Measurement of Line Characteristics and of Track Irregularities by Means of DGPS and INS

Th. Lück[1], B. Eissfeller[1], C. Kreye[1] & P. Meinke[2]

[1] Institute of Geodesy and Navigation,
University FAF Munich, Neubiberg, Germany.
[2] Computer und Kommunikation GmbH, Starnberg, Germany.

Thorsten.Lueck@UniBw-Muenchen.de

BIOGRAPHY

Thorsten Lück is a research associate at the Institute of Geodesy and Navigation at the University of the Federal Armed Forces Munich. He studied Electrical Engineering at the universities of Stuttgart and Bochum. Since 1998 his research area has been the integration of inertial navigation system with differential GPS.

Prof. Dr.-Ing. Bernd Eissfeller is Full Professor and Vice-Director of the Institute of Geodesy and Navigation at the University of the Federal Armed Forces Munich. He is responsible for teaching and research in the field of GPS/GLONASS and inertial technology. Until the end of 1993 he worked in industry as a project manager in the development of GPS/INS navigation systems. From 1994-2000 he was head of the GNSS Laboratory.

Christian Kreye received a diploma in Geodesy in 1998 from the University of Hannover. He has started as a research associate at the Institute of Geodesy and Navigation of the Federal Armed Forces in 1999. His research area has been different applications of integrated GNSS/INS systems, with special emphasis on low-cost INS.

ABSTRACT

The evaluation of existing line characteristics and geometric track irregularities, being perhaps dangerous for dynamic safety of railway systems, becomes more and more evident with rising use of tilting trains like the German ICE3 or ICT, as the resulting irregularities may lead to the danger of train derailment. To identify track defects, a new approach of measuring technique using differential GPS and an inertial navigation system to determine the absolute position and ultrasonic devices to determine the peculiar properties of the geometric track quality was developed.

By combination of differential GPS (DGPS) and inertial navigation system (INS) the position and the rigid body motions of a measurement platform at a self propelled draisine is determined. This platform is used additionally as a base for measuring the relative position of the left and right railhead vertically and laterally by ultrasonic sensors, so that their position can be described in an earth fixed co-ordinate system.

The basic principles of this measurement system are explained as well as the results of railway field tests (together with the Austrian Railways ÖBB) are demonstrated. An accuracy in the millimeter range has been proven. The speed of the measurement draisine was up to 50 km/h. Wavelengths of up to 200 m can be determined.

1 INTRODUCTION

For a long time the European railways are interested in the determination of the response of fast railways on long wavelength track irregularities and in the identification of significant defects and their influence on the potential of derailment [7]. Within an expert group (C 210) founded by the European Rail Research Institute (ERRI) in particular the correlation between railway response and track defects was discussed.

Since then within the European research project DYSAF (DYnamisc SAFty) the endangerment for derailment especially for tilting trains like the German ICE3 or ICT is considered. One aim within this project is to identify track defects with wavelength of 2 up to 150m within millimeter accuracy. The system was tested with respect to accuracy and repeatability on a test track of about 20km length at up to 40km/h velocity thus leading to a geometric sample rate of at least 20cm.

2 TRACK IRREGULARITY MEASUREMENT SYSTEM (TIMS)

The system design is based on the integration of Differential GPS (DGPS) with an Inertial Navigation System (INS) for positioning. The primary task of the system is to acquire high-precision data for post-processing (Figure 2).

To determine the higher dynamics of the measurement platform, a precise inertial navigation system (SIGMA30, SAGEM, France) is used. The INS position is then augmented using carrier phase positions of the differential GPS system to eliminate inertial errors.

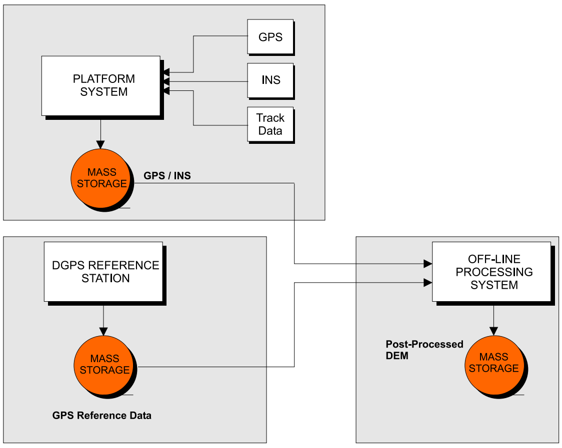

Figure 1: Dataflow of TIMS

Surveying of the rail heads is done by use of ultrasonic sensors in two perpendicular directions. The distance between platform and rail heads is measured in horizontal and vertical direction. Considering the attitude and position of the platform determined by the positioning system, the absolute position of both rail heads can be derived.

