Exploring the reliability and usability of a portable GPS unit

Jostein Sageie, Per Chr. Hagen, Roy M. Istad, Bjørn Kristoffersen and Ingunn Fjørtoft

Vitenskapelig bedømt (refereed) artikkel

Jostein Sageie & al. Exploring the reliability and usability of a portable GPS unit

KART OG PLAN Vol. 67. pp 47– 54 P. O. Box 5003, NO-1432 Ås. ISSN 0047-3278

Low-cost portable GPS units (Garmin Forerunner 201/301) were tested for reliability and usability. Static measurements were used to examine positional accuracy. With the GPS units placed on a geodetic point, positions were recorded continuously for about 8 hours a day for 23 days ($N = 110\ 228$). To examine distance accuracy, predetermined distances were measured using GPS units mounted on a minitractor and driven on an athletic ground. Both tests were performed in an open space scenario with no objects hindering or reflecting GPS signals. To document the impact of multipath and «lost fixes», a free movement test was carried out using a GPS unit mounted on a person walking close to and around a tall building. Estimated standard deviation from the static measurements was less than 2m in both east-west and north-south directions. This is better than the specifications for the GPS units. There was, however, strong positive dependence between consecutive static measurements and some GPS units sometimes exhibited the same bias over a period of several hours. There was also variation among the GPS units in both the static and distance measurements.

Key words: Global Positioning System, usability, reliability, static measurements, distance measurements, free movement measurements

Jostein Sageie, senior engineer. Department of Economics and Computer Science, Telemark University College, NO-3800 Bø. E-mail: jostein.sageie@hit.no
Per Chr. Hagen, associate professor. Department of Economics and Computer Science, Telemark University College, NO-3800 Bø. E-mail: per.chr.hagen@hit.no
Roy M. Istad, assistant professor. Department of Economics and Computer Science, Telemark University College, NO-3800 Bø. E-mail: roy.istad@hit.no
Bjørn Kristoffersen, assistant professor. Department of Economics and Computer Science, Telemark University College, NO-3800 Bø. E-mail: bjorn.kristoffersen@hit.no
Ingunn Fjørtoft, associate professor (Ph.D.). Faculty of Art, Folk Culture and Teacher Education, Telemark University College, NO-3800 Bø. E-mail: ingunn.fjortoft@hit.no

Introduction

Global Positioning Systems (GPS) are becoming more applicable in commerce and research in areas such as environmental studies, geology and sports. Portable and low cost GPS receivers are available on the market and their use is becoming increasingly common in everyday tasks and in leisure time, exercise and sports. GPS equipment is playing a key role in the so-called «mobile mapping» market, including map updates of roads, vehicle navigation and tracking of outdoor sport activities. In sports such as orienteering, athletes are tracked by portable GPS units and the chosen route is shown on a screen, allowing the audience to follow the race and the performer to analyse his/her track priorities (TracTrac APS). Spatial data is increasingly being applied in sport sciences to determine where physical activity occurs.

Rodriguez, Brown and Troped (2005) examined reliability and validity of GPS units and explored their usability to track physical activity. Their study revealed problems in recording positions in free movement tests where environmental structures such as tall buildings may cause outliers. This was also discussed in a study by Phillips et al. (2001) in which outliers occurred when satellite reception was blocked by tall buildings or reflected from vehicles and other objects. They used another kind of GPS equipment and considered an uncertainty of about 10–20 meters in the recordings as satisfactory for their study. In spite of limitations in the applied technology, both studies recommended GPS monitoring as a promising means for tracking movement patterns and physical activity.

Research issues

The main objectives of this study were to evaluate the reliability and accuracy of positions collected using GPS units of the type Garmin Forerunners 201/301 (GFs). The only difference between the two models is that 301 has an additional heart rate monitor.

Research questions:

- How reliable and accurate are positions collected using GFs?
- How reliable are track distances calculated from collected positions?
- How do buildings and environmental objects affect position accuracy and track distance reliability in free movements?

Methods and experimental design

Three types of measurements were carried out:

- Static measurements where all GPS units were positioned on a geodetic point.
- Distance measurements where all GPS units were mounted on a minitractor driven on an athletic ground.
- Free movement measurements where one GF was mounted on the wrist of a person walking close to and around a tall building.

