

Quality of Map-Matching Procedures Based on DGPS and Stand-Alone GPS Positioning in an Urban Area

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SUMMARY

The use of GIS & GPS systems for urban navigation is mostly affected by the determination of reliable spatial and temporal data along the different road segments. During the last decade, the Laboratory of Geodesy has developed and operated a “closed” navigation and positioning system in the city of Thessaloniki. The VECON system produces its own spatial and temporal data based on GPS and GIS technologies. A very important issue, concerning the spatial but also the temporal data of this system is the quality of Map-Matching procedures. In this paper, the developed statistical models for Map-Matching are being tested on the basis of DGPS and Stand-Alone GPS positioning.

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1. INTRODUCTION

A major problem for land navigation systems in urban areas is the quality of spatial and temporal data along the different road segments. The accurate positioning of a vehicle on the digital road network model is of paramount importance for all kinds of land navigation applications, such as fleet management systems, in-car navigation systems etc. Usually, fleet management systems operate by using GPS technology (Stand-Alone GPS or Kinematic DGPS methodology) to initially determine the position of each vehicle. In addition, a GIS software platform is used to make available digital cartographic data and network analysis capabilities.

Stand-Alone GPS can provide a horizontal positional accuracy of approximately 15 m when Selective Availability (S/A) is turned off by the U.S. Department of Defense. Differential GPS (DGPS) can significantly improve GPS accuracy down to 1 to 5 m when combining and post-processing satellite data collected by the vehicle GPS receiver with data collected by a reference GPS station. Real-time Differential GPS provides similar accuracy when the vehicle GPS receiver corrects its position by using differential corrections radio-transmitted by a reference GPS station in real-time. In an urban built environment, the implementation of both techniques may face certain limitations, namely lack of visibility to the necessary number of satellites (GPS and DGPS) and poor or blocked continuous reception of radio transmissions of differential corrections (DGPS). Other navigation systems can be used for improving the accuracy of GPS positioning, for example dead reckoning systems with digital compass and vehicle odometer.

Many times, the level of positional accuracy obtained is insufficient to ensure that the estimated position of a vehicle's location corresponds to the certain digitally mapped road on which the vehicle is actually travelling. Taking into account that the road network in an urban area is known in the form of a digital map, special computer algorithms can be employed to correlate the computed vehicle location with the road network segments and translate the vehicle raw positions onto the road network, matching the calculated position to the nearest digital road. This vehicle tracking on a given road segment is known as Map-Matching.

Many different algorithms have been devised for map-matching, each of which having advantages and disadvantages. A mathematical framework for map-matching of vehicle positions using GPS is given by Scott and Drane (1994). In this approach, a curve is fitted to a sequence of GPS points by statistical computations. Bernstein and Kornhauser (1996), Kim et al. (1996), and White et al. (2000) use point-to-point matching techniques, mapping the GPS point to the closest node of the road network or point-to-curve matching, mapping the GPS point to the closest line (arc) of the network by computing the minimum distance from

the point to the curve. White et al. (2000) and Taylor et al. (2001) use curve-to-curve matching techniques, comparing a curve defined by a series of GPS points to known curves of the digital map of the area, incorporating or not heading information. Linear regression analysis has been used by Lakakis (2000) to fit GPS points to a certain road centreline. Greenfeld (2002) reviews several approaches for solving the map matching problem and proposes a weighted topological algorithm.

An interesting question is how the accuracy of the measurements can affect the map-matching algorithms when using Stand-Alone GPS receivers instead of DGPS now that SA (Selective Availability) has been turned off. In this paper, the developed statistical models for map-matching are being tested on the basis of DGPS and Stand-Alone GPS positioning.

2. THE SPATIAL DIGITAL MAP DEVELOPMENT

GPS data were gathered with the help of a land navigation system developed in the Laboratory of Geodesy, Department of Civil Engineering under the name VECON System (VEHICLE CONTROL and NAVIGATION SYSTEM) (Savvaïdis et al., 2000a). VECON System has been designed so that it can be used both for building its own digital map and for monitoring traffic conditions in the sense of travel time computations (Savvaïdis et al., 2001).

