# CHALLENGES OF KINEMATIC MEASUREMENTS

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**Key words**: Kinematic measurements, kinematic model, dynamic model, automated measurements, synchronisation

## SUMMARY

Most surveyors can operate and manage their instruments if no object or instrument movements occur. But what happens if the instrument or the surveyed object is moving? New problems arise like e.g. synchronisation of the measurements and modeling of the movements. Multi-sensor-systems and their application play an important part for kinematics too. These and other related tasks, investigations and practical solutions are summarized under the term kinematic measurements. They play an important part for the new Working Group 5.4 "Kinematic Measurements" within FIG Commission 5 "Positioning and Measurements".

This contribution will discuss the way from static to kinematic measurements and give definitions for basic terms like synchronization, realtime, kinematics and dynamics. A general definition of the term kinematic measurement task will be given too, taken into account the measurement as well as the evaluation process. Besides new automated measurement instruments and processes the dynamic models for moving objects are of essential importance.

In the last section the author will give exemplary solutions for kinematic measurements like synchronization of total station measurements, realtime positioning for machine guidance, modeling of vehicle movements and automatic GNSS low-cost monitoring.

# CHALLENGES OF KINEMATIC MEASUREMENTS

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## 1. INTRODUCTION

In the past surveyors thought static, while measuring and evaluating measurements. In general it was assumed that a point was not moving. This is true e.g. for real estate measurements or stacking out of traverses or railway lines. The state control network was in general assumed as stable too. This stability theorem was considered to be valid even for monitoring surveys, since during the measurements no object movements were considered. The model for deformation analysis was the so-called identity model that do not takes into account time and acting forces like loading effects or temperature.

This static view of the world begins to be seen as old-fashioned. Different causes lead to this change of mind. One is the improved understanding of the movement behavior, e.g. due to the knowledge of geophysics and the monitoring of plate tectonics it is clear that the coordinates of state survey systems are not stable. The same is true for points on monitored objects. For both applications the availability of automated measurement systems delivering continuous measurement time series is crucial. The second important cause for the necessity of kinematic metrology is the enhanced need for efficient data acquisition. Often kinematic data acquisition e.g. of roads or railway tracks is much faster than the traditional static point determination. The kinematic acquisition may be realized by vehicles, trains, by foot, using Unmanned Aerial Vehicles (UAVs) and airplanes as well as satellites. In this case the movement of the sensor has to be modeled, the acquired object is assumed to be stable. The third cause is the requirement of realtime positions e.g. for control or guidance issues.

## 2. DEFINITION OF KINEMATICS

### 2.1 Metrology

Some years ago kinematic measurement techniques were defined as follows: “Kinematic measurements last from some seconds up to approx. 24 h. Longer measurement periods result in static measurements. Kinematic measurements require continuous operation.” This definition is vague and out-dated. The first point of criticism is the fact that nowadays the separation between classical geodetic instruments and modern electronic measurement techniques does not exist anymore. Nowadays measurement techniques should be called kinematic, if the consideration of time is required due to the movement of the object or the sensor (Foppe et al. 2004).

Since time is of great importance for all kinematic applications and a huge number of these applications requires a so-called realtime reaction, a short discussion of the term realtime in given in the following. In common speech realtime capability means that results are available without time delay. Obviously this is technically impossible. This had lead to a definition which was used for geodetic application in the past: “Realtime capability means the availabil-

ity of results before the next measurement values are acquired." In some situations the definition may hold true, but in general this will lead to the fact that the algorithm will run smoothly, but this will not assure realtime. In the following the author describes an example. If an algorithm determines point velocities within 1 second, this is realtime for monitoring surveys, since the availability of the results is not required faster. In contradiction if the same system is used for a Advanced Driver Assistance System like collision warning for a car running with 150 km per hour on a highway, car velocity is delivered too late (1 s means 42 m in this case) and therefore the realtime requirement is not met. Obviously realtime is defined by the application. The correct definition is given in the following: "Realtime capability means the provision of application-related results at the required point of time with the required quality".
After this excursus the author reverts to kinematic measurement or metrology. Figure 1 summarizes and classifies all possible kinematic measurement tasks according the movement of the sensor or/and the object as well as the status of the trajectory to be determined.