2.1 POSITIONING OF MEASUREMENT PLATFORM

Based on the operational principle of the project the platform positioning system consists of three sub-systems:

- Platform measurement equipment to be elastically mounted on a self propelled trolley (figure 2) containing
    - the sensor sub-system
    - data handling sub-system including a data archiving and mass storage facility
    - time synchronization
- DGPS reference station
- Off-line processing system

The measuring device consists of an elastically supported platform, of which the inertial position is determined, and of a measurement system for the rail heads to determine the vectors between platform and rail heads (figure 4). To determine the platform position, a high precision inertial navigation system (INS, SAGEM SIGMA30) is rigidly mounted on the platform to measure the high frequency system dynamics. The inertial position is then augmented with position solutions of a differential GPS system (NovAtel, MiLLennium). The GPS antenna is also rigidly mounted on the platform using a stable mast spanned with shrouds to prevent mechanical oscillations (figure 2). A block diagram of the platform system is shown in figure 3.

Figure 2: Self propelled trolley of the Austrian railways (ÖBB) used for track measurements with measurement platform mounted.

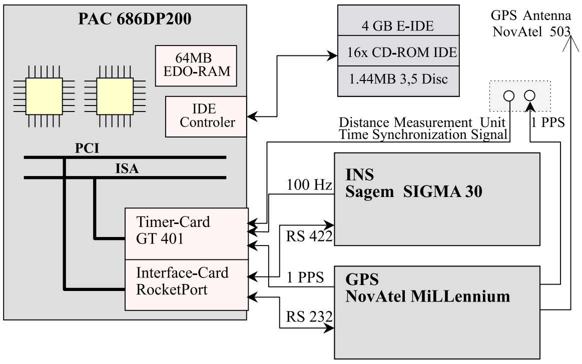

Figure 3: Block diagram of TIMS

2.2 RELATIVE MEASUREMENT OF THE RAIL HEADS

The gap between the rigid structure of the platform and the rail heads is designed to be 5 - 20 mm. Ultrasonic measurement units are used to determine the distances toward the top and the slope of the rail head. Track irregularities of the rail head will be analyzed according to figure 5. After the separation into gauge, vertical profile, cross level and alignment the four parameters are examined to find certain track defects.

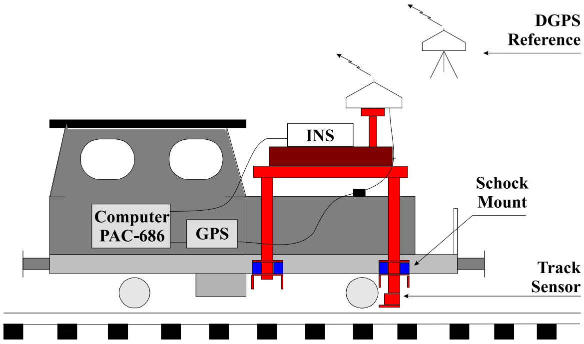

Figure 4: Track Irregularity Measurement Concept

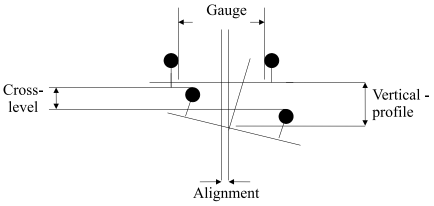

Figure 5: Definition of track parameters

3 SYSTEM COMPONENTS

The system to determine the inertial position (positioning system) uses the following hardware components:

- SAGEM SIGMA30, Inertial Navigation System (INS)
- NovAtel MiLLennium RT-2 RTK GPS L1/L2 receiver with Choke-Ring Antenna (503, NovAtel)
- Dolch PAC-686, dual-pentium personal computer with Multiport Serial Card (RocketPort, COMTROL) and an event timer card (GT401, Guide Technology)

