Car Collision Warning System Based on RTK GPS

Milan HOREMUZ, Sweden

Key words: RTK, GPS, road safety, Kalman filter

SUMMARY

Many serious traffic accidents happen when a car drives over to the opposite lane. An effective way to prevent such accidents is to mount a barrier between opposite driving directions in form of cable fence. This is a quite expensive solution, which is not applicable on all roads. Therefore it is desirable to find alternative methods.

One possible alternative is to use GPS, namely a RTK method (Real Time Kinematics), which is capable to deliver sufficiently accurate position to compute if the car drives in correct lane and if the distance to the road edge is safe. The basic concept of the warning system is to place the actual position of the car into a precise road model and to compute if the car is outside or on its way out of the correct lane. If so, the system will warn the driver.

This paper describes a prototype of such a warning system. The system was tested on 10 km long road section. The car performed 38 intentional manoeuvres that should trigger alarm. The evaluation of the tests was done visually, using video sequence synchronised with the graphical output from the warning system. 32 manoeuvres were correctly alarmed by the system. The system issued 32 false alarms during 40 minutes driving. However, most of them had only short duration, less than 0.2 s.

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1. INTRODUCTION

Many serious traffic accidents occur when a car drives over to the opposite lane. An effective way to prevent such accidents is to mount a barrier between lanes in form of cable fence. This is quite expensive solution, which is not applicable on all roads. Therefore it is desirable to find alternative methods.

One possibility is to use a collision avoidance system based on camera and radar sensors, which are available on the market, for example Barber and Clarke (1998), Jansson e. al (2002). Such systems use radar sensor to determine the range and relative velocity between the car and other objects. The camera with image analysis software can determine the position of the car relative to the lane painting. The collision avoidance systems are performing very well in avoiding collisions between cars travelling in the same lane and in the same direction. It is more difficult to handle the scenarios where the car is meeting another car travelling in opposite direction. In this case, the meeting car can be falsely identified as a collision object, especially in curves. The weakness of the camera sensor is weather and visibility dependency. For example the road edges cannot be reliably recognised from the images if there is snow coverage on the road.

In this paper we study the possibility use GPS, namely RTK method (Real Time Kinematics), which is today routinely used for machine guidance, for example Baertlein at. al. (2000). This method is capable to deliver sufficiently accurate position to compute if the car drives in correct lane and if the distance to the road edge is safe. The basic concept of the warning system is to place the actual position of the car into a precise road model and to compute if the car is outside or on its way outside the correct lane. If so, the system will warn the driver.
The warning system consists of two components: a GPS receiver with RTK function and a computer with software that evaluates the position of the car relative to the road model and issues warning if the car is outside or is heading outside the correct lane. We named this system VSKTH (Varningssystem KTH). The prototype was tested with GPS receiver Trimble R7, which updates the position 20 times per second.

2. ANALYSIS AND SYSTEM SPECIFICATION

2.1 Positioning sensor

The warning system is built solely on GPS sensor with real time kinematics (RTK) functionality. It means that the receiver must be able to receive RTK corrections either via radio modem or via GSM modem. The corrections are generated by one or more reference receivers. The precision in horizontal position is according to the manufacturer's specification 10 mm + 1ppm, where ppm (parts per million) is distance dependent part of the error. It expresses the growth of the positional error in millimetres per kilometre distance from reference station. This precision is valid for synchronized RTK mode. In this mode the GPS receiver waits for the corrections, which are generated with 1 Hz frequency. It means that the position is available only once per second with certain delay, which depends on the communication link between reference and roving receiver. The delay is in range of 1 – 2 s. In this application a higher update frequency and shorter delay is required. Therefore it is more suitable to use so called low-latency mode, in which the roving receiver uses ”older” corrections to compute current position. In this way it is possible to compute position immediately after the roving receiver performs observations towards satellites. Today, there are receivers on the market with up to 20 Hz position update frequency. The drawback of this mode is lower precision: 20 mm + 1 ppm. The position is delivered with delay 20 ms (Trimble 2003), which is caused by receiver’s hardware and software; in the following text we will denote it as hardware delay HD.