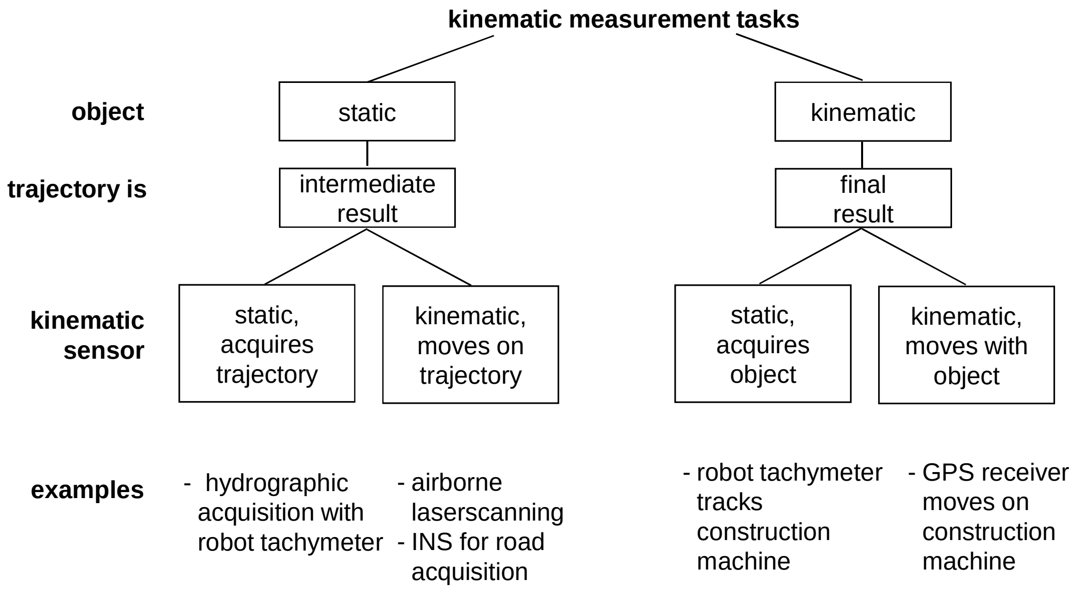


Figure 1: Classification of kinematic measurement tasks (Foppe et al. 2004)

The determination of a trajectory is an indication for kinematic measurements even in the case that the sensor and the object is static. This is the case for the example on the left-most position in figure 1: the hydrographic acquisition of a lake bottom (static object) using a robot tachymeter (static sensor). Here the reflector is moving and therefore describing the trajectory that is an intermediate result only. The other possibilities and examples are not explained in detail and can be taken from figure 1 (here the abbreviation INS stand for inertial navigation system).

## 2.2 Evaluation

Besides kinematic metrology the possibility to evaluate time-dependent measurement using adequate evaluation models is necessary. A possible and physically-justified classification of models is adopted from deformation analysis (Welsch & Heunecke, 2001). The different models are defined with respect to the possibility to built reality by geometry, time and acting forces.

- Identity Model / Congruency Model
  Geometric changes among minimum two points of time are investigated. The point movements are assumed to be zero. Time and acting forces are not considered. An example is the well-known statistical analysis of deformations.
  Static Model
  Static states of an object are investigated with respect to the different acting forces. Time is not considered. As an example a load experiment of a bridge may serve.
- Kinematic Model
  Time-related movements are described without consideration of acting forces. For the modelling more than two points of time are required. The model for the circle movement of a vehicle is an example.
- Dynamic Model
  Here the time-dependent movements are regarded as reactions of the object on the time-dependent acting forces. This is the most realistic picture of reality. A good example is to use the same model then in the kinematic case but introducing the steering angle as acting force.

In general, if someone talks about kinematic measurements, trajectories have to be determined and the evaluation has to use kinematic or dynamic models. Typical methods and techniques are time series analysis, regression and least square adjustment as well as filter techniques, where the Kalman filter is of particular importance (e.g. Kuhlmann, 2004).

### 2.3 General definition

The proceeding sections have dealt with characteristics of kinematic measurements as well as of kinematic and dynamic evaluation. Now the question arises, how a geodetic engineer defines a kinematic task or problem. In the context of this paper all tasks that need minimum one of the two aspects: kinematic measurements and kinematic or dynamic evaluation models. Figure 2 gives an overview including examples for all possible measurement and evaluation combinations. The field of kinematic tasks is framed by a solid line, whereas the purely static tasks are framed by a dotted line. This means that kinematic tasks are static or kinematic measurements evaluated in kinematic or dynamic models. Static evaluation of kinematic measurements do not exist.