The VECON System consists of two parts, the control station and the vehicle sensors:

a. The control station, which involves:

- A base GPS station. In this case the base GPS station is the Continuous Reference GPS station that has been operational by the Laboratory of Geodesy since the end of 1999 (Savvaïdis et al., 2000b).
- A Geographical Information System and other software for processing of data and computations.
- Communication unit (UHF radio network).
- Operator(s).

b. The vehicle sensors, each of which involves:

- A GPS receiver (RTCM ready).
- Communication unit.
- An operator (driver).

The basic model used for processing of the measured Stand-Alone GPS and DGPS points and computing the accuracy of the best-fitted curve is a linear regression model. For every road segment, the corresponding GPS points are being fitted to the linear equation:

$$Y = \alpha + \beta X + \varepsilon .$$

The confidence interval or prediction zone for \hat{Y}_0 is given by:

$$\hat{Y}_0 - t_{\alpha/2} \cdot s_{\hat{Y}_0} \leq Y_0 \leq \hat{Y}_0 + t_{\alpha/2} \cdot s_{\hat{Y}_0} .$$

The reliability zone of model parameters α and β is

$$\hat{\alpha} - t_{\alpha/2} s_{\hat{\alpha}} \leq \alpha \leq \hat{\alpha} + t_{\alpha/2} s_{\hat{\alpha}} \qquad \hat{\beta} - t_{\alpha/2} s_{\hat{\beta}} \leq \beta \leq \hat{\beta} + t_{\alpha/2} s_{\hat{\beta}} .$$

One of the targets, regarding the regression model itself, is to construct the confidence intervals and, consequently, to perform the tests of hypotheses about the model's parameters. Furthermore, an additional assumption has to be made, this time about the probability law of the regression residuals. In our case, taking into account that our sample population is large enough, the normal distribution is the one that expresses most satisfactorily the behaviour of the residuals (Davis, 1973). The F-test of the model parameters (Doukas, 1989) comes to verify that they are statistically significant and not equal to zero, a fact that empowers the conclusion that there is a strong linear relation between Y and X. Finally, the square sample correlation coefficient (R^2), which can be interpreted as the proportion of total variability in Y that is explained by X, shows the degree of linear relationship between Y and X.

The straight lines described by the linear regression model can produce the digital map. The regression models have as base the data-clouds produced from the GPS points, one cloud per road segment and direction. These linear models can be tested upon the spatial digital map of the road network (if available – otherwise the computed lines themselves gradually built the digital map), On the other hand, these statistical models can work as prediction tools, capable to offer the map-matching. The prediction zone for the regression model can be used as the criterion to attribute each point to the corresponding line. Finally, the reliability zone of the linear model parameters can be used for the determination of the most reliable linear model.

3. THE FIELD OBSERVATIONS

The measurements were carried out in the centre of the city of Thessaloniki, from December 1 to December 14 (14 days). The measurement-route constantly was on Egnatia Street, at a distance of approximately 2 Km: Starting point in front of the Library of the Aristotle University of Thessaloniki and ending point at the Democracy Square. The vehicle moved in two directions: EW from the University to the Democracy Square and WE from Democracy Square to the University. On every-day basis, there were two periods of measurements per day, during morning (2 hours, from 10:00 to 12:00) and during afternoon (2 hours, from 16:00 to 18:00). Totally, there were 83 passes along this route: 41 during morning hours (21 in the EW direction and 20 in the WE direction) and 42 during afternoon hours, respectively (21 in the EW direction and 21 in the WE direction).

GPS data were collected with the help of the VECON system by using a portable Ashtech GPS (L1/L2) model Z-Surveyor receiver on a vehicle. The antenna was on the roof of the car, stabilized with the help of a strong magnet. All during the drive of the vehicle with the GPS receiver (measurement with recording interval 1 sec, minimum satellites 1, elevation mask 10°), GPS data were also collected by the Continuous GPS Reference Station of the Laboratory of Geodesy, for differential post-processing (DGPS).

4. DATA PROCESSING AND RESULTS

The whole set of the measurements was finally classified into twenty seven (27) data samples for each type of processing (DGPS or Stand-Alone), with the following strategy:

a) There are fourteen (14) data samples for Stand-Alone GPS and thirteen (13) data samples for DGPS. Each one of them is related to a particular day of measurements, respectively. For example, data sample No 3 contains the measurements of the third day; data sample No 9

contains the measurements of the ninth day etc. No solution was reached for Day 348 – data sample 14 and DGPS.

b) After this classification, the other thirteen (13) data samples have a cumulative character each. In simple words, each one contains the data of its related day plus the data of all the previous days. For example, the data sample of the third day contains the data of the first, of the second and the third day. Consequently, the last data sample (No. 14) contains the whole set of data (i.e. the data of all days of the campaign).