How the delay and the update frequency affect the performance of the warning system? Generally we can state that the warning system can detect the change in the driving direction faster, if the sensor has higher update frequency and shorter delay. The system issues a warning based on the computed lateral distance d_L, d_R between the car and the edge of the road – see Figure 1.

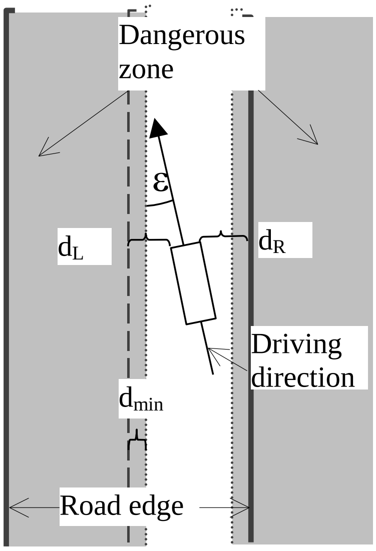

Figure 1. Dangerous zone, lateral distance d and error in course .

If the distance is less than a critical value d_{min}, then the car is in *dangerous zone*. The performance of the warning system depends on the ability to compute actual lateral distance *d* and it depends on update frequency *f* and hardware delay *HD*. If we consider that we need at least one position update to compute the driving direction, then the total delay *TD*, i.e. difference between time of last known position and the time when the warning system computes and displays new position is given by:

$$TD = \frac{1}{f} + HD \qquad (1)$$

We can say that during time TD the motion of the car is not sensed and the lateral distance is changed by Δd. Δd depends on the velocity of the car, error in course ε, update frequency *f* and hardware delay *HD*. Table 1 lists numerical values of Δd computed for car velocity 90 km/h. These values can be used for choosing a suitable value for safety marginal d_{min}.

Table 1. Values of Δd computed for velocity 90 km/h

Update frequency f [Hz]	Δd (ε = 1°) [m]	Δd (ε = 2°) [m]	Δd (ε = 5°) [m]
1	0.45	0.91	2.27
5	0.10	0.21	0.52
10	0.06	0.12	0.31
20	0.04	0.08	0.20

2.2 Precision of GPS position

Depending on availability of RTK corrections and the quality of GPS signals, there are four types of solution that a RTK GPS receiver can produce:

1. RTK fixed solution, expected precision is on cm-level. This solution is available only when uninterrupted GPS phase observations and RTK corrections are available.
2. RTK float solution, expected precision is on dm-level. This solution is typically available shortly after the start of the receiver or after the re-acquiring of GPS signal or RTK corrections.
3. DGPS solution, expected precision is 1 - 3 m. In this case the RTK corrections are available, but GPS signal is too weak to perform phase observations. This is usually the case when many of available satellites are behind the trees.
4. Autonomous solution, precision 10 - 20 m. This solution is generated, if the RTK corrections are not available.

2.3 Road model

A precise road model is a prerequisite for correct functionality of the warning system. By road model we understand a database of coordinates of points that describe the geometry of road. Such database can be created by surveying discrete points along the road’s edges or along the middle line. The method of surveying should guarantee sufficient accuracy; preferably below 0.15 m. Usually the existing databases are not accurate enough for this purpose. In the following text a section of the road between two surveyed points will be referred as *segment*.

3. KINEMATIC MODEL FOR POSITIONING

Kalman filter seems to be the most appropriate tool for the computation of position, velocity and acceleration of the car in real time. We use PVA (position velocity acceleration) model to describe the motion of the car (Schwarz et. al. 1989). We have chosen this model, because we assume that the car undergoes just smooth motions, without any abrupt changes of acceleration and the driving direction. In this model, the kinematic state of the car is described by six parameters:

$$\mathbf{x} = \begin{bmatrix} x & y & v_x & v_y & a_x & a_y \end{bmatrix}^T \tag{2}$$

where

x, y	are horizontal coordinates expressed in Swedish national reference system RT90
v_x, v_y	are x and y components of velocity
a_x, a_y	are x and y components of acceleration