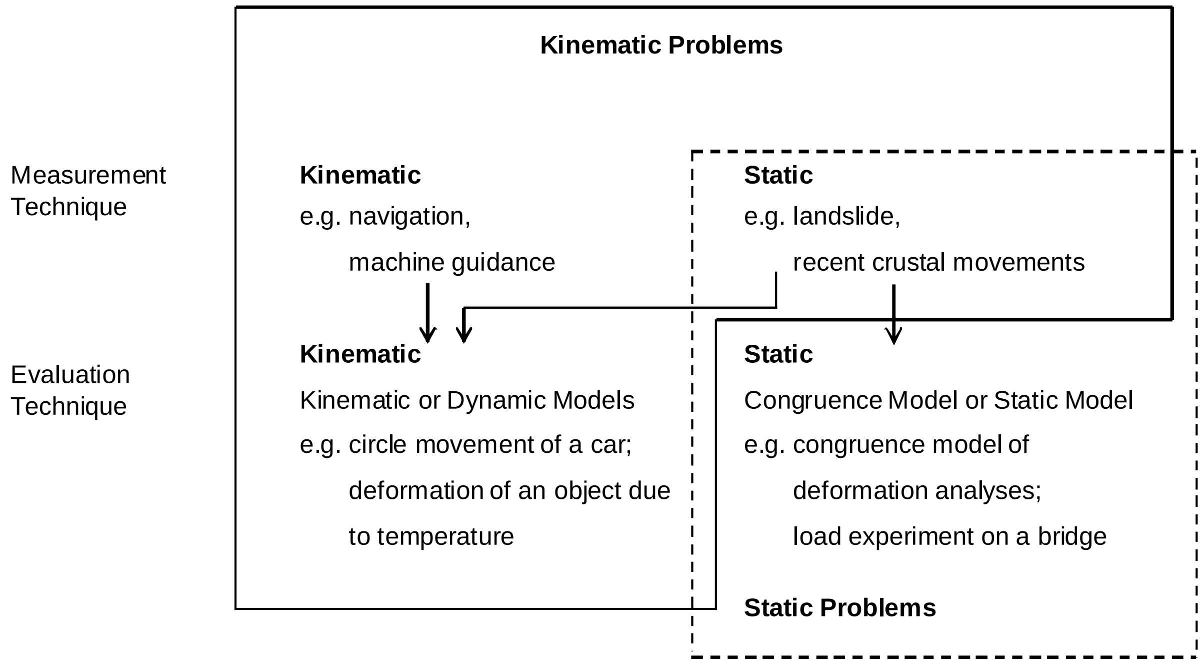


Figure 2: Kinematic and static tasks (Fopp et al. 2004)

## 3. MULTI-SENSOR-SYSTEMS

For several kinematic tasks multi-sensor-systems are required or in any case are very helpful. Since this term is in vogue in numerous disciplines including geodesy some general remarks should be made. Already at this stage the reader should consider that the tachymeter (total station) is one instrument that contains several sensors like distance meter, horizontal and vertical direction measurement, inclinometers, thermometer and much more. This means that any surveyor deals with multi-sensor-systems in his daily work; but not necessarily in a kinematic way.