For the reference station the following hardware components are used:

- NovAtel MiLLennium RT-2 RTK GPS L1/L2 receiver with Choke-Ring Antenna (503, NovAtel)
- portable pentium personal computer (NotePAC 586-200, Dolch)

3.1 SYNCHRONIZATION

The GT401 timing board is triggered with the 1 PPS output of the MiLLennium RT-2 GPS receiver which is synchronized to GPS time. The INS uses it's own time base but provides a trigger signal for each message it sends to the serial port on a 100 Hz basis, leading to an ambiguity for the 50 Hz navigation data. These trigger signals are time-tagged by the event timing card and are read from the navigation software once per second. When reading INS data from the buffered serial port, the time of transmission of every message is estimated by the logging software. The corresponding time tag of the trigger signal is then determined by a least square estimator.

3.2 GPS RECEIVER

The NovAtel MiLLennium RT-2 RTK provides dual frequency GPS performance. Featuring Narrow Correlator and P-code Delayed Correlation Technologies, the receiver outputs pseudorange and full wavelength carrier phase observations for both L1 and L2 frequencies. Real pseudorange and carrier phase are provided at up to 4 Hz using two independent serial line interfaces. Table 1 shows some major specifications of the receiver.

The GPS data is processed in postmission mode using the software package **GeoGenius** by Terrasat/Germany.

Characteristics	
· Accuracy in mm-range using offline processing	
· L1-C/A code and carrier phase	
· L2-P code and carrier phase	
· 4 Hz data rate for position	
· 4 Hz data rate for pseudo ranges	
Specifications	
· position accuracy	
stand alone	
SA off	15 m CEP
SA on	40 m CEP
differential	
code (L1, C/A)	0.75 m
· measurement precision	
L1 carrier phase	
single channel	3 mm RMS
differential channel	0.75 mm RMS
· dynamics	
acceleration	6g
velocity	515 m/s

Table 1: Specification of the MiLLennium RT-2 RTK GPS receiver

To eliminate multipath errors, a choke ring antenna is used for both, rover an reference station (figure 6). To minimize errors due to multipath and shadowing, the antenna has been set on a mast with the phase center above the roof of the train.

3.3 INERTIAL NAVIGATION SYSTEM (INS)

The SAGEM SIGMA30 is a high accuracy, unclassified strap-down ring laser gyro inertial navigation system (INS). It provides three serial interfaces. Whereas two interfaces are for data logging only, the third interface provides programming capabilities of the navigation computer of the INS. Beside navigation data the INS provides semi-raw inertial data on a $100\ Hz$ basis with 4 bytes each, leading to accuracies of $15/2^{31}\ rad/s$ for rotation rate and $50/2^{31}\ m/s^2$ for acceleration at a maximal input rotation rate of $\pm 15\ rad/s$ and maximal accelerations of $\pm 50\ m/s^2$. On a second high rate line, navigation data is provided with an accuracy of $< 0.1\ mm$ for the position, $< 0.2\ mm/s$ for velocity and $< 1/10''$ for attitude. Table 2 shows some technical data of the used inertial navigation system.

For programming and initiating the different modes (standby, alignment, navigation) the third (standard command line) interface is used. To avoid unsteady position solutions of the INS, the ZUPT mode can be deactivated after the initial alignment.

3.4 ULTRASONIC DISTANCE MEASUREMENT UNIT

To measure the distance between the platforms lever arms and the rail heads, four ultrasonic sensors are used. They measure the horizontal and vertical distance on both sides of the rail. Measurements are synchronous to the inertial

Performance	
· Position (X,Y)	$< 4\ m \pm 0.07\%$ of travel distance
· Altitude	$< 4\ m \pm 0.07\%$ of travel distance
· Azimuth	$0.5\ Mil = 1.688\ arcmin$
· Pitch and Roll	$0.3\ Mil = 1.013\ arcmin$
Characteristics	
· Size	210 x 210 x 420 mm
· Weight	19 kg
· Power requirements	50 W nominal, 18-32 VDC
· Cooling	free convection
· Periodic calibration	not required
Operating conditions	
· Latitude range	75^o North to 75^o South
· Temperature	-30^oC to $+60^oC$
· Vibrations	Track vehicles
· Shock	Howitzer gun fire
· Environment	per MIL-STD 810 C

Table 2: Specification of the SIGMA30 strapdown INS

measurements and are triggered by the INS 100Hz synchronization signal.