Each of the above mentioned data samples, resulted into a simple linear regression model. Tables 1 and 2 show the Standard Deviation Errors of Regression Models and $\hat{\beta}$ factors for every model in cases of WE and EW directions for Stand-Alone and DGPS processing respectively. The optimum regression linear model for each case was selected on the base of the minimum standard deviation error of parameter $\hat{\beta}$ of the model equation. In general, the best fitted model was the one which also had the minimum standard deviation error. Exception of this conclusion can be seen only in rather small samples like the models of Days 342 and 344. The resulting optimum Regression Models and their basic elements are described in Table 3. Finally, Tables 4 and 5 show the prediction (map-matching) zone of the optimum models fitted to the Stand-Alone and DGPS points respectively for three confidence levels (0.950, 0.975 & 0.995).

Stand-Alone GPS and DGPS trajectory points were plotted against the digital map of the city:

- Figure 1 shows the GPS points distribution along the road segment under consideration for the EW direction and the Stand-Alone GPS processing.
- Figure 2 shows the GPS points distribution along the road segment under consideration also for the EW direction and DGPS processing.
- Figure 3 shows the confidence intervals of the optimum regression models in relation to all available computed GPS points for EW & WE directions separately (Stand-Alone GPS processing)
- Figure 4 illustrates a detail of the confidence intervals of the optimum regression models in relation to the available computed Stand-Alone GPS points shown in Fig.3
- Figure 5 shows the confidence intervals of the optimum regression models in relation to all available computed GPS points for EW & WE directions separately (DGPS processing)
- Figure 6 illustrates a detail of the confidence intervals of the optimum regression models in relation to the available computed DGPS points shown in Fig.5

Table 1. Standard Deviation Errors of Regression Models and $\hat{\beta}$ factors for every model in cases of WE and EW directions & Stand-Alone processing (Confidence level 0.950)

Data Sample No	GPS DAY	Model STD Error WE direction	$\hat{\beta}$ STD Error WE direction	Model STD Error EW direction	$\hat{\beta}$ STD Error EW direction
1	335	8.0764	0.000586	6.4655	0.000381
2	336	179.7720	0.008503	7.4581	0.000344
3	337	11.0764	0.000757	19.4025	0.000704
4	338	18.2495	0.001645	11.6198	0.000518
5	339	4.4953	0.000288	2.8175	0.000130
6	340	6.3847	0.000274	7.1747	0.000280

7	341	4.8282	0.000263	7.7496	0.000347
8	342	6.6261	0.000408	8.6450	0.000426
9	343	6.5246	0.000389	6.6047	0.000367
10	344	9.6412	0.000575	6.2958	0.000287
11	345	12.3752	0.000978	6.1522	0.000319
12	346	11.9805	0.000954	6.4899	0.000311
13	347	11.4256	0.000876	12.5379	0.000711
14	348	11.6987	0.000901	6.8874	0.000354
15	335-336	147.7441	0.005830	7.0801	0.000257
16	335-337	121.6619	0.004115	14.1520	0.000362
17	335-338	---	---	13.5930	0.000300
18	335-339	---	---	12.1462	0.000241
19	335-340	---	---	11.3857	0.000201
20	335-341	---	---	10.9745	0.000180
21	335-342	---	---	10.8181	0.000168
22	335-343	---	---	10.5740	0.000158
23	335-344	8.8874 (Day 336 excluded)	0.000181 (Day 336 excluded)	10.2321	0.000146
24	335-345	8.7433 (Day 336 excluded)	0.000170 (Day 336 excluded)	10.0130	0.000138
25	335-346	8.7956 (Day 336 excluded)	0.000174 (Day 336 excluded)	10.0513	0.000134
26	335-347	8.7401 (Day 336 excluded)	0.000172 (Day 336 excluded)	10.0765	0.000132
27	335-348	8.7388 (Day 336 excluded)	0.000172 (Day 336 excluded)	10.0732	0.000128

Table 2. Standard Deviation Errors of Regression Models and β factors for every model in cases of vehicle movement in WE and EW directions & DGPS processing (Confidence level 0.950)