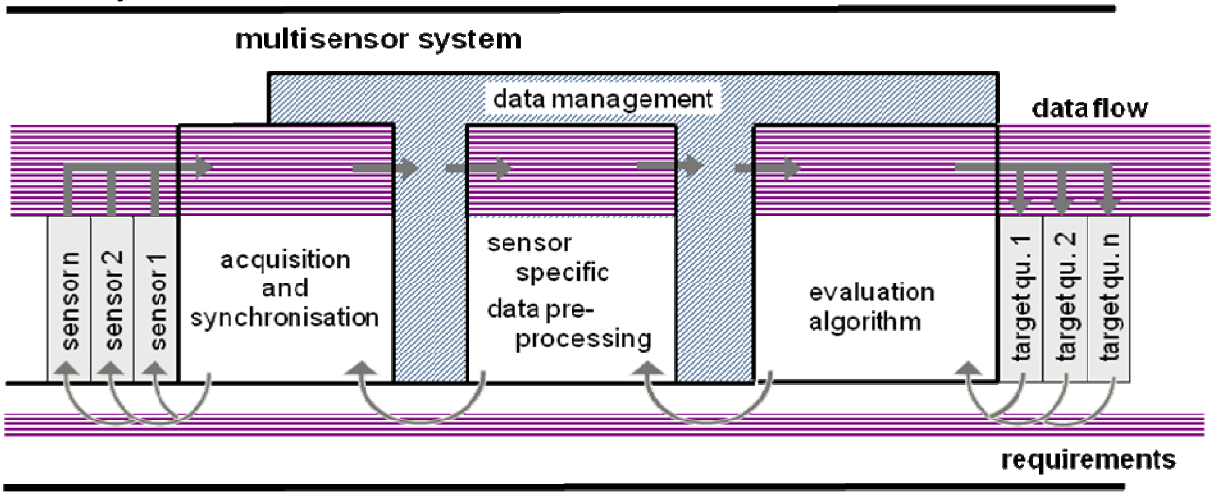


Figure 3: Structure and processes of multi-sensor-systems

Figure 3 shows the general structure of a multi-sensor-system. The processes start with data acquisition and synchronization using the sensors, followed by sensor specific data preprocessing and finally an evaluation algorithm that delivers different target quantities. Around the different process steps data management should be built. In the ideal case these different steps may be separated and the multi-sensor-system are called modular. The interfaces between the different processes as well as the data base have to be clearly defined. For more details concerning the processes the author refers to Schwieger (2011). In the design phase of a multi-sensor-system the direction of the "data flow" is inverse. The requirements e.g. the standard deviation for the target quantities are the initial point. The required evaluation algorithm is derived and further on. Finally the requirements for the sensors can be defined and they may be chosen accordingly.
There is a common division of multi-sensor-systems according to their characteristics given in the following (Schwieger, 2011):

- <u>Space-distributed systems</u>
  In this case similar sensors are installed at different measurement sites. This is an typical example e.g. for monitoring surveys by measuring time-varying coordinates of a landslide by GNSS or total station.
- <u>Redundant systems</u>
  For this system different sensors acquire the same measurement quantity. In this way the possibility to control the measurements and to find errors within the acquired data is given. A good example is the determination of the position using a GNSS receiver and a total station.
- <u>Complementary systems</u>
  Here different sensors acquire different measurement quantities that are required to determine a target quantity. Typical examples are the determination of a horizontal angle and a horizontal distance to estimate the 2D-coordinates or the measurement of the yaw rate and the acceleration to realize dead reckoning for moving vehicles.

Of course these types may occur separately or combined. A combined example is a mobile positioning system comprising a GNSS receiver, a gyroscope and an accelerometer. Here with the help of the accelerations and the yaw rates of the gyroscope local coordinates can be determined in a complementary system. Finally the GNSS receiver provides co-ordinates for a redundant system. In a contradiction the low-cost GPS monitoring system described in section 4.3 is a space-distributed system solely.

## 4. CURRENT CHALLENGES

This section deals with an examplary overview of different research topics related to the field of kinematic measurents as well as multi-sensor-systems. The investigations are examples of the research fields of the Institute of Engineering Geodesy at University of Stuttgart. This is due to practical reasons. Other examples from different research instititions or practitioners could have been presented too. The main task of the author is to show the wide field of applications of the newly established Working Group 5.4 "Kinematic Measurements" within FIG Commission 5 "Positioning and Measurement".

### 4.1 Machine guidance and total stations

This application deals with a total station as complementary multi-sensor-system. Talking about machine guidance the movement of the machine has to be tracked. As time has to be considerd during the measurement process it is a kinematic measurement task. The prediction of the position as well as the filtering of the noisy data is realised using different dynamic models within a Kalman filter. The kinematic model of the Kalman filter is discussed in the next section. The whole measuerment process is integrated into the closed-loop system to guide the machine on a given trajectory (Schwieger & Beetz, 2007).
In this section one focusses on time-related problems and solutions occuring for kinematic tachymeter measurements. To understand the related investigations some definitions are given in the following (compare figure 4).

- Dead time
  This is the time elapsed from the data acquisition up to the results available at the computer. This is important for realtime applications, especially control tasks. Measure: determination and consideration in pre-processing or evaluation algorithm.
- Relative synchronisation
  All time stamps of the acquired sensor data (points in time of data acquisition) are known. If this is not known, the time difference between acquisition points of time of two sensors is the synchronisation error. This is important for all applications, even in post-processing.
  Measure: equidistant sampling rate or event-based acquisition.
- Absolute synchronisation
  The time stamps of all sensors are known in one global time scale e.g. by using the pps-signal of a GNSS receiver to transform all time stamps into GPS time. For local navigation tasks and engineering geodetic applications this synchronisation is without importance.