Using a switch, the trigger signal can be applied to the sensors by the operator. The time when the switch is used is determined by the GT401 timing card. Thus a precise correlation to the inertial measurement data is possible. Figure 6 shows one lever arm and the corresponding ultrasonic sensors. The horizontal distance is measured from the inner side to the rail head.

4 KALMAN FILTER DESIGN

The Kalman filter is used for error estimation and correction of the INS. When considering an integration of both, GPS and INS, the integration can be made at different levels [4, 3, 5].

To fulfill the required positioning resolution on the track of approximately 20 cm at a speed of up to 30 km/h, position and attitude data has to be provided with at least 42 Hz. As the INS can provide position, attitude and velocity at 50 Hz, an integration on position level is feasible.

As a basis for the Kalman filter design, the filter concept, developed by Schmidt [10] is used, which describes the fundamental error dynamics of an inertial system. This basic design is then augmented with additional states resulting from error analysis of the sensors.

The used filter design considers the major error sources of the INS and their impact on the navigation errors [1, 11]. As the used INS is a high precision one, relevant error states are gyro drift and accelerator bias while the scale factor errors can be neglected.

Figure 6: Strapdown INS Sigma30 with GPS Chokering Antenna (left). On the right side the left lever arm with the ultrasonic sensors for the vertical and lateral distance measurements is shown.

4.1 STATE VECTOR

The state vector of the filter consists of the following elements:

$$\mathbf{X}_{INS} \quad = \quad [\delta\boldsymbol{\Theta}, \delta\mathbf{v}, \delta\mathbf{r}, \mathbf{d}, \mathbf{b}]$$

The first nine states represent the INS navigation errors:

$\delta\boldsymbol{\Theta}$	Vector of attitude error with respect to north, east and down axes
$\delta\mathbf{v}$	Vector of velocity error in latitude rate, longitude rate and altitude rate
$\delta\mathbf{r}$	Vector of position error in latitude, longitude and altitude

The next 6 states result from the error analysis and express the major INS sensor error sources:

$\mathbf{d}$	Vector of uncompensated gyro drift
$\mathbf{b}$	Vector of uncompensated accelerometer bias

4.2 DYNAMIC COUPLING AND STATE TRANSITION

The dynamic coupling between states is expressed by the dynamic design matrix **F** with white process noise input

$$\dot{\mathbf{x}} = \mathbf{F} \cdot \mathbf{x} + \mathbf{w}$$

The transition matrix, necessary for prediction of states and covariance is obtained by

$$\Phi \approx \mathrm{I} + \mathbf{F} \cdot \delta\mathrm{t} + \frac{1}{2}\mathbf{F^2} \cdot \delta\mathrm{t}^2$$

The dynamic matrix **F** is shown below with brief explanation of the submatrices:

$$\mathbf{F} \quad = \quad \left(\begin{array}{ccccc} & & & \mathbf{C_b^n} & \bar{0} \\ \multicolumn{3}{c}{\mathbf{F_{Free}[9x9]}} & \bar{0} & \mathbf{DC_b^n} \\ & & & \bar{0} & \bar{0} \\ \bar{0} & \bar{0} & \bar{0} & -\mathbf{I} \cdot \beta_{\mathrm{g}} & \bar{0} \\ \bar{0} & \bar{0} & \bar{0} & \bar{0} & -\mathbf{I} \cdot \beta_{\mathrm{a}} \end{array}\right)$$

The 9x9 submatrix $\mathbf{F}_{\text{Free}}$ is taken from [10]. β are the three dimensional correlation coefficients of the gyros (index g) and accelerometers (index a) error models. $\mathbf{I}$ is the 3x3 unity matrix.

