



Integration of GNSS and Loran-C

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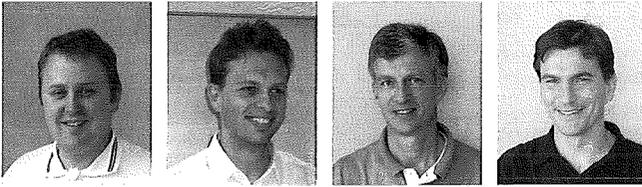
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Abstract

For many navigation applications, e.g. in urban or mountainous areas, insufficient satellite visibility of the Global Navigation Satellite System (GNSS) is an issue. This problem can be reduced by integrating GNSS with other dissimilar systems, where the drawbacks of the individual systems compensate each other.

An attractive option is the terrestrial radio navigation system Loran-C. Integrating GNSS and Loran-C improves the reliability and availability of the positioning information significantly. Within the GLORIA (GNSS and Loran-C in Road and Rail Applications) project, funded by the European Community (EC), the development and evaluation of a hybrid navigation receiver is demonstrated [1]. This innovative approach opens the door to new applications and to major improvements in existing application designs for land transport.

Zusammenfassung

Viele Landanwendungen der Navigation, vor allem im städtischen bebauten Bereich und im alpinen Raum, leiden unter der schlechten Satellitensichtbarkeit von Global Navigation Satellite Systems (GNSS). Diese Schwierigkeiten können durch eine Integration von GNSS mit anderen, verschiedenen Systemen kompensiert werden. Die Idee der Integration beruht darauf, dass ein Sensor die Nachteile der anderen Sensoren kompensiert. Neben der Verwendung von autonomen Navigationstechniken wie Koppelnavigation (dead reckoning) oder Inertialnavigation sind terrestrische Radionavigationssysteme wie z.B. Loran-C eine gute Ergänzung zu GNSS. Die Integration von GNSS und Loran-C erhöht die Zuverlässigkeit und Verfügbarkeit von Positionslösungen signifikant.

Dieser Bericht präsentiert die Entwicklung und Evaluierung einer neuen hybriden Empfängergeneration im Rahmen des von der EU finanzierten Projektes GLORIA (GNSS and Loran-C in Road and Rail Applications). Die Innovation beruht auf einer Integration von Rohdaten. Dieser neuartige Zugang verbessert bestehende Anwendungsmöglichkeiten und öffnet Türen für neue Betätigungsfelder auch außerhalb der Landnavigation.

1. Introduction

Envisaged are navigation solutions for land application focused on road and rail transport, but not exclusively limited to these domains. In the future, also pedestrian navigation will be favoured by reduced receiver size and weight.

In land navigation, specific situations with various environments are given: On the one hand, there are urban areas with high buildings and typical infrastructure of a city. On the other hand, no artificial infrastructure is present in rural areas, but we have to cope with limitations in signal reception due to difficult topography. Due to the required direct line-of-sight between satellites and receiver, today's satellite navigation systems most frequently used are not able to deliver position information every time in every environment.

The U.S. Global Positioning System (GPS), is the best-known GNSS system [2]. For navigation applications, primarily C/A-code measurements

are used to derive the position information. Also carrier phase smoothing of code measurements is sometimes applied. For improving the accuracy and reliability of satellite-based positioning, Space Based Augmentation Systems (SBAS), like the American WAAS (Wide Area Augmentation System), the European EGNOS (European Geostationary Navigation Overlay Service), and the Japanese MSAS (Multi Satellite Augmentation System) can be used. Also terrestrial techniques (Eurofix in Europe) support high performance requirements in navigation by broadcasting augmentation information. Integrity information and enhanced accuracy of position solutions are the most important benefits resulting from these augmentation systems. However, it is not possible to overcome all insufficiencies of GPS. Beside the required direct line-of-sight to the satellites, the most critical problem is the accidental or deliberate jamming of satellite signals [3].

But GPS is not the only satellite-based navigation system, which is open for civil use: GLO-NASS (Global Navigation Satellite System) is the

Russian pendant to GPS. At present, only 7 of 24 necessary satellites are operational, but there exist plans of the Russian government to modernise the GLONASS system within the next years and to regain Full Operational Capability (FOC). However, GLONASS has the same problems and insufficiencies like GPS due the similar system properties.