Data Sample No	GPS DAY	Model STD Error WE direction	$\hat{\beta}$ STD Error WE direction	Model STD Error EW direction	$\hat{\beta}$ STD Error EW direction
1	335	12.8529	0.00168	1.0216	0.000140
2	336	3.9222	0.00040	1.3579	0.000084
3	337	1.5285	0.00015	1.4422	0.000092
4	338	9.3842	0.00070	1.4000	0.000081
5	339	1.5867	0.00016	6.1434	0.000516
6	340	1.2848	0.00014	4.9268	0.000321
7	341	1.6415	0.00023	1.6843	0.000117
8	342	1.0227	0.00024	2.0682	0.000167
9	343	---	---	1.9367	0.000177
10	344	0.7995	0.00017	3.3877	0.000241
11	345	2.5049	0.00064	1.6080	0.000236
12	346	---	---	---	---
13	347	---	---	2.2984	0.000217
14	348	---	---	---	---
15	335-336	10.4685	0.00085	1.3552	0.000074
16	335-337	7.5217	0.00046	1.4148	0.000059
17	335-338	8.3750	0.00040	1.4625	0.000049

Data Sample No	GPS DAY	Model STD Error WE direction	$\hat{\beta}$ STD Error WE direction	Model STD Error EW direction	$\hat{\beta}$ STD Error EW direction
18	335-339	7.6640	0.00033	2.7650	0.000087
19	335-340	7.1205	0.00028	3.2642	0.000093
20	335-341	6.7909	0.00026	3.0778	0.000081
21	335-342	6.7184	0.00025	3.0335	0.000075
22	335-343	---	---	2.9693	0.000071
23	335-344	6.6869	0.00024	3.0428	0.000068
24	335-345	6.6073	0.00024	3.0199	0.000067
25	335-346	---	---	---	---
26	335-347	---	---	2.2984	0.000064
27	335-348	---	---	---	---

Some remarks on the evaluation of the statistical procedure and the results obtained:

1. The regression model errors approached very well the normal distribution.
2. The regression models Y to X and X to Y were same in practical level.
3. In all model cases in our study, the R^2 is almost 1.0 and sign F is almost 0.
4. Because of the characteristics of DGPS processing, it was impossible to compute vehicle trajectory points in six cases of daily measurements.



Figure 1. Stand-Alone GPS points distribution along the road segment under consideration in the EW direction

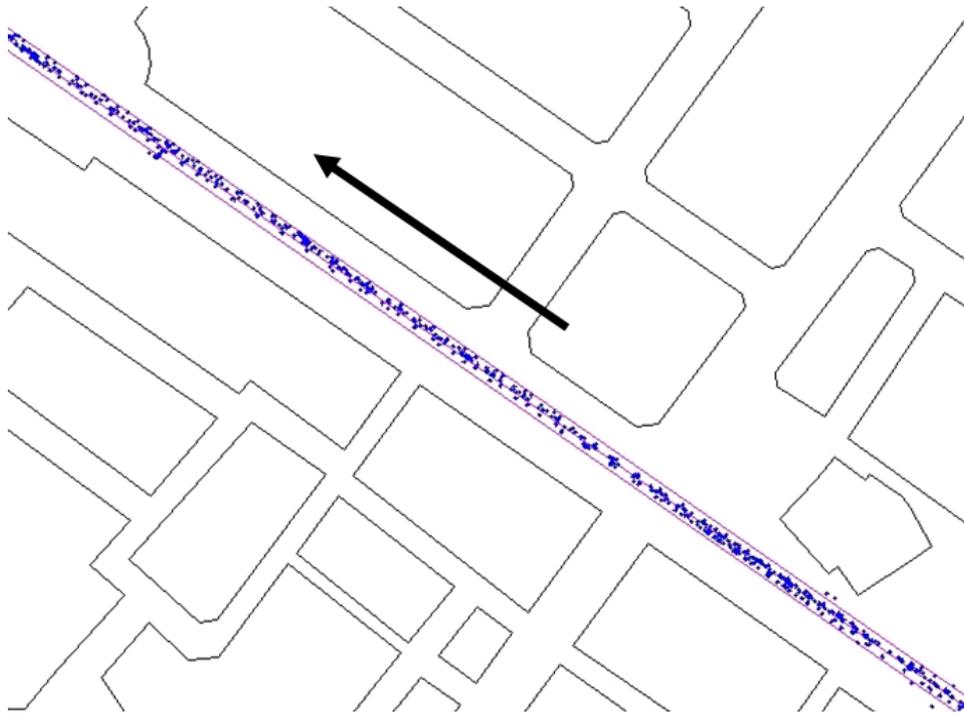


Figure 2. DGPS points distribution along the road segment under consideration in the EW direction