The $\mathbf{C_b^n}$ Matrix is the transformation matrix between body and navigation frame and is needed to relate sensor errors, normally defined in body coordinates to the navigation errors defined in local horizon frame.

$$\mathbf{C_b^n}=\begin{pmatrix} \cos\gamma\cos\beta & \cos\gamma\sin\beta\sin\alpha & \cos\alpha\sin\beta\cos\gamma \\ & -\sin\gamma\cos\alpha & +\sin\gamma\sin\alpha \\ \cos\beta\sin\gamma & \sin\gamma\sin\beta\sin\alpha & \cos\alpha\sin\beta\sin\gamma \\ & +\cos\gamma\cos\alpha & -\sin\alpha\cos\gamma \\ -\sin\beta & \cos\beta\sin\alpha & \cos\alpha\cos\beta \end{pmatrix}$$

with

α	Roll
β	Pitch
γ	Azimuth

The scaling Matrix $\mathbf{D}$ transforms linear velocity to latitude or longitude rate.

$$\mathbf{D} = \begin{pmatrix} \frac{1}{R} & 0 & 0 \\ 0 & \frac{1}{R\cos\Phi} & 0 \\ 0 & 0 & -1 \end{pmatrix}$$

4.3 OBSERVATIONS

Six different observations are used to update the Kalman filter:

- Three dimensional carrier-phase position
- Three dimensional instantaneous Doppler velocity

The observation, used to update the filter, is the difference between INS and GPS computed position:

$$\mathbf{r}_{\text{INS}} - \mathbf{r}_{\text{GPS}} = \delta\mathbf{r} + \mathbf{n}$$

with

$\mathbf{r}$	position vector
$\delta\mathbf{r}$	vector of position error (states)
$\mathbf{n}$	white noise

The velocity error is derived by differencing INS and GPS velocity:

$$\mathbf{v}_{\text{INS}} - \mathbf{v}_{\text{GPS}} = \mathbf{D}^{-1}\delta\mathbf{v} + \mathbf{n}$$

The velocity difference has to be related to the velocity error state via the scaling matrix $\mathbf{D}$ described above.

4.4 SMOOTHING

Due to the analysis of the measurement data in post processing, all data of a complete set of measurements can be taken into account for the calculation of the position within the Kalman filter. Using the so called *optimal smoother*, all data is processed in positive time axis and afterwards - with the knowledge of all error states and covariances - in backward direction. This allows a further reduction of the variances of the position solution.[2]. Figure 7 show the principal of the so called *optimal smoother*.

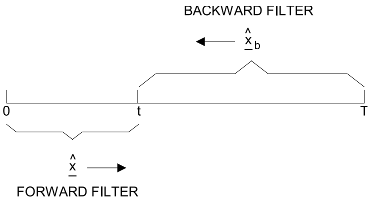

Figure 7: Principal of the *Optimal Smoother*

5 EVALUATION OF THE PROTOTYPE TIMS

On two successive days in September 2000 several test runs were performed on a auxiliary route of the Austrian railways (ÖBB) near St. Pölten. Below first of all the setup and surveying of the measurement platform will be described following first results from the test runs.

5.1 SETUP AND SURVEYING OF THE MEASUREMENT PLATFORM

Measurements of the track geometry respectively their defects with millimeter accuracy requires a survey of all sensors with at least submillimeter accuracy. Due to platform scale and big distances between the sensors, a survey of the system in the laboratory was not possible. Surveying the platform with the required accuracy could therefore only be managed using geodetic techniques. To do so, the antenna phase center as well as the ground plate of the INS and three reference points on each lever arm where marked to be easily located through a theodolite.

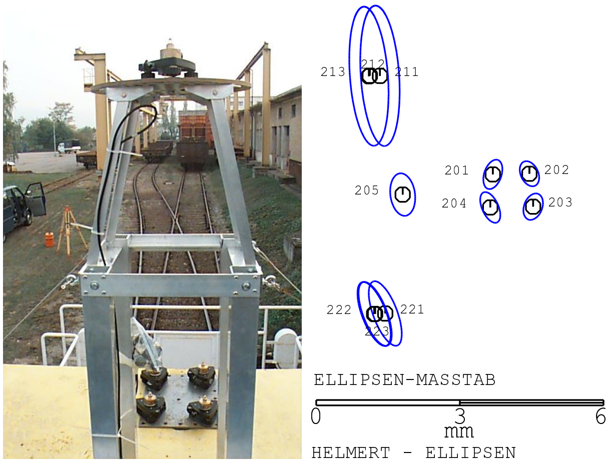

Figure 8: Marked reference points on groundplate for INS and GPS phase center. On the right side, all reference points and their error ellipsoids are displayed.