Galileo is Europe's future satellite navigation system and its FOC is scheduled for 2008. This new civilian system belongs to the enhanced GNSS-2 level. [4]

There exist various approaches to overcome the shortcomings connected to satellite navigation. One promising candidate is to supplement satellite-based navigation by data of other sensors. The concept of this sensor fusion technique will be outlined in the subsequent sections.

2. Sensor fusion

Sensor fusion means a combination of different sensors to compensate drawbacks of one sensor by another. Some candidate sensors and systems are listed below.

2.1. Autonomous Navigation Techniques

Autonomous positioning techniques, i.e., techniques without support by an external system like terrestrial transmitters or satellites, are relative methods. This means that they determine positioning information relative with respect to a given reference station. To get the absolute position information, e.g. an initialisation of the autonomous navigation system has to be carried out. Due to propagation and accumulation of various measurement errors, autonomous techniques frequently suffer from accuracy degradation over time.

Electronic compasses for direction determination and odometers for relative distance measurements may be regarded as autonomous sensors. Differential odometers deliver distance and direction changes at once. Inertial navigation systems (INS) can also be used for measuring relative distance and direction variations. However, high quality INS are very expensive.

2.2. Radio navigation

Terrestrial Radio navigation uses on the one hand existing radio networks, like mobile phone or digital TV transmitter, and on the other hand

dedicated navigation systems, like Loran-C. Position solutions derived from measurements in cellular networks and digital TV networks are characterised by a good availability, but currently cannot meet the performance requirements of land navigation. Loran-C, on the other hand, fulfils the minimal position accuracy in the test areas. Other features of the Loran-C signal are the high signal strength and a wavelength in the low frequency range. Due to these characteristics, a good signal penetration in all outdoor environments is given. In addition to the navigation signal, an augmentation signal (Eurofix) can simultaneously be transmitted via the Loran-C carrier. Main disadvantages of Loran-C are:

- Hardly predictable propagation effects of the carrier, if the signal travels over landmasses. This unknown signal propagation delay is referred to as ASF (Additional Secondary phase Factor) and can cause degradations of the absolute positioning accuracy down to some kilometres.
- Due to organisational uncertainties, the future of the system is unknown [6,7].
- Long signal integration times of measurements limit the use of current receivers for dynamic applications.

2.3. Mathematical methods and options of fusion

A very common mathematical method for combining different sensors and systems is to use a Kalman filter. The Kalman filter is a recursive and linear algorithm for the optimal estimation of various navigation parameters, which is based on a dynamic model of the vehicle motion. For more information about Kalman filtering in navigation applications see [6]. Also an epoch-per-epoch adjustment algorithm can be applied for the fusion of various sensors.

Generally, sensors can be loosely or tightly coupled. The integration of data can be done on the position data level (loose coupling) or on raw data level (tight coupling). The integration on the position data level offers the advantage that each system works independently and outputs an individually computed position. These individual positions are then integrated within the filter algorithm. When integrating the sensors on raw data level, all raw measurements are used together to deliver a common position solution. The advantage is that the integrated system provides useful navigation information even if one of the individual systems fails to compute an individual position.

When integrating different sensors and system, various aspects have to be discussed: Most sensors deliver measurements or position data based on different coordinate reference frames and time reference systems. GPS, e.g., uses the coordinate reference frame WGS-84 (World Geodetic System 1984). The position of the Northwest European Loran-C System (NELS) stations are also given in WGS-84 coordinates. If necessary, coordinates of different Cartesian reference frames can be harmonised by performing a seven-parameter coordinate transformation also called Helmert transformation. The time reference systems in use for the GPS/Loran-C integration are GPS system time and UTC (Universal Time Coordinated) as realized by the NELS control centre at Brest (France). The time synchronisation can be achieved by considering an additional unknown parameter to be solved within the estimation process. Note that there is a variable time offset between GPS time and UTC of 13 seconds (May, 2003).

Finally, it has to be mentioned that different systems deliver measurement or position data on different accuracy and availability levels. Another task in sensor fusion is the calibration of the integrated system which can be done in laboratory tests and setups.

3. Realization

The choice of sensors for an integrated navigation system depends on the characteristics of the various candidate systems. E.g., the terrestrial system Loran-C has a dissimilar signal characteristic compared to the space based GPS. Common vulnerabilities are almost not present. Another advantage for this combination is the good signal penetration of Loran-C in GPS hostile environments, like dense canopy in rural areas, or between high buildings in cities. Although Loran-C has low absolute accuracy, the relative (repeatable) accuracy of the system is very high and even comparable to GPS. The idea when combining the two systems is therefore to calibrate the absolute accuracy of Loran-C (i.e. to remove the influence of ASFs) during phases of good GPS availability and to use the calibrated Loran-C signal to continue the position computation during phases of limited GPS availability or also during complete GPS outages.