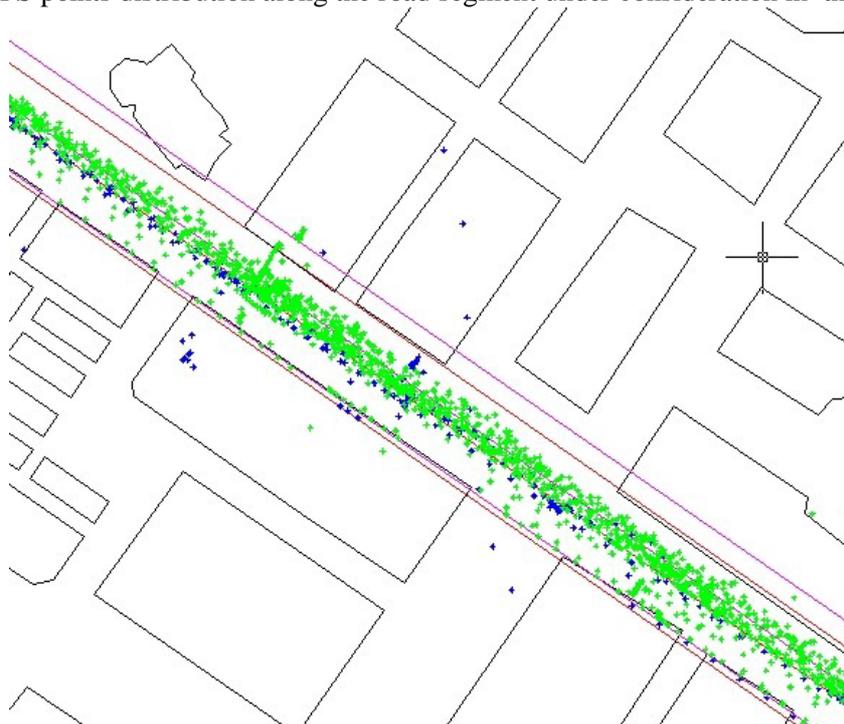


Figure 3. Confidence intervals of the optimum regression models in relation to all available computed Stand-Alone GPS points for EW & WE directions separately

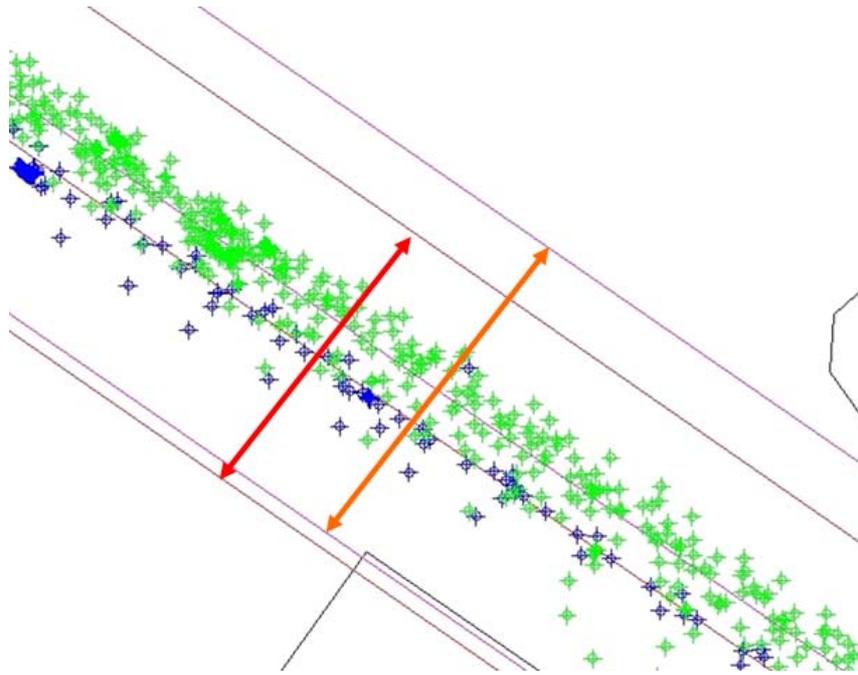


Figure 4. Detail of the confidence intervals of the optimum regression models in relation to the available computed Stand-Alone GPS points shown in Fig.3