We tested 8 GFs with software versions 3.50/2.63. MapSource version 6.9.0.1 Beta was used to download data from the GPS units to a PC and to transform positions to coordinates in UTM zone 32 WGS 84. High precision RTK-GPS was used to establish the geodetic point. The elevation angels at the geodetic point are: 12 gon (N), 4 gon (W), 7 gon (S) and 4 gon (E). The length of the reference line (428.8m) was established from the certificate for the athletic ground (Stadium Høgskolen Bø – Telemark, 2003).

The static and distance measurements were carried out with no obstacles hindering satellite signals and no objects implying multipath. A GPS software (Mission Planner) was used to determine periods with poor satellite geometry or a limited number of available satellites. Such periods were so few and so short during our static and distance measurement sessions that these phenomena could be ignored in the further analysis of the data.

Static measurements. Static measurements were carried out over a 23 day period (22 August to 29 September 2005). Measurements were carried out 8 hours per day on average. The GPS units were positioned in a circle around the geodetic point with coordinates E = 503 274.30, N = 6 585 505.92 UTM zone 32 WGS 84. The distance from the geodetic point to the GPS unit antennas was 7cm.

Distance measurements. Distance measurements were carried out in five sessions: three on 11 August 2005 and two on 24 October 2005. The GPS units were moved along a reference line, the line between two running lanes. Figure 1 shows the running track and how the GPS units were mounted on a traverse on the minitractor. The distance from the centre of the traverse to the outermost GPS unit was 33cm. The tractor was driven at a constant speed a number of laps along the reference line. The driving precision was estimated to be ±15cm from the reference line.

Figure 1. The running track, the minitractor and the GPS units mounted on the traverse.

Travelled distance for each GPS unit was adjusted with respect to the unit's position on the minitractor traverse, orthogonal to the driving direction. The innermost GPS unit, number 6, travelled a known distance of 427m per lap. Number 4 was mounted outermost and travelled a known distance of 431m per lap. These adjustments are shown in the first row of data in Table 2 (p. 51).

Free movement measurements. To explore the impact of objects implying «lost fixes» and multipath, a test was conducted using a GF mounted on a person who walked around a tall building less than 10m away from the walls. The free movement test lasted 9 minutes and was carried out 24 October, 2005.

Data processing. The GPS data was downloaded into text files, one file for each GPS unit. For each observation, the text files contained the date and time, and *E* (east-west), *N* (north-south) and *H* (height) coordinates, as well as some other attributes. The text files were loaded into a single MS Access database table using standard import tools and assigning the corresponding GPS unit number to each time/space observation (see Table 1). The *pid* column is automatically generated by MS Access and serves as a unique identification of the row. The data sets needed for analysis and GIS presentations were extracted from this table. The database table for the static measurements has 110 228 rows (23 days, 8 GPS units, ca 8 hours per day, ca 30–60 second logging rate).

Table 1. The database table.

pid	gps	date	time	E	N	H
1	1	22.08.2005	07:52:08	503272	6585506	75
2	1	22.08.2005	07:52:24	503272	6585506	74
3	1	22.08.2005	07:52:58	503272	6585506	74
...	...	...	...	...	...	...
110227	8	29.09.2005	15:42:41	503275	6585506	64
110228	8	29.09.2005	15:42:53	503275	6585506	64

Results

Static measurements. When a GPS unit is used to measure coordinates for a fixed point over a continuous period of time, many consecutive measurements are equal. On the first day (22 August), 623 consecutive measurements over a period of 8 hours were made using GPS unit 1. All of the first 322 measurements (from 7:52 to 11:45) had *E*-coordinate 272 (the 3 last digits in meters). The rest had *E*-coordinate 273 (from 11:46 to 15:21), except for 4 measurements which were 272. Figure 2 is a plot of the *E*-coordinate as a function of time for the 623 measurements.

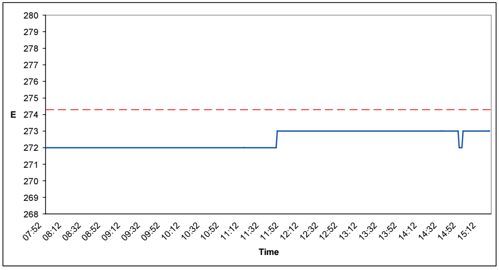

Figure 2. E-coordinate GPS unit 1, 22 August.