The combination is also suitable for additional sensors, although the mentioned combination

can already fulfil the user requirements for many land transportation applications.

In the GLORIA project, GPS and Loran-C have been combined within one receiver type called DURAN (Dual Radio Navigation Receiver). This receiver integrates three major components, i.e. the LORADD prototype (innovative Loran-C receiver), a commercial GPS receiver, and a micro-processor for carrying out all computations.

3.1. DURAN Components

The LORADD is a fully digital, multi-chain, all-in-view Loran-C (and Chakya) receiver. It includes two 16-bit analog-to-digital (AD) converters, which operate at a sampling frequency of 400 kHz, and a high-end digital signal processor (DSP). The range-measurement loops track the incremental phase of all received and selected Loran-C signals. Since the phase of a signal may only be measured within one cycle, the receiver tracks each station from an unknown starting point that is "arbitrarily" fixed when turning on the receiver. The initial unknown number of full carrier cycles between the receiver and each transmitter station is obtained by tightly coupling the LORADD to the GPS component of the DURAN (this procedure is denoted as Loran-C calibration). Apart from its Loran-C navigation functionality, the LORADD also supports Eurofix, i.e., the GNSS augmentation service relying on Loran-C as a data link. Along with the receiver, Reelektronika has developed a prototype of an omni-directional magnetic field (H-field) antenna for the LORADD. According to earlier investigations, the H-field of the Loran-C signals provides a better penetration into urban areas than the electric field (E-field) [8].

The GPS part of the DURAN is realised by a commercial GPS receiver board developed by NovAtel (i.e., the GPS component is a common off-the-shelf (COTS) product) [9]. Although the OEM4 also provides carrier phase tracking on both GPS carrier frequencies (L1 and L2), only L1 C/A-code pseudorange measurements are processed within the DURAN.

The OEM4 was chosen since it is a high-quality instrument, which avoids introducing errors into the DURAN navigation solution that are typical of low-cost GPS receivers. The receiver is used together with its corresponding geodetic GPS antenna.

The heart of the DURAN is the integrated navigation software (IntNav) designed by TeleConsult-Austria (www.teleconsult-austria.at). In the

present version of the prototype, the IntNav software runs on a high-performance Pentium-type processor. For a future miniaturisation, this processor will be replaced by a more suitable DSP.

3.2. IntNav – The GPS and Loran-C integration software

As it becomes clear from the previous sections, the fusion of GPS and Loran-C should allow to compensate the main disadvantages of the individual systems. E.g., the low absolute positioning accuracy of Loran-C can be compensated by GPS, whereas Loran-C can bridge GPS outages caused by limited satellite visibility. Thus, performing a GPS-aided calibration of the Loran-C measurements seems to be the most convenient way to realise the integration. The calibration is carried out during phases of good GPS satellite visibility by a continuous computation of the theoretical Time of Arrival (TOA) of Loran-C signals and a comparison of that value with the corresponding measured TOA. The difference between computed and measured TOA yields a calibration value for the respective Loran-C station. During limited GPS availability, these calibration values are used to compensate the low absolute accuracy of Loran-C and, thus, to continue the position computation with near GPS-accuracy. The computation of Loran-C calibration values uses a simplified propagation model of Loran-C signals and bases on the current estimated receiver position. To ensure the reliability of the calibration, it is further essential to apply an automated decision-making procedure for deciding whether the GPS performance is qualified for calibrating Loran-C.

To realise these theoretical considerations, TeleConsult Austria has developed the GPS – Loran-C integration software IntNav. Although

GPS and Loran-C snuggle together in this integration software, it has to be distinguished between individual pre-computational parts and a common integration part:

GPS pre-computations

Positions of GPS satellites: As GPS satellites move around the earth, the position of satellites has to be computed for each measurement epoch. The corresponding information can be derived from the broadcast ephemerides, which are transmitted by the GPS system itself.

Compensation of GPS signal propagation effects: The propagation of GPS signals is mainly affected by the ionosphere and the troposphere. Therefore, the integration software is able to apply models for compensating these propagation effects: The influence of the ionosphere is reduced by the broadcast 8-coefficients ionospheric model, whereas the influence of the troposphere is reduced by the modified Hopfield model. Applying these models to the measurements is optional.