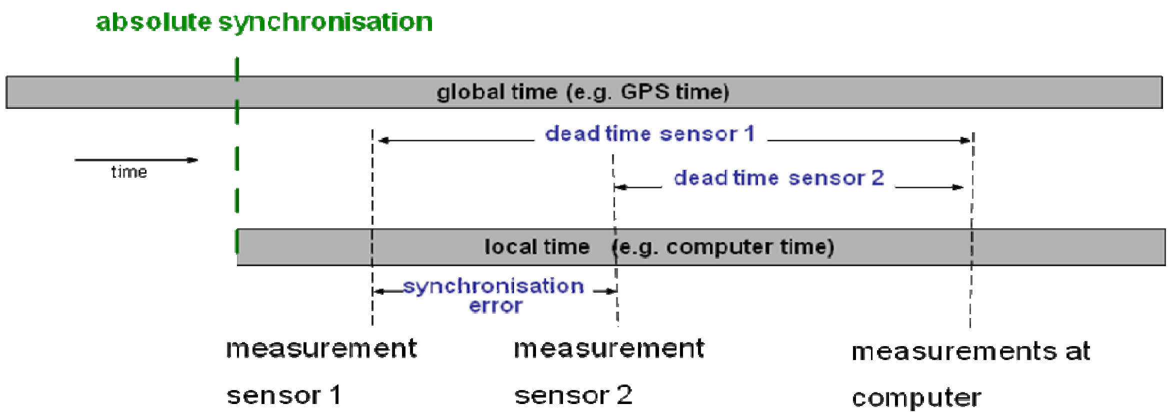


Figure 4: Dead time, absolute and relative synchronisation

For tachymeter measurements absolute synchronization does not exist. Relative synchronization was a large problem in the last years (e.g. Stempfhuber, 2004). Numerous publications have dealt with the problem by proposing solutions e.g. for determining the error by given co-ordinates. Nowadays the synchronisation error is less than one millisecond (e.g. Trimble 2007). Therefore the guidance related problems taking into account maximum velocities of up to 1 m/s show maximum position equivalents to the synchronization error of 1 mm.

Another topic is the consideration of dead time for realtime applications. In Beetz (2012) dead time values of 25 to 40 ms are given for up-to-date total stations. Figure 5 shows the effect of the belate position information within a control system requiring closed-loop systems. If the positions should be determined correctly, at $t_k$ the system has to recognize that a curve drive begins. If the position is determined at the centre of gravity, the curve is recognized at $t_{k+1}$ only. This means that the reaction of the system will be too late. The respective deviation, the so-called control deviation, shows the offset from the given trajectory.

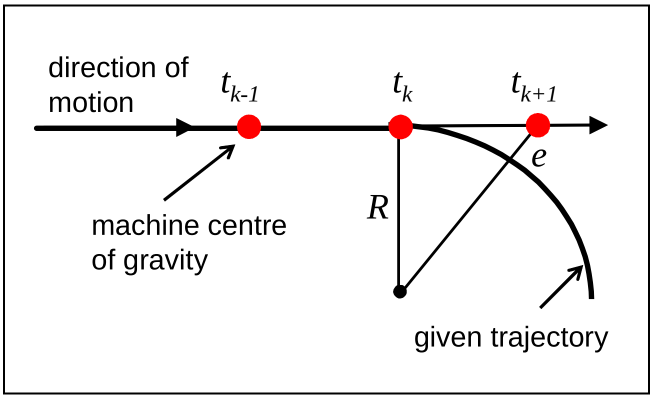


Figure 5: Effect of dead time within a closed-loop system (Gläser et al., 2008)

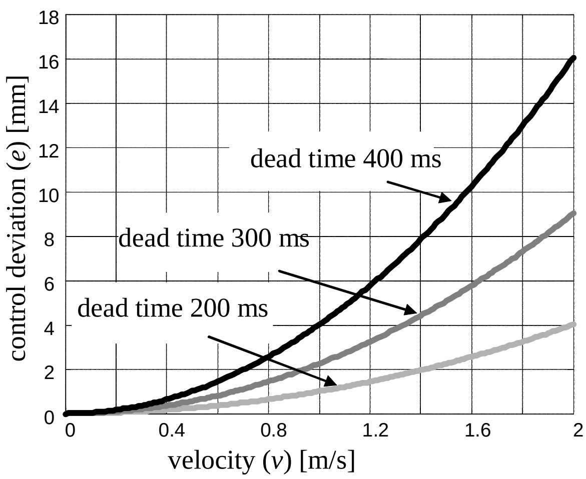


Figure 6: Control deviations for different velocities and dead times (Gläser et al., 2008)

Figure 6 presents that longer dead times and higher velocities give rise to the deviations. These deviations may reach values larger than one cm. This is not acceptable, if one takes into account the accuracy requirements of up to 5 mm for curb and gutter pavers (Stempfhuber, 2006) or the realized control quality of below 2 mm for laboratory simulator results (Beetz, 2012). Therefore the so-called anticipated computation point that shifts the measured position from the centre of gravity to the front using the orientation of the moving vehicle (compare figure 7 and Beetz & Schwieger, 2008). This was the procedure to realize the before mentioned sub-2-mm control RMS.