Particularly the positions of the ultrasonic sensors were not visible from observation points at only one side of the measurements vehicle. Therefore it was necessary to build up a six point network around the train with legs between 5 and 25 meters. Because of the high accuracy requirements the essential distances needed to fix the network scale were determined by the parallactic angle concerning a 1-meter subtense bar. Then the coordinates of the target points defining the mutual 3D-position of the three different sensors could be determined by the spatial intersection of the lines of sight from the observing theodolites (measurement of horizontal and vertical angles concerning two observation points) in the local network system.

An additional stabilization of the network geometry was possible by the double-sided determination of the target points defining the INS ground plane and the phase center of the GPS antenna. Using a free network 3D-adjustment optimized concerning the object points with a reliability of 0.61, the vectors between the different sensors could be determined with an accuracy of 0.3 to 1.7 mm depending on the particular observation geometry. Finally the transformation of the vectors in the coordinate system of the INS was carried out.

5.2 TEST RUNS

Data of a total distance of approximately 120 km were acquired by successive travels over the test range, which had a total length of about 20 km. Figure 14 shows a part of the test range between rail station Traisen/Markt via Traisen and Wilhelmsburg to Spratzern. In addition the position of the reference station is marked.

The accuracy of the GPS carrier phase position solution was in the range of $< 3mm$ for the horizontal components and $< 5mm$ for the vertical under well conditions (figure 9).

After compensation of systematic errors the accuracy of the INS was better than 0.3mm. Figure 10 shows the drift of the free running INS in a period of 10 seconds as well as the residuals after compensation with a polynomial of third order.

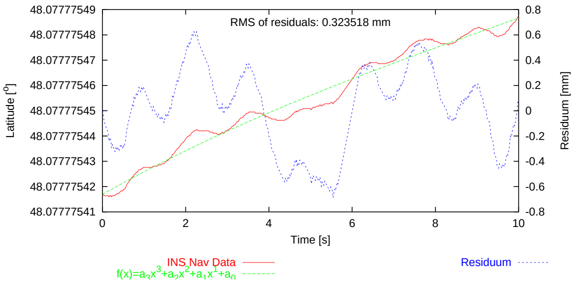

Figure 10: The position accuracy of the INS is - after compensation of systematic errors - in the range of 0.3mm RMS ($0.3mm/s^2$ acceleration error)

Within a time frame of 100s the attitude angles of the platform (roll, pitch and yaw) are shown in figure 11. As can be seen, roll and pitch stay within a range less than 0.5 ° during straight travel. On the left and right edge of the figure the beginning of a curve is indicated by roll and yaw angle.

The filtered position from both, GPS and INS, is shown in figure 12. Due to loss of signal of GPS the position deviation rises until a new position observation is available.

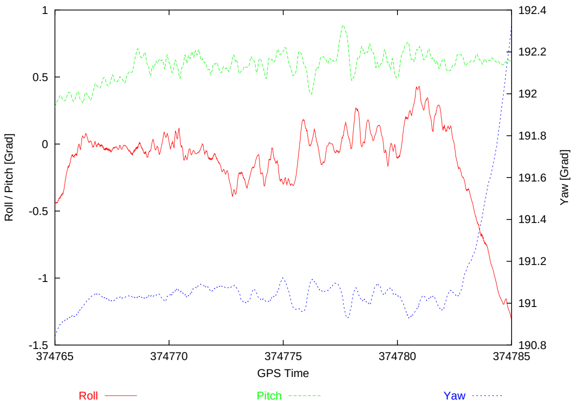

Figure 11: Attitude within curvature.