Computation of measurement weights: To obtain individual weights for GPS measurements, mainly the elevation of the corresponding satellite is considered.

Loran-C pre-computations

Compensation of Loran-C propagation effects: The propagation of Loran-C signals over land-masses is mainly affected by the conductivity of the underground. The propagation delay, which is therefore introduced, is called Additional Secondary Factor (ASF). The pre-computation part of IntNav corrects Loran-C TOAs by applying calibration values, which have been derived during phases of good GPS availability.

Smoothing of Loran-C TOAs: The software has a built-in low-pass filter, which can optionally be applied to smooth Loran-C measurements.

Programming language	C/C++
Currently supported OS	Win 9x, Win 2k, Linux
Application environment	Console
Currently supported navigation systems	GPS, GLONASS, Loran-C
Measurement value	GNSS pseudoranges, Loran-C TOAs
Operation modus	Selectable: Real-time - Post-processing
Calibration of Loran-C	GPS-aided, real-time
Data pre-filtering	Elliptic low-pass filter
Quality check of solution	RAIM, DOP computation
Position computation algorithm	Selectable: Epoch-wise Adjustment - Kalman Filter
Overall structure	Modular, expandable
Currently supported devices	Ashtech GG24, NovAtel OEM4-3151R, Locus SatMate 1000 & 1020.

Table 1: Features of IntNav Software

Computation of measurements weights: The quality of Loran-C measurements is in a first approximation indirectly proportional to the distance between Loran-C transmitter and receiver. This is also the main input for individual Loran-C weight computations.

GPS and Loran-C integration part

The core of the IntNav software is an adjustment algorithm, which performs the integrated position computation. Besides the current position of the receiver, also some quality information, i.e., an estimation for the position accuracy, is obtained. The common integration part further consists of various consistency checks of the measurements, as well as a Receiver Autonomous Integrity Monitoring (RAIM) algorithm.

Concluding, Table 1 summarises the main features of the IntNav software.

The software is currently subject to further development and modification. Because of its modular structure, it can easily be adapted to various platforms and operating systems. Also the list of supported navigation devices can easily be expanded.

4. Receiver test and evaluation

The major aim of the tests was to compare the results of the DURAN with stand-alone GPS (re-

ference case) and to investigate the potential benefits of the new receiver for road applications. Rail applications were also treated within the GLORIA project but will not be presented in this report. For all tests, the two chains of the Northwest European Loran-C System (NELS) with the master stations at Lessay (France) and Sylt (Germany) have been used. These Loran-C chains provide the best reception quality within the testing areas in the Netherlands, France, and Belgium for the major environment types rural, urban, highway. In these areas 14 static and kinematic tests were performed.

The test vehicles were not specifically modified for the tests. All measurement data were recorded in the internal memory of the receivers. The investigation of the DURAN performance was mainly done in post processing. The required offline version of the IntNav software used in this case operates completely analogous to the real-time version installed in the DURAN. The main advantage of post processing analysis is, that certain parameters of the algorithms can be modified to achieve better overall performance of the receiver. This optimization phase was carried out in parallel to the investigation of the receiver performance. Afterwards, the resulting final settings of the software were stored in the receiver for online position computing.