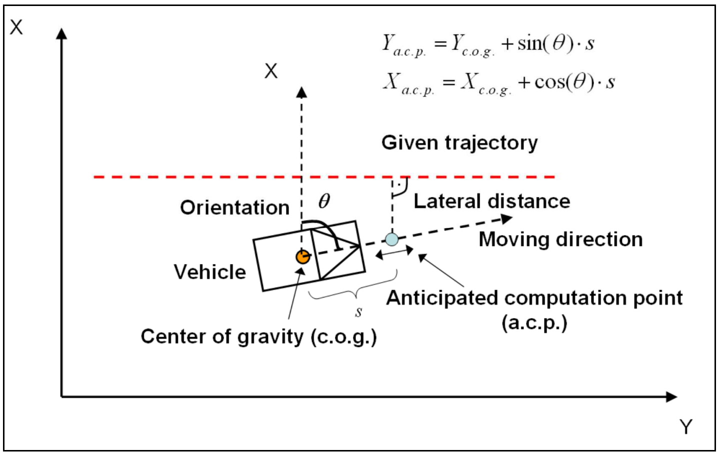


Figure 7: Anticipated computation point (Beetz & Schwieger, 2008)

### 4.2 Modeling of movements

One key aspect of kinematic measurements is their evaluation within kinematic or dynamic models. In this section the author shows some aspects of finding the correct and most applicable model. The section focuses on kinematic models and do not includes acting forces. The way the measurement data is acquired is not discussed in this section. The sensors that can be used are not of importance, since only simulated data is used to evaluate the difference with respect to reality, if different models are chosen. The background at IIGS for the simulation Schweitzer (2012) is the redundant and complementary multi-sensor-system described e.g. in Schwieger et al. (2005) (compare figure 8).

Figure 8: Measurement vehicle of IIGS

For the movement of vehicles a non-accelerated circle drive is generally assumed (Aussems, 1999, Eichhorn, 2004, Ramm, 2007 ). For details regarding the equations and the respective derivation the author refers to the references given before. Within the courses taught at Institute of Engineering Geodesy in Stuttgart a very simple model for a non-accelerated straight line is developed to be more time-efficient compared to the circle model, since the computational effort is much smaller. On the other hand simplifications lead to falsifications, when the car drives an arc. Figure 9 presents the two approaches graphically. In Schweitzer (2012) more details about the two compared models and the data simulation can be read.

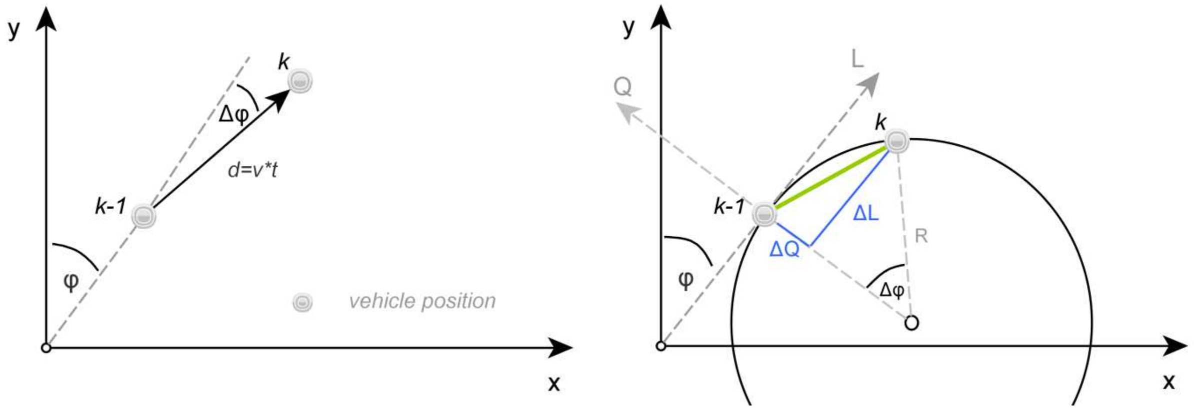

Figure 9: Straight line and circle model (Schweitzer 2012)

