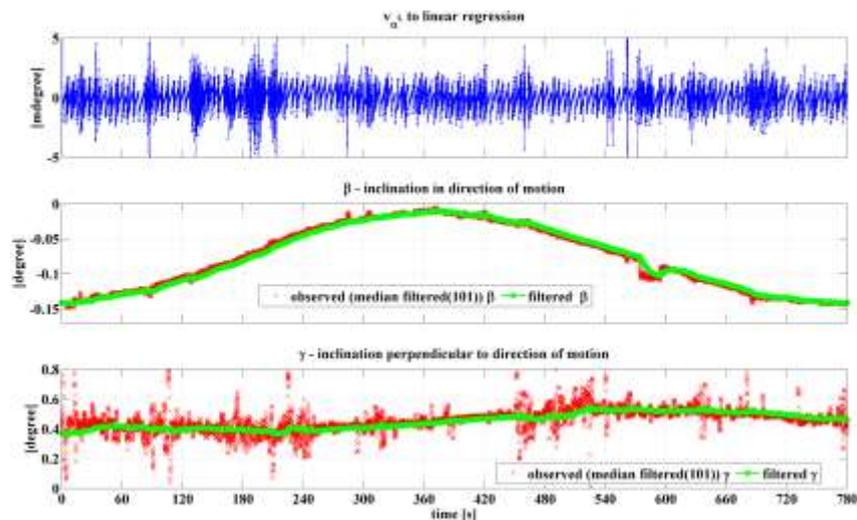
Figure 5 and Figure 6 present a subsample of the estimated state parameters by the AEKF, which was discussed in detail in Section 3. The elements of the matrix of process noise in the AEKF are rather pessimistic values mainly based on experiences with the different sensors and the first practical datasets. One main topic of the ongoing research work is to get a better understanding of the process noise and to perform a variance component estimation to improve the filtering results. For the data acquisition a phase-based laser scanner *Zoller+Fröhlich Imager 5006*, one *Trimble* GPS receiver *R5700* with *Geodetic Zephyr* antenna and two *Schaevitz LSOC-1°* inclinometers were used.

In Figure 5 the filter effect is clearly visible for the first three state parameters in an Earth Centered, Earth Fixed (ECEF) coordinate system. The blue triangle in the middle of the trajectory represents the center point of the filtered positions or translation vector of the MSS, respectively. In the upper part of Figure 6 the residuals obtained within a linear regression of the local orientation  $\alpha^L$  are shown. Due to the constant rotation of the TLS about its vertical

axis, we expect a linear relationship between  $\alpha^L$  and time. Therefore, the residuals are quality indicators. The oscillations of the residuals as well as their quantity could be explained with the resolution of the horizontal motor. This will be investigated in the future. In the lower part the filter effect is clearly visible for the filtered inclinations. The jump in  $\beta^L$  at the time range 500–600 s is interpreted as error due to the equipment, e.g., wiring, and not due to an incorrect filtering process. This error will not appear in another experiment. The higher noise level for  $\gamma^L$  can be explained due to experiences with the used sensor.



**Figure 5:** Observed and filtered trajectories of the ARP in an ECEF coordinate system



**Figure 6:** Upper part: residuals of the local orientation; lower part: observed and filtered inclinations

Table 1 shows a brief overview of the statistical values of the difference between filtered and observed state vector elements. Please note that for the ARP positions the Euclidean distance

is used as representative value to illustrate the filtering results in the 3D space, whereas for the other components the difference between the filtered and observed value is computed.

**Table 1:** Statistical values of the difference between the filtered and observed state vector

	$\ \mathbf{X}^G - \overline{\mathbf{X}}^G\ $	$\alpha_{Scan}^L - \overline{\alpha}_{Scan}^L$	$\beta_{Scan}^L - \overline{\beta}_{Scan}^L$	$\gamma_{Scan}^L - \overline{\gamma}_{Scan}^L$
min	0.1 mm	-0.0265 °	-0.0150 °	-0.5286 °
max	36.5 mm	0.0219 °	0.0308 °	0.7439 °
mean	5.9 mm	$7.3 \cdot 10^{-7}$ °	$-5.5 \cdot 10^{-6}$ °	-0.0069 °
std	3.4 mm	0.0013 °	0.0040 °	0.0663 °

## 5. CONCLUSIONS AND OUTLOOK

This paper gives an overview about the anew algorithm for the estimation of the transformation parameters, which are required for the direct geo-referencing strategy of terrestrial laser scans at the GIH. It is based on an AEKF which was modified and optimized by contrast with the first approach. So no longer pseudo-observations are required. In addition the horizontal motor steps of the laser scanner were introduced as observation data to improve the filter. In the ongoing work about the current strategy there are future plans to realize the on-the-fly access and to avoid the workaround with the point cloud extraction procedure for the horizontal motor steps. One can sum up that the results of the anew algorithm show the potential of the strategy.

The topics of the ongoing research will be the performing of the complete geo-referencing procedure by the transformation of at least two laser scans of the same scene from different stations and a detailed analysis of the differences for homologous points in the laser scans. In order to get a better understanding of the process noise further investigations are needed, such as performing a variance component estimation. The improvement of the observation strategy with initialization measurements for the global azimuth as well as to obtain an inclination plane will also be a topic of the future work.

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## BIOGRAPHICAL NOTES

**Jens-André Paffenholz** received his Dipl.-Ing. in Geodesy and Geoinformatics at the Leibniz Universität Hannover. Since 2006 he has been research assistant at the Geodetic Institute at the Leibniz Universität Hannover. His main research interests are: terrestrial laser scanning, industrial measurement systems, and process automation of measurement systems. He is active in the Working Group 4.2.3 “Application of Artificial Intelligence in Engineering Geodesy” of the IAG Commission 4 (Positioning and Applications).

**Dr. Hamza Alkhatib** received his Dipl.-Ing. in Geodesy and Geoinformatics at the University of Karlsruhe in 2001 and his Ph.D. in Geodesy and Geoinformatics at the University of Bonn in 2007. Since 2007 he has been postdoctoral fellow at the Geodetic Institute at the Leibniz Universität Hannover. His main research interests are: Bayesian Statistics, Monte Carlo Simulation, Modeling of Measurement Uncertainty, Filtering and Prediction in State Space Models, and Gravity Field Recovery via Satellite Geodesy.

**Prof. Dr. Hansjörg Kutterer** received his Dipl.-Ing. and Ph.D. in Geodesy at the University of Karlsruhe in 1990 and 1993, respectively. Since 2004 he has been a Full Professor at the Geodetic Institute of the Leibniz Universität Hannover. His research areas are: adjustment theory and error models, quality assessment, geodetic monitoring, terrestrial laser scanning, multi sensor systems, and automation of measurement processes. He is active in national and international scientific associations. In 2009 he became a Vice President of the DVW – Gesellschaft für Geodäsie, Geoinformatik und Landmanagement. In addition he is member of the editorial boards of three scientific journals.

## CONTACTS

Jens-André Paffenholz  
Tel. +49 511 762 3191  
Email: paffenholz@gih.uni-hannover.de

Dr. Hamza Alkhatib  
Tel. +49 511 762 2464  
Email: alkhatib@gih.uni-hannover.de

Prof. Dr. Hansjörg Kutterer  
Tel. +49 511 762 2461  
Email: kutterer@gih.uni-hannover.de

Geodätisches Institut  
Leibniz Universität Hannover  
Nienburger Str. 1  
30167 Hannover  
GERMANY  
Webpage: [www.gih.uni-hannover.de](http://www.gih.uni-hannover.de)

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