A kinematic model can be generally written in linear form as:

$$\dot{\mathbf{x}} = \mathbf{F}\mathbf{x} + \mathbf{G}\mathbf{u} \tag{3}$$

where **F** is dynamic matrix, which in case of PVA model takes following form:

$$\mathbf{F} = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{4}$$

$$\mathbf{G} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 1 & 0 \\ 0 & 1 \end{bmatrix}, \quad \mathbf{u} = \begin{bmatrix} \omega_{\dot{a}x} \\ \omega_{\dot{a}x} \end{bmatrix} \tag{5}$$

G is a shaping matrix and **u** is a vector of random acceleration with covariance matrix

$$\mathbf{Q} = E\left[\mathbf{u}(s)\mathbf{u}^T(t)\right] = \begin{bmatrix} q_{\dot{a}x} & 0 \\ 0 & q_{\dot{a}y} \end{bmatrix}. \tag{6}$$

The choice of the numerical values of q in matrix **Q** determines the weight of the predicted parameters **x.** In other words, matrix **Q** expresses the degree of correctness of the PVA model. Value q = 0 means that we assume perfect conformance of the model with reality. If we set too low values of q, then there is a risk that the system will detect the change of the driving direction with larger time delay. For this reason we used relatively high, empirically determined value q = 0.1 $m^2 s^{-3} Hz^{-1/2}$. By doing so, the filter relays more on the current observation and the computed trajectory of the car will not be as smooth as it would be using smaller values of q.

We used standard Kalman filter formulation described in Brown (1992) with the following steps:

1. Initialisation: estimation of starting values for position, velocity, acceleration and their covariance matrix. We use three consequent measured positions (x_1, y_1, … x_3, y_3) for the computation of these values:

$$\mathbf{x}_0 = \begin{bmatrix} x_3 & y_3 & \frac{x_3 - x_2}{\Delta t} & \frac{y_3 - y_2}{\Delta t} & \frac{x_3 - 2x_2 + x_1}{\Delta t^2} & \frac{y_3 - 2y_2 + y_1}{\Delta t^2} \end{bmatrix}^T \tag{7}$$

$$\mathbf{Q}_{x,0} = \mathrm{diag}\left(\sigma_x^2 \quad \sigma_y^2 \quad \frac{2\sigma_y^2}{\Delta t^2} \quad \frac{2\sigma_y^2}{\Delta t^2} \quad \frac{4\sigma_x^2}{\Delta t^4} \quad \frac{4\sigma_y^2}{\Delta t^4} \right) \tag{8}$$

2. Prediction:

$$\mathbf{x}_k = \mathbf{T}\,\mathbf{x}_{k-1}, \quad \mathbf{Q}_{x,k} = \mathbf{T}\,\mathbf{Q}_{x,k-1}\mathbf{T}^T + \mathbf{Q}_k \tag{9}$$

3. Computation of gain matrix:

$$\mathbf{K}_k = \mathbf{Q}_{x,k}\mathbf{H}_k^T \left[\mathbf{R}_k + \mathbf{H}_k \mathbf{Q}_{x,k} \mathbf{H}_k^T \right]^{-1} \tag{10}$$

4. Update state vector using measurements from current epoch:

$$\hat{\mathbf{x}}_k = \mathbf{x}_k + \mathbf{K}_k \left[\mathbf{L}_k - \mathbf{H}_k \mathbf{x}_k \right] \tag{11}$$

Store state variables for the next epoch:

$$\mathbf{x}_k = \hat{\mathbf{x}}_k \tag{12}$$

5. Update covariance matrix:

$$\hat{\mathbf{Q}}_{x,k} = \left[\mathbf{I} - \mathbf{K}_k \mathbf{H}_k \right] \mathbf{Q}_{x,k} \tag{13}$$

Store covariance matrix for next epoch:

$$\mathbf{Q}_{x,k} = \hat{\mathbf{Q}}_{x,k} \tag{14}$$

Steps 2 to 5 are repeated for everey new GPS observation. Symbol (^) denotes the optimum estimate and subscript k denotes epoch number. **T** is transition matrix that can be obtained by solving the differential equation (3):

$$\mathbf{T} = e^{\mathbf{F}\cdot\Delta t} = \begin{bmatrix} 1 & 0 & \Delta t & 0 & \Delta t^2/2 & 0 \\ 0 & 1 & 0 & \Delta t & 0 & \Delta t^2/2 \\ 0 & 0 & 1 & 0 & \Delta t & 0 \\ 0 & 0 & 0 & 1 & 0 & \Delta t \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{15}$$