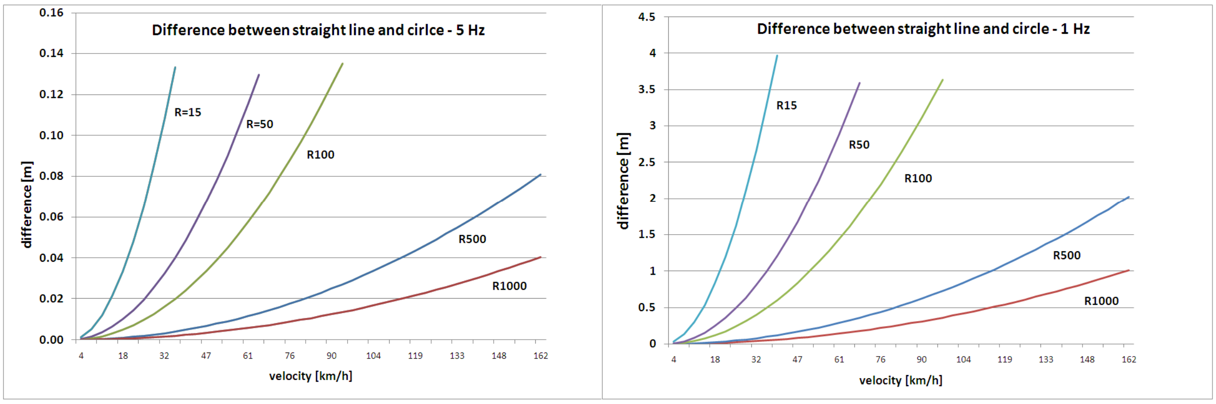

Figure 10: Differences between the two models considering velocity, arc radius and data rate (Schweitzer 2012)

Figure 10 shows the calculated differences between the two models. In both graphs the differences are given for the prediction of one epoch to the next one. Of cause a higher data rate delivers lower differences in the next epoch, which is well represented by the comparison of left and right figure. Addionally a smaller radius *R* or a higher velocity lead to higher differences. If one has a closer look at the two graphs, the difference has to be cosidered for precise applications as e.g. described in the section before, since the deviation reach the cm-level even for low velocities and a data rate of 5 Hz. If the models are used for normal navigation tasks (e.g. Schwieger et al., 2005) this difference is not of importance, since the accuracy level is in the m-to-3m-level. This assessment changes, if the data rate is lowered to 1 Hz: in this case the model difference is obvious even for low velocities. Consequently the circle model has to be considered. Despite of these use cases there are plenty occassions, where the simple straight line model is sufficient for the model prediction. In phases without orientation changes the straight line model has to be used in any case.

### 4.3 Automated low-cost GNSS monitoring system

This sections deals with a quite different application: the monitoring task as one of the key tasks of engineering geodesists. The movements of the monitored objects are slow meaning that time is not an issue during the measurement process. Consequently the measurements are not kinematic but their evaluation shows a need for kinematic or even dynamic models. The measurement system that is in development in the moment uses low-cost GPS receivers that are space-distributed to monitor any possible object e.g. a landslides or buildings. The system comprises a router including a ublox-LEA-6T receiver and a communication module, the GPS-antenna ANN-MS that is protected against multipath effects by a metal shielding, a WLAN-antenna for communication among the different receivers and the central station, and an autonomous power supply consisting of a solar panel, a back-up battery and a charge controller (compare figure 11). For more details about the system as well as the mesh topology to connect the different stations automatically is referred to Schwieger & Zhang (2012).

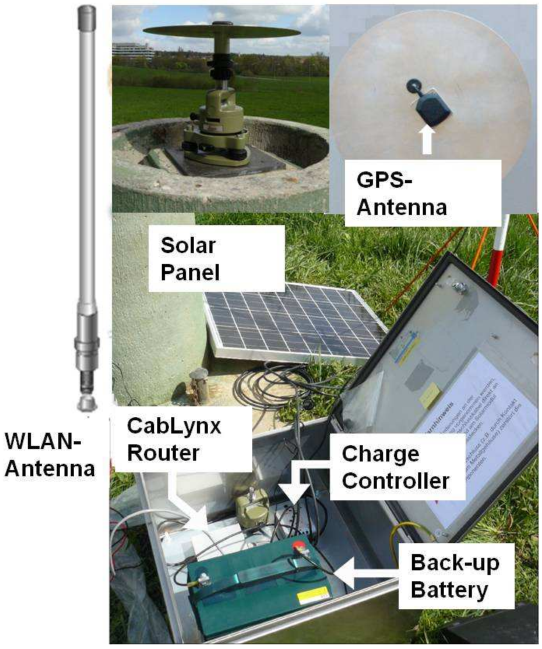


Figure 11: Station of the automated low-cost GNSS Monitoring Systems (Schwieger & Zhang 2012)

Currently the system comprises two complete autonomous systems and one central station without power supply. In 2011 some test measurements were realised in a district of Stuttgart, in Vaihingen (Roman 2011). Two problems had to be solved. One is to ensure continuous communication between the autonomous stations and the central station. The second is the use of the low-cost receiver for precise positioning on geodetic level. If the results are comparable to geodetic level results, the efficiency of monitoring could be widely improved, since the costs for GNNS monitoring will be reduced by a factor of 5 to 10 for each station.