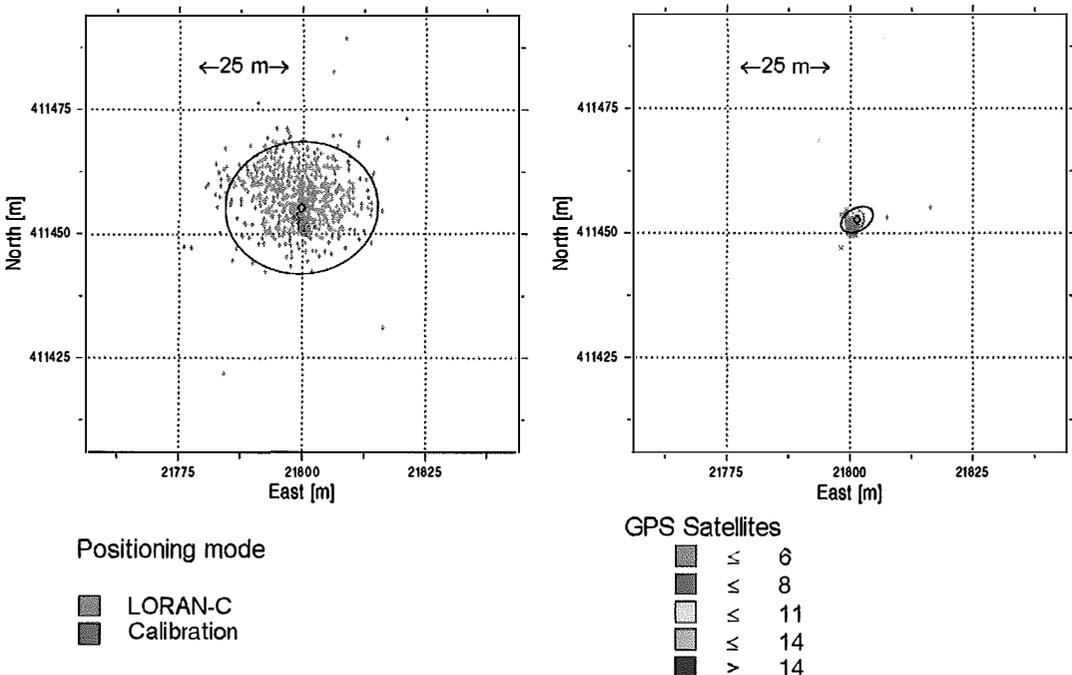


Figure 1: Loran-C Position (left) and GPS Position solution (right)

Method applied	Error ellipse (95%)		Bias [m]		Avail. w.r.t. time [%]	Max. out. [s]
	axes [m]	orient. [°]	north	east		
GPS stand-alone (reference case)	3.5 / 2.2	59	-	-	99.2	2
DURAN (fully integrated)	3.5 / 2.2	60	0.0	0.0	100	0
Calibrated LORAN-C	16 / 13	87	2.3	-1.3	93.2	15

Table 2: Numerical results of Static test Eiffel tower

TeleConsult employed some additional measurement equipment for determining alternative GPS reference trajectories. The additional equipment comprised two geodetic Ashtech GPS receivers (GG24, Z12) and the corresponding antennas. In case of GPS outages, no reference data are available. Still, the quality of the DURAN results may be derived from the tests: the resulting trajectories should continue smoothly during GPS outages. The data can be interpreted visually and the consistency of the DURAN results with the nominal trajectories can be verified using map information.

It was clear from the beginning, that even under optimised conditions the variance of the Loran-C position solution would be larger than for GNSS. The test near the Eiffel tower in Paris (F) was performed to investigate the static positioning quality of the Loran-C component of the DURAN and underlines our assumption [Figure 1, Table 2].

Kinematic tests are represented by a test on a motorway south east of Brussels (B). Figure 2 shows the details of the test track during a GPS outage. The DURAN is able to bridge the outage even though there are some short Loran-C outages as well [Figure 2, Table 3].