All the 623 measurements were below the correct *E*-coordinate which was 274.30. For this GPS unit on this day, there was a bias to the left which lasted for more than 8 hours and for 623 consecutive measurements (Figure 2).

On the next day, 23 August, there was also a clear bias to the left for the same GPS unit (see Figure 3). Approximately 2/3 of the measurements were 270, more than 4m below the correct value. On the third day, 24 August, 98% of the measurements were 275, slightly above the correct value.

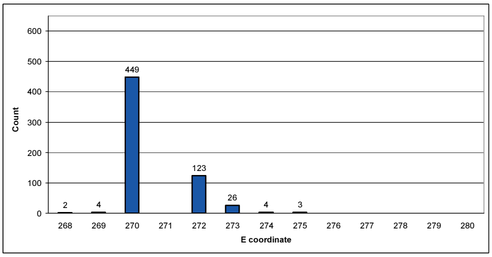

Figure 3. Histogram of E-coordinates for GPS unit 1, 23 August.

Consecutive measurements over a continuous period of time are often equal and they are always very close. One day all measurements for a GPS unit were below the correct value; another day all measurements from the same unit were above the correct value. The variation was not random, and a strong dependence between consecutive measurements was exhibited. This dependence can be described and measured by the *autocorrelation*. Autocorrelation is defined as the correlation between measurement n and measurement $n+i$, where i is the lag between the two measurements ($i = 1, 2, 3, \ldots$).

For the 623 measurements of the E-coordinate on 22 August, the estimated autocorrelations were close to 1.0, the maximum possible value. All autocorrelations at lag 1 to 15 are between 0.90 and 1.0. This indicates a strong positive dependence between consecutive measurements. If these measurements are used to estimate coordinates and standard deviations with formulas that presuppose independent observations, the results will be misleading and wrong.

To obtain independent observations, 1 measurement per day per GPS unit was selected randomly. The 23 selected observations from GPS unit 1 on 23 different days are shown in Figure 4.

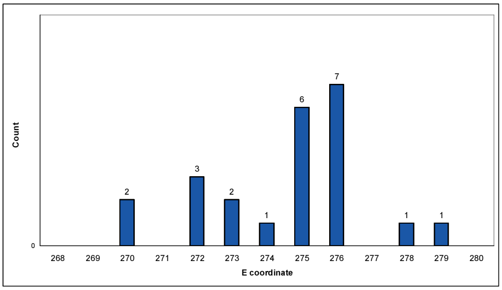

Figure 4. Histogram E-coordinates, GPS unit 1, 1 measurement randomly selected each day.

These 23 selected measurements have estimated autocorrelations close to 0.0 and can be regarded as independent observations. Estimates of the E-coordinate and the standard deviation are respectively $\overline{X}_1 = 274.57$ and $S_1 = 2.27$m. A 95% confidence interval for the E-coordinate based on this set of measurements is 274.57 ± 0.98m.

Figure 5 is a plot of the measured E-coordinate from all 8 units on 22 August. When they measured the same fixed point at the same time, the 8 GPS units had different biases. Unit 3 (blue line) had the largest bias on 22 August, 2–5m below the correct value all day long. The other units measured values closer to the correct value, mostly below but during some periods above the correct value. One day with particularly large variation among the GPS units was 29 August. Most values from unit 3 were 4m above the correct value, while most values from unit 6 were 4m below the correct value.

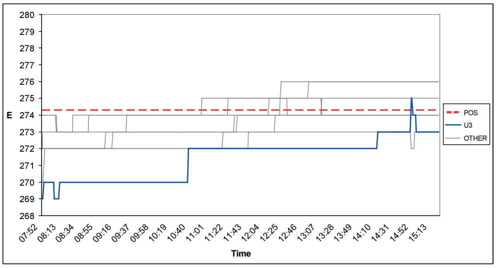

Figure 5. E-coordinate 22 August, all GPS units.

When standard deviation was calculated for each of the 8 GPS units based on the 23 measurements that were assumed independent, the estimate varied from 1.0 m to 2.4m. Nearly the same values were obtained when standard deviation estimates were calculated using *all* measurements from *all* 23 days for each GPS unit (13 000 – 14 000 measurements). Estimated standard deviation for unit 1 was $S_1 = 2.27$m based on the 23 independent measurements (Figure 4) and 2.25m based on all measurements (Figure 6). This is not surprising because observations from many days will provide a representative distribution of measurement values even if consecutive observations within a given day are dependent.