Δt is time interval between GPS observations. **L** denotes vector of observations, i.e. horizontal coordinates expressed in national reference system:

$$\mathbf{L}_k = \begin{bmatrix} x & y \end{bmatrix}^T \tag{16}$$

R is covariance matrix of observations:

$$\mathbf{R} = \begin{bmatrix} \sigma_x^2 & 0 \\ 0 & \sigma_y^2 \end{bmatrix} \tag{17}$$

The elements of this matrix are available together with the coordinates from GPS receiver.
H is design matrix that relates state vector with observations:

$$\mathbf{H} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{18}$$

$\mathbf{Q}_k$ is covariance matrix of $\mathbf{w}_k$ given by:

$$\mathbf{w}_k = \int_k^{k+1} \mathbf{T}_{k+1,\tau}\mathbf{G}_\tau\mathbf{u}_\tau d\tau \tag{19}$$

$$\mathbf{Q}_k = E\left[\mathbf{w}_k \mathbf{w}_k^T\right] = \begin{bmatrix} \Delta t^5 q_{\dot{a}x}/20 & 0 & \Delta t^4 q_{\dot{a}x}/8 & 0 & \Delta t^3 q_{\dot{a}x}/6 & 0 \\ 0 & \Delta t^5 q_{\dot{a}y}/20 & 0 & \Delta t^4 q_{\dot{a}y}/8 & 0 & \Delta t^3 q_{\dot{a}y}/6 \\ \Delta t^4 q_{\dot{a}x}/8 & 0 & \Delta t^3 q_{\dot{a}x}/3 & 0 & \Delta t^2 q_{\dot{a}x}/2 & 0 \\ 0 & \Delta t^4 q_{\dot{a}y}/8 & 0 & \Delta t^3 q_{\dot{a}y}/3 & 0 & \Delta t^2 q_{\dot{a}y}/2 \\ \Delta t^3 q_{\dot{a}x}/6 & 0 & \Delta t^2 q_{\dot{a}x}/2 & 0 & q_{\dot{a}x}\Delta t & 0 \\ 0 & \Delta t^3 q_{\dot{a}y}/6 & 0 & \Delta t^2 q_{\dot{a}y}/2 & 0 & q_{\dot{a}y}\Delta t \end{bmatrix} \quad (20)$$

4. DESCRIPTION OF ALGORITHM

The software reads in position from GPS receiver, finds the segment in the road model and computes the distance to the road edges. If the distance is shorter than critical value d_{min}, then the system triggers alarm "*In dangerous zone*". The GPS position is then used to update state vector using the above-described Kalman filter and predicted position (3 s ahead) is computed. If this predicted position falls into the dangerous zone, the alarm "*Heading into dangerous zone*" is triggered. In the next step, the software computes the difference between the direction of the road and computed direction of velocity vector. If this difference is statistically larger than zero, then alarm "Wrong course" is triggered.

5. TEST SETUP

We tested the warning system on road number 68, approximately 10 km stretch between cities Horndal och Hästbo, located 150 km west from Stockholm. This part of the road was surveyed by mobile mapping system Visimind, which is based on combination of GPS, inertial navigation and digital camera sensors. The standard error of surveyed coordinates is 15 cm. The result from this surveying was a list of coordinates of points on the middle line and the width of the road. The distance between surveyed points was 10 m on straight sections and 5 m in curves.

During this experiment we used GPS receiver Trimble R7 with antenna Zephyr placed on the roof of the car – see Figure 2.