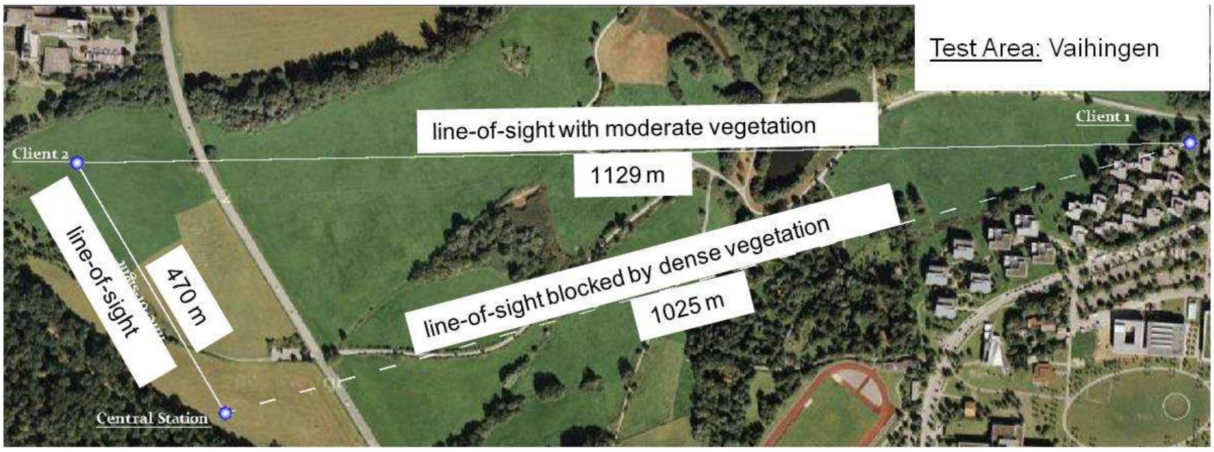


Figure 12: Test area Vaihingen (Roman, 2011, Schwieger & Zhang, 2012)

For the first issue the three receivers were put to measure. One station (client 1) has the line of sight blocked by dense vegetation. Nevertheless the data transport via WLAN could be realised via client 2 to the central station. This could be proved by shutting down client 2. Thereafter no data from client 1 reached at the central station showing on one side that WLAN communication needs line-of-sight and on the other side that the automatic redirection of the data using mesh topology works fine.

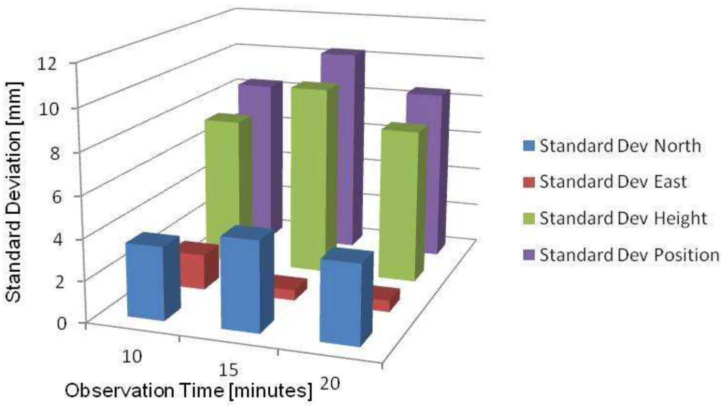


Figure 13: Standard deviations of baseline client 1 to central station (Roman, 2011)

The second issue deals with the accuracy of the approximately 1 km baseline determined by the low-cost sensors. Up to now the system is under development so that only a few results are available. Figure 13 shows the standard deviations of different observation time spans for the baseline client 1 to central station. Obviously the standard deviations are below 1 cm for obeservation times between 10 and 20 minutes. Schwieger & Zhang (2012) presented that the reliablity and automation of the solution is possible beginning with 20 minutes observation time span. Additionally it could be shown that there are still some deviations to given coordinates that are up to 2 cm. Here investigations to identify the reasons have to be realised in the future. If the robust WLAN communication will be validated and the accuracy level will be further improved GNSS monitung will do an efficiency jump with respect to costs.

## 5. SUMMARY AND FIG WORKING GROUP 5.4

This contribution gives some essential definitions and classifications with respect to kinematic measurements and evaluations and multi-sensor-systems as well as to time-related terms. In the following examples were given to highlight the wide application field of this interesting topic. The author focuses on time-related problems for realtime control applications, on the efficient choice of an appropriate model for vehicle movements and on communication and accuracy solutions for GNSS monitoring surveys. These examples show the variety of kinematics but they do not show everything; the possibilities are numerous. This is the reason that the newly established Working Group 5.4 ”Kinematic Measurements” within FIG Commission 5 ”Positioning and Measurement” is put into place. The active members are looking for further support. More information can be found at http://www.fig.net/commission5/wgroups/wg5_4_11_14.htm.

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## BIOGRAPHICAL NOTES

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