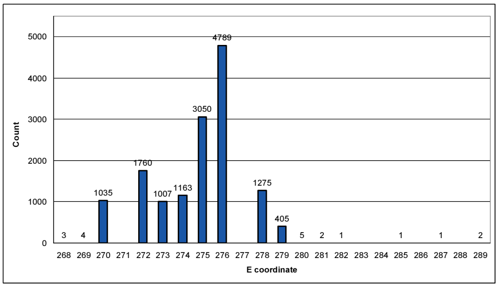

Figure 6. Histogram E-coordinate, GPS unit 1, all measurements.

Estimated standard deviation based on all measurements from all 8 GPS units is S = 1.80m. For independent and normally distributed measurements, 95% of all observations lie within two standard deviations. Here, however, not all measurements are independent. Nevertheless, 91% of all of the measurements here (N = 110 228) fall within the interval of the *correct value ± two standard deviations*, that is 274.30 ± 3.60 = [270.7, 277.9] meters. If the endpoints are rounded making the interval [271, 278] meters, 95% of all measurements fall within the interval.

The results for the N-coordinate are very similar to those for the E-coordinate. Estimated standard deviation of the N-coordinate based on all observations is 1.87m, nearly the same as that of the E-coordinate.

Very few observations lie more than 3 and 4 standard deviations from the correct value (± ca 5.5m and ± ca 7.5m, respectively). In the E direction, only 0.08% of the observations are more than 3 standard deviations from the correct value and only 0.01% more than 4 standard deviations. In the N-direction, the corresponding percents are a bit higher but still very low: 0.4% and 0.2%, respectively.

Distance measurements. In the first measurement session (11 August 2005, 10:00am), the GPS units were moved at a constant speed of 7km/h or 1.94m/s. On the average, positions were recorded every 17th second, i.e. every 33rd meter. This means 5 recordings in each curve, or that each curve may be interpreted as 4 straight lines of equal lengths. We could as well have measured the perimeter of a regular octagon instead of the two half circles (Figure 7).

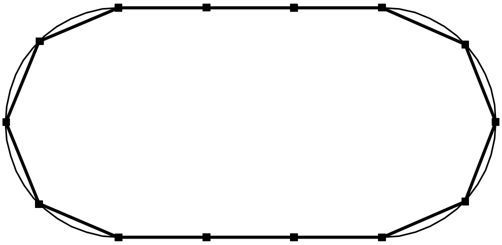

Figure 7. Polygon adjusted running lane. The two curves add up to an octagon.

The perimeter of a regular octagon has 97.45%[1] of the length of the perimeter of the circle it is inscribed in. The distance measured by each GPS unit is compared to this polygon adjusted distance (Table 2, data row 3).

The speed and the number of laps varied for each of the five measurement sessions. Therefore, it is not straightforward to analyse and report the results as a whole, but in Table 3 we have calculated the difference between known and measured distance and the standard deviation of this difference. The

Table 2. Results from session number 1. Polygon adjusted curves: Octagon (8 sides).

	GPS-1	GPS-2	GPS-3	GPS-4	GPS-5	GPS-6	GPS-7	GPS-8
One lap (m):	430	429	427	431	428	427	429	430
3 laps (m):	1291	1287	1282	1292	1284	1280	1286	1289
Polygon adjusted (m):	1271	1267	1262	1272	1264	1261	1266	1269
Measured distance (m):	1262	1283	1281	1288	1249	1258	1276	1265
Difference (m):	-9	16	19	16	-15	-3	10	-4

Table 3. Difference (m) from known distance for all GPS units for each session.

Session	Average known distance	Average measured distance	Difference	Standard deviation of the difference
1:	1266.5	1270.3	3.8	13.0
2:	1688.6	1699.4	10.8	12.3
3:	1270.8	1271.4	0.6	19.3
4:	2533.0	2552.4	19.4	17.6
5:	7200.5	7191.3	-9.2	84.9

---

[1] $(8/\pi)\cdot\sin(\pi/8) = 0.9745$

calculations are based on tables such as Table 2 for the remaining four measurement sessions.