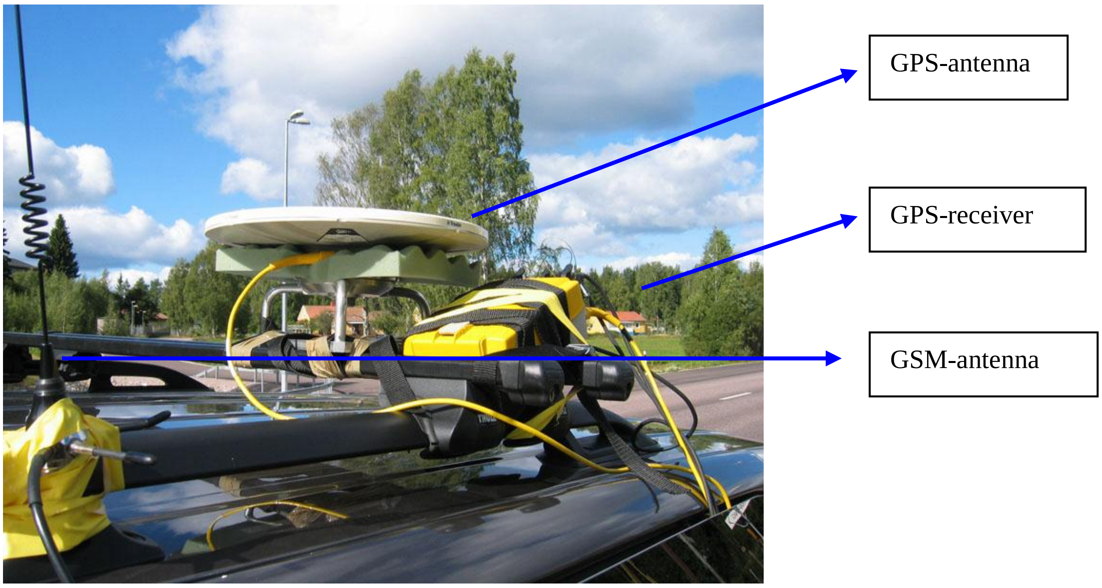

Figure 2. GPS receiver and antenna mounted on the roof of the car.

We drove the stretch several times with speed up to 90 km/h. We performed intentionally several manoeuvres (38) that should trigger warnings, like overtaking and turning towards road edge. Altogether we collected data from 40 minutes of driving. To be able to evaluate the performance of the warning system, we placed a video camera inside the car. Using sound signals generated by the software we could synchronize the video with the graphical output from the system – see Figure 3.
The analysis of the results was performed by visual inspection of the synchronised video. We counted:

- How many false alarms were triggered, i.e the car was not in dangerous zone nor heading there and the system issued an alarm.
- How many correct alarms were triggered.
- How many times no alarm was triggered when the car was in or heading into dangerous zone

The number of satellites and their geometry varied during the test-driving. During 96% of the total driving time, four or more satellites were available and during 76% of time the PDOP was better than 8. In the following analysis we disregard the situations when less then 4 GPS satellites were available.

Figure 3. Output from the warning system synchronised with video.

6. TEST RESULTS

6.1 False alarms

In total there were 32 false alarms triggered during 40 minutes driving, but most of them (21) had very short duration – only 0.2 s. Figure 4 shows the duration of all false alarms. Most of the false alarms occured with autonoumos solution and with high PDOP value. If we take away all 0.2 s long false alarms and those alarms triggerd when PDOP is larger than 10, then only four false alarms are left. All these four alarms have duration 0.4 s and are of type ”*Heading into dangerous zone*”.

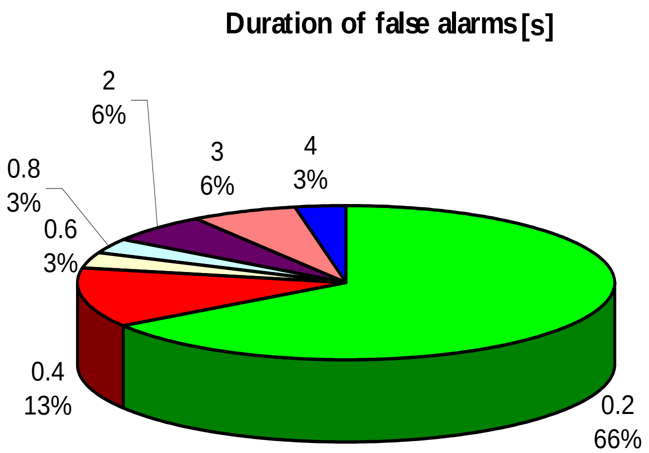

Figure 4. Duration of false alarms

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6.2 Correct alarms

During test-driving we did 38 different manoeuvres that should trigger an alarm. In 32 cases the alarm was issued correctly and in 6 manoeuvres no alarm was triggered. This happened with autonomous (4x) and DGPS (2x) solution. In all these 6 manoeuvres the system showed the position of the car correctly, i.e. in dangerous zone, but the alarm was not triggered because of low precision of the GPS solutions. System issues an alarm only if the car is in dangerous zone with 99% probability. Figure 5 shows the type of GPS solution when the correct alarms were triggered.