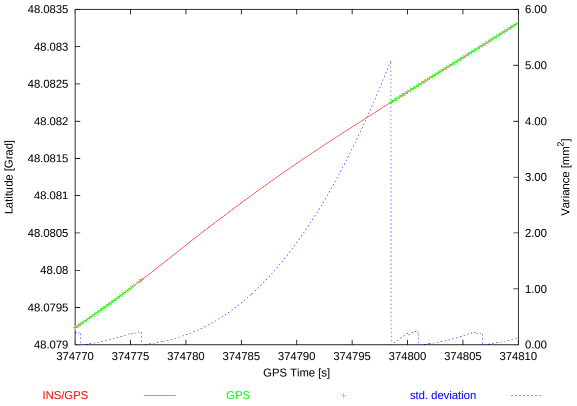

Figure 12: Integrated position solution. During loss of GPS signal, the position deviation rises exponentially until a new observation is available.

For further analysis, the exact position of the rail heads were calculated in accordance to figure 13.

Using these data, the cross level, gauge and centerline could easily been calculated using

$$
\begin{aligned}
s_{gauge} &= |P_{left} - P_{right}| \\
s_{cross-level} &= |P_{left}| - |P_{right}| \\
P_{center} &= \frac{1}{2}(P_{left} + P_{right})
\end{aligned}
$$

The results as shown in figure 15 allow the separation of the track in straight lines (cross level equal zero), curves (cross level unequal zero but constant) and transition lines (cross level rising or falling). In curves, the gauge variation is also clearly observable. The position of curves is marked in the overview of figure 14.

6 CONCLUSIONS

Integration of both, INS and GPS measurements is a well known technique. However, limiting factors must be considered under the prerequisite of high accurate surveying in the millimeter range.

One major point is exact timing between all sensor data, as already a time lag of 1ns causes a location error

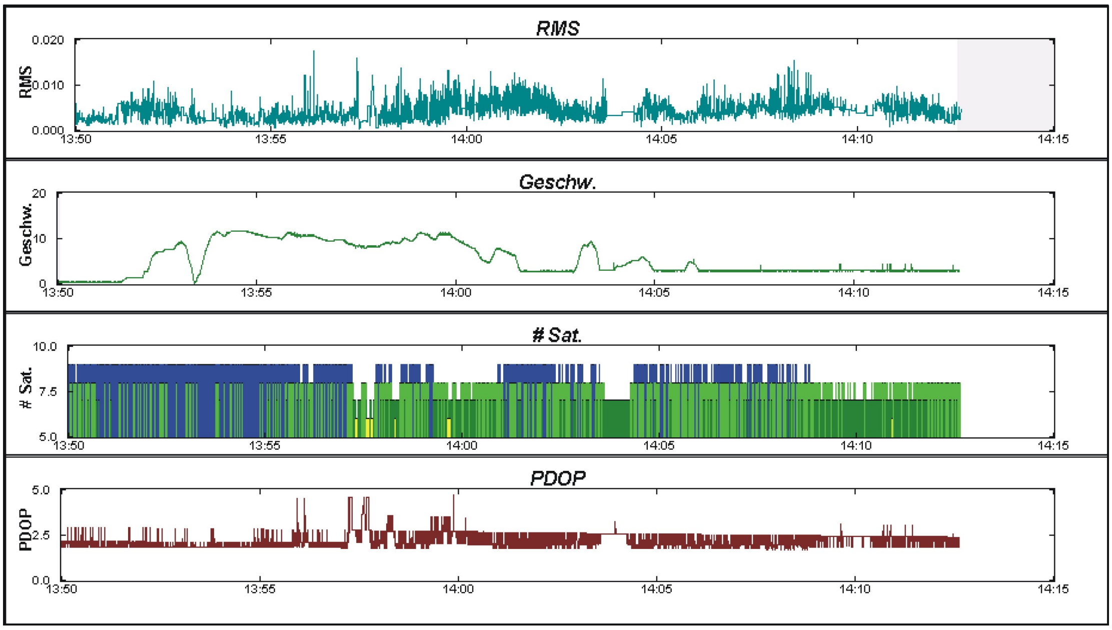

Figure 9: Results of GPS data postprocessing. The standard deviation for the differential GPS position solution is about 3mm under well conditions.

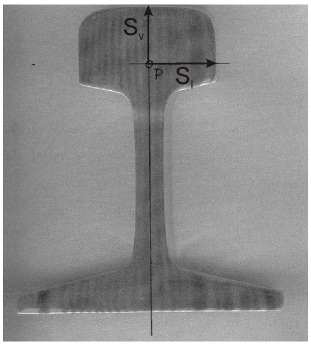

Figure 13: The reference point P for the rail head position is defined to be $S_v = 27.5mm$ below the surface with a distance of $S_l = 31.5mm$ from the flange.

of 1mm at 30km/h speed.