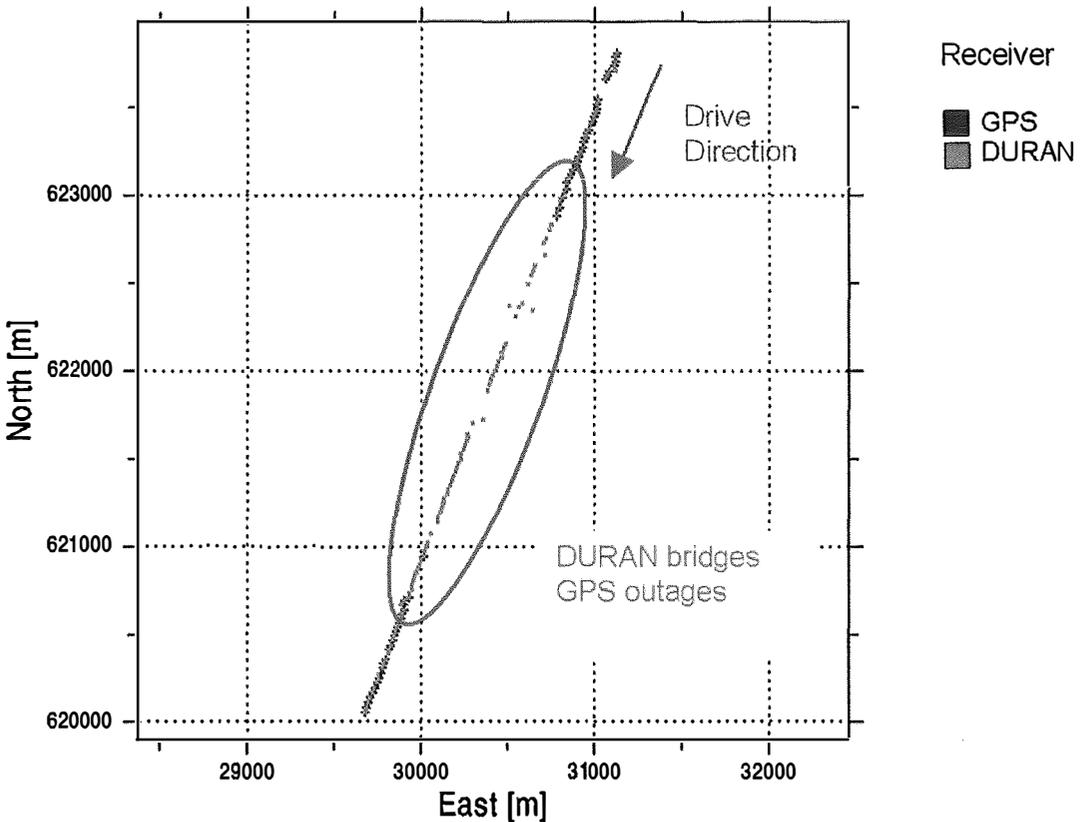


Figure 2: Kinematic test motorway

Receivers	Availability w.r.t. time [%]	Maximum outage duration [s]
GPS stand-alone (reference case)	91.0	76
DURAN (fully in- tegrated solution)	99.7	37

Table 3: Numerical results of kinematic test motorway

5. Summary and outlook

The approach to integrate GNSS and Loran-C is feasible and is verified by good test results. The DURAN increases temporal and local availability of the positioning solution in case of partial GPS outages. Also the overall continuity of the integrated navigation system can be increased. Further, most of the requirements of navigation in road applications, like route guidance of private vehicles, tracing of vehicles for floating car data, and monitoring of dangerous goods on road can be met.

However, there are still some subjects – especially concerning Loran-C – to be investigated in more detail than they are known today. The major drawback of the current DURAN prototype is its limited resistance against electromagnetic disturbances. Furthermore, the improved reacquisition time of the receiver cannot be exploited at the moment because of the required recalibration of the Loran-C data after a Loran-C outage. If such an outage occurs simultaneously with a GPS outage, the new calibration of Loran-C can only be performed if GPS is “back at service”. Further improvements are possible in the issue on when to use GPS to calibrate the Loran-C ranges. Especially for automotive applications, the miniaturisation of the receiver is crucial. DURAN has a large potential in this domain that needs to be exploited in the close future.

The currently limited accuracy of Loran-C in Europe is also caused by the sparse network of transmitter stations available. Further, it was em-

phasised that a significantly increased performance could be achieved if the network was extended only by a few additional transmitter stations.

References

- [1] Abwerzger G., Beyer J., Legat K., Maurer M., Meinhard D., Pfister J., van Willigen D. (2001): GLORIA – Integrating GNSS and Loran-C for high requirement applications. *Galileo's World*, 2(3): 10–16.
- [2] Department of Defense (2001): Global Positioning System standard positioning service performance standard. U.S. Assistant for GPS, Positioning, and Navigation, Defense Pentagon, Washington, DC 20301-6000.
- [3] Department of Defense and Department of Transportation (2002a): 2001 Federal Radionavigation Plan. U.S. National Technical Information Service, Springfield, Virginia, DOT-VNTSC-RSPA-01-3/DOD-4650.5.
- [4] Department of Defense and Department of Transportation (2002b): 2001 Federal Radionavigation Systems. U.S. National Technical Information Service, Springfield, Virginia, DOT-VNTSC-RSPA-01-3.1/DOD-4650.5.
- [5] European Commission (2002): Galileo – The programme for global navigation services. ESA Publications Division, Noordwijk.
- [6] Hofmann-Wellenhof B, Legat K, Wieser M (2003): Navigation – Principles of positioning and guidance. Springer, Wien New York. (In print.)
- [7] NovAtel Inc. (2002): „NovAtel OEM4 Specification Sheet“; available under www.novatel.com
- [8] Pfister J., Kraft M., Legat K., Abwerzger G. (2002): Assessment Report; GLORIA D10 WP5.
- [9] Reelelektronika b.v. (2002): „Receiver system prototype: DURAN“; GLORIA D8-B WP4.
- [10] Volpe National Transportation Systems Center (2001): Vulnerability assessment of the transportation infrastructure relying on the Global Positioning System. Final Report, August 29.

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