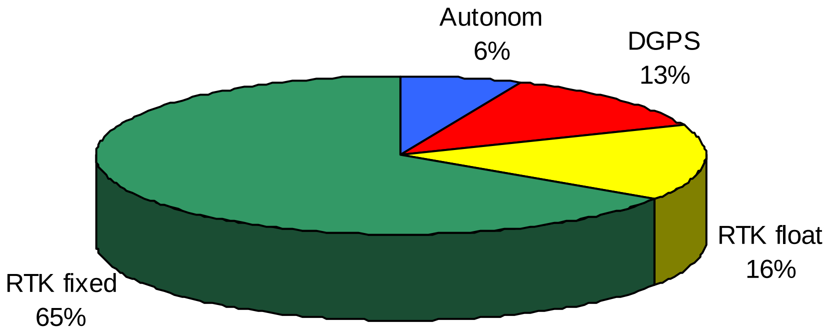

Figure 5. Type of solution when correct alarms were triggered.

7. CONCLUSIONS

Based on the analysis of the test-driving, we can conclude that the system works satisfactory if RTK float or RTK fixed solution is available. This is usually the case in open areas outside the cities. When driving in urban areas, the signals from satellites are often interrupted or blocked by obstacles.

During our test the system issued quite many false alarms, which can be disturbing for driver. Most of these alarms were of type "*Heading into dangerous zone*" and "*Wrong course*". We have shown that the number of the false alarms can be decreased significantly, if the alarm is issued only in the case when it is computed during time period longer than 0.2 s. Another reason for false alarms was bad satellite geometry, i.e. large PDOP, so it is necessary to weight down the observations with large PDOP.

Our test showed that the autonomous solution has better precision than expected. If PDOP value was less than 8, the system showed correct position of the car relative to the road edges. Even during manoeuvres the computed position was in very good agreement with real position of the car.

Despite of very promising results shown by our test, currently there are limitations that prevent broader use of such system. First of all, in many countries, including Sweden, the precision of existing road models is not sufficient for this purpose. Secondly, the price of RTK GPS receivers is high. This is because of relatively small user group of such receivers. But it can be assumed that the price will decrease with increasing number of users. Another issue is availability of RTK corrections. Currently there are just limited areas covered by such corrections but it can be assumed that the coverage will grow as the demand for this service is also growing.

Since the purpose of this project was to study feasibility of using GPS as a sensor in the warning system, we did not address all issues connected to practical implementation of the system, like integrity and reliability of GPS, detection of sensor failures, the form of alarm suitable for driver, etc. It should be also pointed out that GPS has its advantages and limitations. This is statement is true for other navigation sensors as well. Therefore it would be beneficial to add other complementing sensors that can provide positional information when the GPS solution ids not available.

8. LIST OF ABBREVIATIONS

GSM Global System for Mobile communications
f position update frequency
HD hardware delay
TD total delay
PDOP Positional Dilution of Precision, a number that describes the effect of satellites geometry on the positioning precision. The lower PDOP is the better precision is expected. Usually a value below 8 is acceptable.

RTK Real Time Kinematic
GPS Global Positioning System

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BIOGRAPHICAL NOTES

Milan Horemuž, PhD. is employed as researcher in the Royal Institute of Technology in Stockholm since 1996. Previously he worked in Slovak Technical University in Bratislava where he received his PhD degree in geodesy. His current research interest is precise GPS positioning for deformation measurements and application in traffic research.

CONTACTS

Horemuz Milan, PhD
Royal Institute of Technology
Department of Transport and Economics
Division of Geodesy
Teknikringen 72
100 44 Stockholm
SWEDEN
Tel. + 46 8 790 73 35
Fax + 46 8 790 73 43
Email: horemuz@kth.se
Web site: http://www.infra.kth.se/geo/