As uncertainties of the vectors between the sensors lead directly to the overall accuracy, the distances between all sensors must be known with submillimeter accuracy. However, as phase center variations (PCV) of the GPS antenna are in the range of several millimeter, these must be taken into account and corrected dynamically [12].

Similarly the mechanical stability of the platform must be considered, as stimulation of the platform may lead to mechanical oscillations which influence the vectors between the sensors.

Under close consideration of all these factors, the positioning of the platform with an accuracy in the millimeter range as well as the derivation of the absolute rail head position from the platform reference point is feasible.

ACKNOWLEDGMENTS

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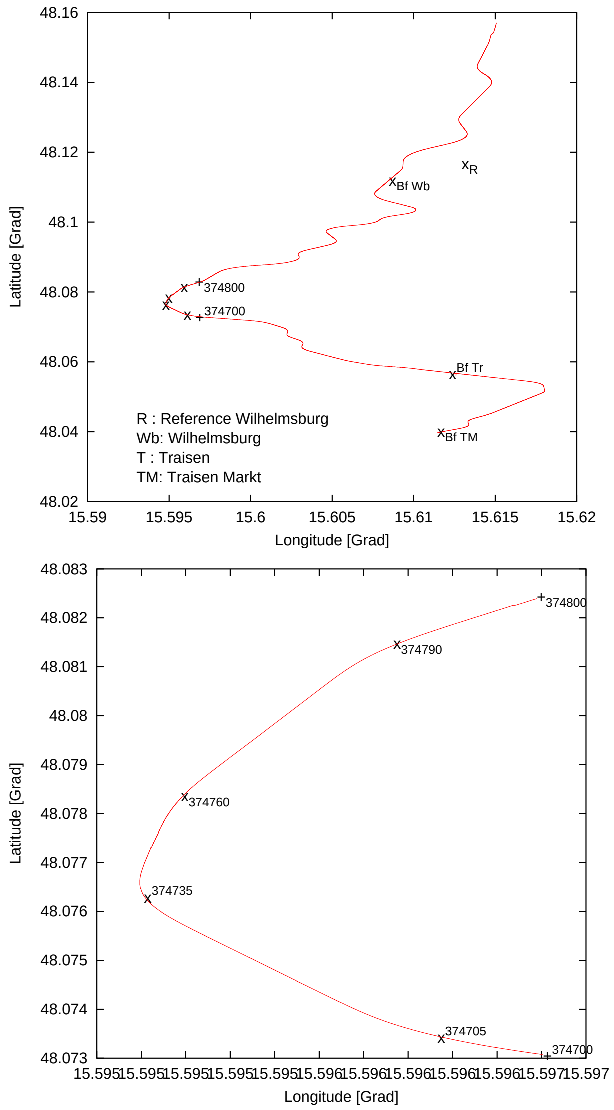

Figure 14: Part of the test track near St. Pölten/Austria.

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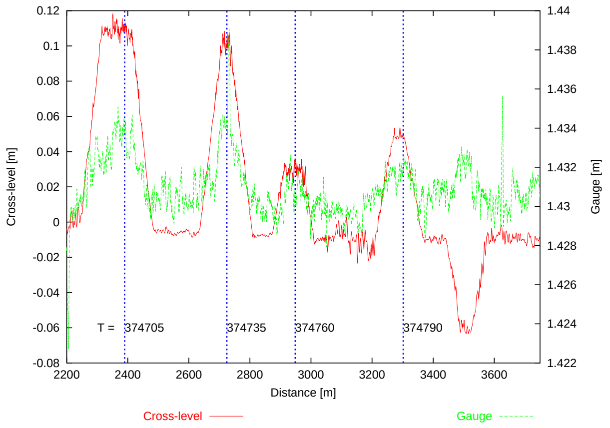

Figure 15: Gauge and cross-level for a specific part of the track. Every trapezoid in the cross-level plot represents a curve (circular arc) with flanking transition curves.

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