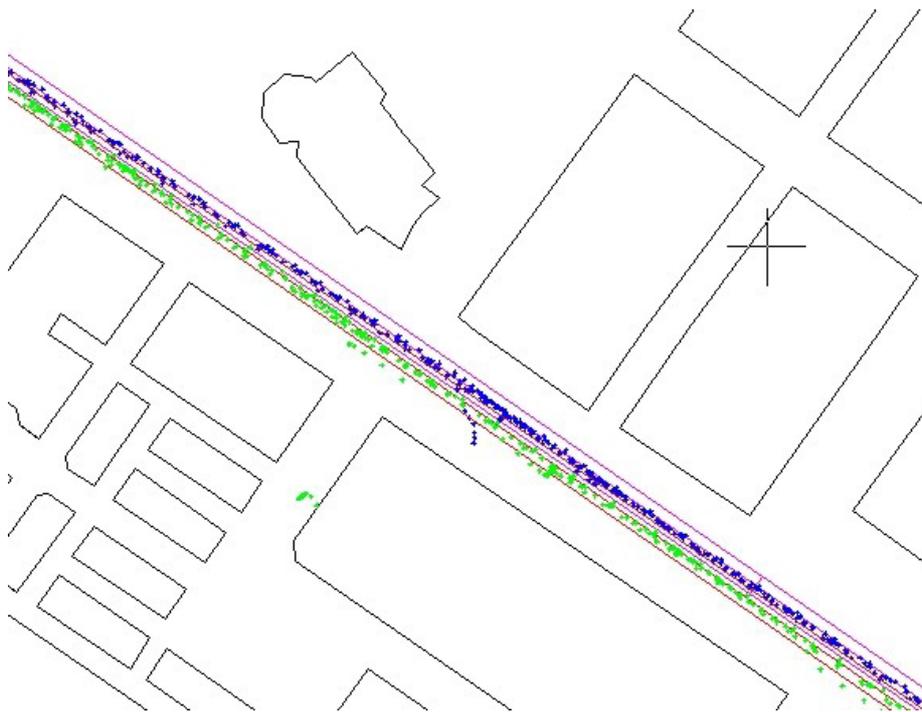


Figure 5. Confidence intervals of the optimum regression models in relation to all available computed DGPS points for EW & WE directions separately

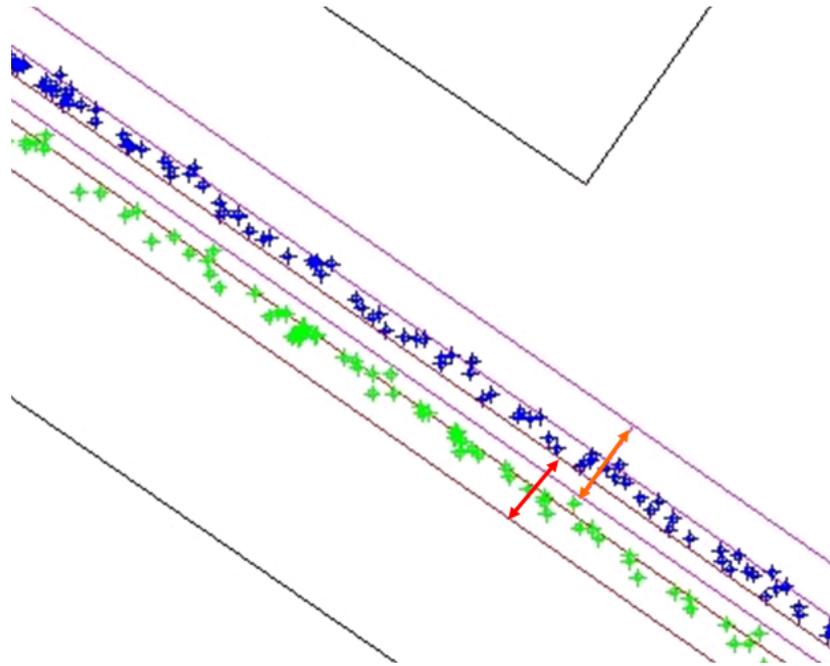


Figure 6. Detail of the confidence intervals of the optimum regression models in relation to the available computed DGPS points shown in Fig.5