Note that the standard deviations are all quite small compared to the known length. In session 2, for example, the standard deviation is only 12.3m compared to the known distance of 1689m. However, row 5 in Table 2 shows that the GPS units differ in their deviation from the known distance. This is more evident in Table 4, where we compare the deviation from the known distance for each measurement session and each GPS unit.

Table 4. Difference (m) from known distance for each GPS unit for each session.

Session	GPS-1	GPS-2	GPS-3	GPS-4	GPS-5	GPS-6	GPS-7	GPS-8
1:	-9	16	19	16	-15	-3	10	-4
2:	-12	24	18	15	-4	15	19	11
3:	-23	25	23	6	-26	-5	12	-7
4:	-13	38	17	27	34	6	35	11
5:	-106	149	40	0	-70	24	-8	-103

Free movement measurements. The track from the free movement test presented in Figure 8 shows that accuracy and reliability of positions decreases substantially when moving close to a tall building. Positions on the roof and tracks crossing the roof are clearly errors. The positions marked in the figure with 1, 2 and 3 are typical outliers. At numbers 2 and 3 we can also see a «tracing back on track positions» effect.

Discussion

Static measurements. From the 23 independent observations, we calculated the 95% confidence interval, 274.57 ± 0.98m, which is a good and precise estimate of the correct *E*-coordinate, 274.30. To perform this kind of estimation, a number of independent observations of the coordinates of the same point are needed, e.g. observations from different days. If a GPS unit of this type is used over a continuous period of time, the result will be strongly dependent observations and an almost constant bias which may be up to 4–5m either to the left or to the right. Such observations can not be used for estimating coordinates and standard deviations.

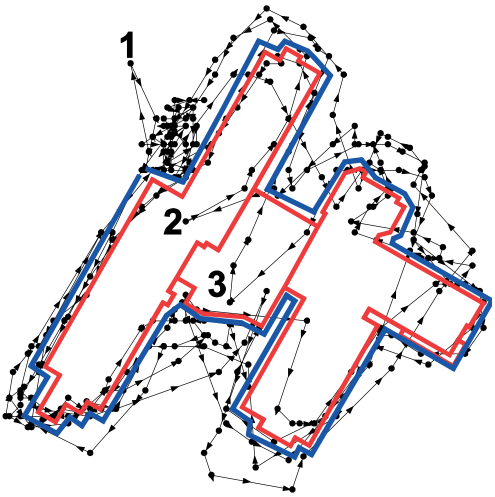

Figure 8. Movement pattern showing outliers on a track (blue line) close to a tall building.

We found that the interval *correct value ± approximately two standard deviations* contained 95% of all measurements. To get an interval that contains *at least* 95%, we can use the *correct value* ± 4m. This is called a prediction interval. One should, however, notice that this interval contains 95% of the observations when the measurements are independent, e.g. the measurements are from several different days. If a GPS unit is used continuously for several hours on one day, there is a risk that all measurements will lie outside the 95% interval because of the dependence and the bias.

Distance measurements. We have seen that the standard deviations are small compared to known distances. Considering that there are several possible sources of inaccuracy, these results seem surprisingly good. Table 4 indicates that there is a variation between the GPS units regarding distance measurement. Some of them always read lower values, some of them always read higher values, and some of them occasionally read both lower and higher values for the distances. Note that this is based on only 5 independent measurements for each of the 8 GPS units and that the measurements are of different lengths and are carried out at different driving speeds.

We have documented the occurrence of systematic bias in the recorded positions (static measurements). Systematic bias may not be a problem in calculating distance since the distance between the points remains the same through a parallel displacement.

The GPS units calculate distance between two consecutively recorded positions as the length (in whole meters) of the straight line connecting them. The total distance of a track is the sum of such lengths.

Since there are time gaps between the recorded positions, in addition to positional inaccuracy, it is not clear what the actual travelled path looks like. The same set of recorded positions may occur from two quite different paths. Since the distance measured by the GPS units is a sum of linear lengths, this will represent the *shortest* possible path that could have been travelled to generate the recorded positions.

Imagine that a GPS unit is moved on the boundary of a circle, at constant speed, to calculate the perimeter of the circle. The effect of the time gaps between recordings is that this experiment could as well measure the perimeter of an n-sided polygon with all corner points on the boundary of the same circle. The distance given by the GPS unit (as a sum of linear lengths) will never equal the perimeter of the circle. If positions are recorded more often (smaller time gaps) the number n of polygon sides will increase, the polygon will approach a circle and the measured distances will become a better estimate of the circle's perimeter.

Time settings on the GFs cannot be overrided. Positions are generally recorded every 10–20 seconds, longer if the GPS units are experiencing small movements and about every 45 seconds when at rest.

We wanted to establish, if possible, a level of precision for the calculated distances as an instrumental property for the GPS units based on measurements of known distances. Usually the distances one wants to measure are not known initially. To ensure that our results would be transferable to actual use situations, a running track on an athletic ground was used as «laboratory». Moving around a running track (rather than back and forth in the same direction) has the advantage of minimizing any effects of geographical orientation.

As already mentioned, all GPS units will calculate less than the actual distance under the given conditions. Since the reference line is made up of two straight lines and two half circles (i.e. one complete circle) and there was a time gap between recordings, the reference line could just as well have consisted of two straight lines and two halves of an n-sided polygon. The value of n depends on the average distance between recorded positions, which again depends on the constant driving speed. In our measurements the only two values of n were n=8 (octagon) and n=9. These n-values were used to *polygon adjust* the known distances for each GPS unit.

Free movement measurements. To determine a position, also called «getting a fix», the GF needs free sight to 4 satellites. During free movement the fix can be lost if buildings or other objects hinder the GPS signal. After a «lost fix», the GPS unit will get a new fix when there are sufficient GPS signals (from 4 satellites). The GF seems to give priority to getting a new fix as fast as possible. This functionality strategy may produce outliers and several inaccurate positions until correct positions are achieved. This means that the time from the first fix until a correct position is achieved must be considered a risk period for inaccuracy in the positions.

Conclusions and comments

Static measurements. There is strong positive dependence between consecutive measurements. One may ask why the GPS units often show the same value over periods of several hours. This may be due to some kind of inertia or averaging mechanism in the GPS units, but we have not investigated this question further.

There is some variation among the GPS units when measuring the same point at the same time. Some GPS units may give values above the correct value, other below. The estimated standard deviations also vary somewhat among the GPS units, from approximately 1m to a little more than 2m. Estimated standard deviation based on all measurements from all eight GPS units is 1.8m in east-west direction and 1.9m in north-south direction. The interval *correct value ± 4m* contains at least 95% of all measurements in both directions.

Distance measurements. A reasonable estimate of the distance inaccuracy for the GPS units is two times the standard deviation, about 32m, when the measured distance is about 1270m (an average of the first and third measurement sessions). One must be aware that some GPS units tend to give only lower, and some others only higher, distance readings. There is variation among the GPS units with respect to distance measurements.

Free movement measurements. The GPS units (GFs) are suitable for movement tracking when this is carried out with care. Our results from static measurements have shown that a bias either to left or to the right may last for some hours. This bias can be seen in Figure 9 where it sometimes looks as if the GPS units move inside or on the roof of the building. They do not; they are always outside the building. This bias can also be seen when the route choices taken by tracked orienteerers are shown on a screen at the arena or on TV. Sometimes it looks as if the runners choose to run parallel to a path or a road. Obviously they run on the path or road because that is the fastest and the safest route, but there may be a small parallel displacement due to the bias.

The GPS units examined in this study are, when handled with care, applicable for scientific use. We conclude that the tested instruments, in open space scenarios, proved to be accurate and reliable for static and distance measurements. However, new equipment is already available with specifications indicating improved reliability and usability, so further studies are recommended.

References

Phillips, M. L., Hall, T. A., Esmen, N.A., Lynch, R., and Johnson, D.L. Use of global positioning system technology to track subject's location during environmental exposure sampling. *J. of Expo. Anal. and Environ. Epidemiol*. 11: 207–215, 2001.

Rodriguez, D.A., Brown, A.L. and Troped, P.J. Portable Global Positioning Units to Complement Accelerometry-Based Physical Activity Monitors. *Medicine & Science in Sports & Exercise* 37: 572–581, 2005.

Certificate for Athletic Grounds. Stadium Høgskolen Bø-Telemark**.** Statsbygg-The Directorate of Public Construction and Property, Norway, 2003.

Garmin Ltd. (http://www.garmin.com)

TracTrac APS (http://www.tractrac.dk)