Table 3. The optimum Regression Models and their basic elements
(Confidence level 0.950)

GPS Day / Direction	Type of Processing	Models	Points	STD (m)	STD $\hat{\beta}$ (m)
340 / WE	DGPS	$Y = 4787210.62029 - 0.7029971105 * X$	395	1.28480	0.00014
335-338 / EW	DGPS	$Y = 4785974.32888 - 0.6999752004 * X$	3651	1.46259	0.00005
335-345 / WE	Stand-Alone GPS	$Y = 4786796.28955 - 0.7019892268 * X$	12193	8.72290	0.00017
335-348 / EW	Stand-Alone GPS	$Y = 4784998.22137 - 0.6975968949 * X$	25091	10.10034	0.00013

Table 4. The prediction (map-matching) zone of the optimum models of **Stand-Alone GPS** processing for three confidence levels (0.950, 0.975 & 0.995)

GPS Day / Direction	X	Min Max Mid	\hat{Y}_0	Map-Matching zone [m] (0.950)	Map-Matching zone [m] (0.975)	Map-Matching zone [m] (0.995)
335-345* / WE	409884.8650		4499061.5301	14.3523	17.1007	22.4751
	411593.0850		4497862.3780	14.3511	17.0993	22.4733
	410870.7161		4498369.4732	14.3498	17.0976	22.4712

GPS Day / Direction	X	Min Max Mid	\hat{Y}_0	Map-Matching zone [m] (0.950)	Map-Matching zone [m] (0.975)	Map-Matching zone [m] (0.995)
335-348 / EW	409864.6440		4499077.9184	16.6163	19.7981	26.0204
	411655.0620		4497828.9284	16.6166	19.7986	26.0210
	410669.5814		4498516.3965	16.6155	19.7971	26.0191

* (without day 336)

Table 5. The prediction (map-matching) zone of the optimum models of **DGPS** processing for three confidence levels (0.950, 0.975 & 0.995)

GPS Day / Direction	X	Min Max Mid	\hat{Y}_0	Map-Matching zone [m] (0.950)	Map-Matching zone [m] (0.975)	Map-Matching zone [m] (0.995)
340 / WE	410034.0960		4498957.8356	2.1257	2.5327	3.3287
	411569.1110		4497878.7245	2.1212	2.5275	3.3218
	410919.6883		4498335.2668	2.1162	2.5214	3.3138
335-338/ EW	409905.5750		4499050.5919	2.4071	2.8680	3.7695
	411587.8060		4497873.0719	2.4075	2.8684	3.7700
	410677.4865		4498510.2730	2.4063	2.8671	3.7682

In Stand-Alone GPS processing it is possible to have models with significantly bigger standard deviation error than the others due to the low accuracy of the measurements (for example the Day 336 model). Where existing, these observations were removed from the best fitted model estimation procedure.

In all cases, the standard deviation errors of the models obtained from Stand-Alone GPS data were significantly bigger than the ones obtained from DGPS data. As a result, the map-matching zones from Stand-Alone GPS data in a two direction road segment may have overlay space. So it would be impossible to distinguish the exact road segment travelled, unless heading information (previous points in the array) is to be used.

5. CONCLUSIONS

In this paper, the developed statistical models for Map-Matching were being tested on the basis of Stand-Alone GPS and DGPS positioning. Linear Regression models were fitted to GPS points computed from Stand-Alone GPS and DGPS processing for the same road segment. Differential GPS gave much better results than Stand-Alone GPS, as expected. On the other hand, Stand-Alone GPS could follow the trajectory of the vehicle along bigger parts of the road segment under consideration, because it does not face the limitations of DGPS positioning. But the resulting accuracy of Stand-Alone GPS positioning is not enough for reliable map-matching procedures.

Concerning an organisation with a significant fleet of vehicles, it can be said that the time and money that can be earned by using Stand-Alone GPS systems soon enough can be minimized, because of the many problems and the deficiency of the map-matching models, in

the intersections of the road segments and also the extending overlay of the map-matching zones. In time depth, DGPS positioning will be proven more cost-effective for map-matching applications.

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