Quality control of GNSS-Receivers by accuracy-based analysis

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Abstract. In this paper we present a quality control method for Global Navigation Satellite System (GNSS) receivers. A statistical quality control (SQC) approach for accuracy is proposed, focused on quantitative trueness, precision and location availability analysis of GNSS receivers', based on an independent reference system. The location availability is described as the percentage of the total received data that can be considered precise under n-σ boundaries; being n the level of requested precision. As part of this accuracy-based location availability analysis several filter techniques are tested, in order to select the most reliable for this specific quality control method. A traditional SQC method is compared with Mahalanobis Ellipses Filter (MEF) method, while both are provided by particle filter (PF) position estimation, as the independent reference. The quality control methods are depicted in graphical representation. And the results are analysed from an end-user point of view. Finally a detailed description of the receiver's characteristics and conditions of the measurements are presented as part of a case study. Significant differences between the presented approaches are shown and a quality-oriented assessment is proposed.

Keywords: Quality control, GNSS receivers, Mahalanobis Ellipses Filter, Particle Filter.

1 Introduction

The quality control for GNSS receivers is an important feature to all GNSS-based applications. In this paper we describe the development of a quality control methodology by means of accuracy analysis. Accuracy is described by quantitative values of trueness and precision of the GNSS dataset; while the location availability is described as the percentage of the total received data that can be considered precise under n-σ boundaries; where n is the level of requested precision. Two approaches are presented. First a traditional statistical quality control (SQC) trial, by means of quality control chart (QCC) of the module deviation analysis and easting-northing (E/N) bivariate deviation analysis. Then a new Mahalanobis Ellipses Filter (MEF) approach is tested; by means of Mahalanobis distance evaluation trial of the deviation dataset.

All three trials of both approaches and their correspondent results are used for outlier detection as the proposed quality control methodology. Also a reference based on Particle Filter (PF) is developed and tested for both approaches.

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Fig. 1: GNSS quality description.

A. GNSS Receivers quality control

More and more GNSS-based applications are available for localisation purposes. But no quality control methodology for the GNSS receivers has been developed. One step to the future certification of GNSS receivers is to develop a multiple receivers' quality methodology, focusing on the user side.

In Fig. 1 it can be seen how both software and hardware quality control analysis are possibilities from the system point of view. However from the user point of view, a methodology focused on accuracy and precision will be more representative of the quality of the receiver, as presented in Hodon [1].

Previous studies of quality by means of these mentioned characteristics can be found in Hodon [1] and Grasso et al. [2]. A more detailed method is presented in Grasso et al. [3], providing the theoretical basis for the presented accuracy-based quality control methodology.

GNSS receivers' accuracy, described in Grasso et al. [3], is presented in Fig. 2. Based on the True Score Theory model from Trochim [4], accuracy by means of trueness and precision of the GNSS receiver is based on the deviation analysis:

$$\boldsymbol{Location} = \boldsymbol{Reference} + \boldsymbol{Error}$$

From where deviation is defined as the error term and it can also be divided into two significant components:

$$\boldsymbol{error} = \boldsymbol{deterministic\ error} + \boldsymbol{stochastic\ error}$$

Where deterministic error is the intrinsic error of the receiver's behaviour and stochastic error (or non-deterministic error) is randomly added error to the receiver's behaviour. Location availability is then defined as "the percentage of the GNSS data provided by the system that is considered precise, after filtering with an n-σ from a defined precision threshold":

$$LocAv_{N\sigma} = \frac{N\sigma\ filtered\ number\ of\ samples}{Total\ number\ of\ samples} * 100\%$$

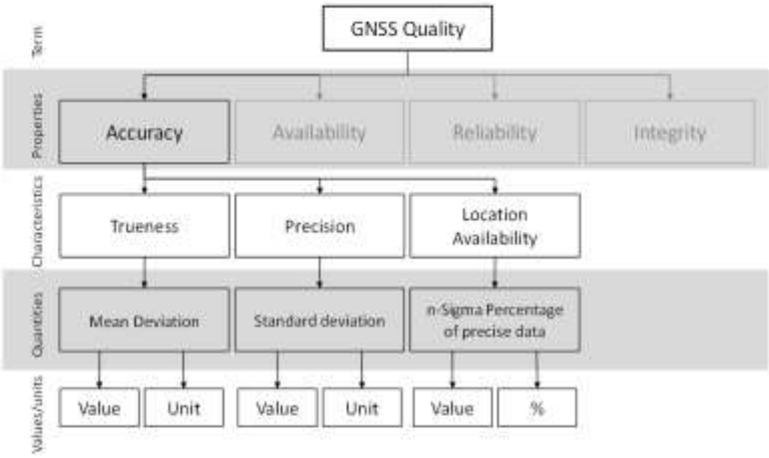

Fig. 2: GNSS Quality attributes hierarchy, focused on accuracy.

B. Particle Filter approach for reference estimation

Particle filter (PF) is a kind of probabilistic suboptimal nonparametric filters, whose main idea is the implementation of sequential Monte Carlo estimation, using particle representation of the probability density function (pdf), as described in Doucet et al. [5] and Arulampalam et al. [6]. Advantages such as the possibility of using PF also for nonlinear systems and the ability of PF to filter any error probability distribution make them not only limited to normal Gaussian probability distribution errors. This is why this filter can be well suited for the problematic of target localization, as seen in Púchyová [7] [8], and GNSS receiver error filtration. Our aim is to estimate the position of the receiver with some error following discrete-time stochastic model:

$$\boldsymbol{x}_k = f(\boldsymbol{x}_{k-1}, \boldsymbol{v}_k)$$

where f is the known function of the state x_{k-1} and v_k is process noise sequence. The measurements have relationship with the state of the receiver through measure equation:

$$\boldsymbol{z}_k = h(\boldsymbol{x}_k, \boldsymbol{u}_k),$$

where h is known function and u_k is the process noise sequence.
Noise sequence v_k and u_k are independent. The filtrated estimation x_k based on the sequence of all the available measurements $\boldsymbol{Z}_k \triangleq \{\boldsymbol{z}_i, i = 1,\dots,k\}$ up to time k is searched, so it is necessary to construct the posterior pdf p(xk|Zk). Then in principle, pdf p(xk|Zk) can be reached recursively in three steps: prediction, update and resampling, involving update of pdf prediction with Bayesian rule:

$$\begin{aligned} p(\boldsymbol{x}_k|\boldsymbol{Z}_k) &= p(\boldsymbol{x}_k|\boldsymbol{z}_k, \boldsymbol{Z}_{k-1}) \\ &= \frac{p(\boldsymbol{z}_k|\boldsymbol{x}_k, \boldsymbol{Z}_{k-1})p(\boldsymbol{x}_k|\boldsymbol{Z}_{k-1})}{p(\boldsymbol{z}_k|\boldsymbol{Z}_{k-1})} \\ &= \frac{p(\boldsymbol{z}_k|\boldsymbol{x}_k)p(\boldsymbol{x}_k|\boldsymbol{Z}_{k-1})}{p(\boldsymbol{z}_k|\boldsymbol{Z}_{k-1})} \end{aligned}$$

For our filtration, a Sampling Importance Resampling (SIR) algorithm from Gordon et al. [9] was used, where the new particles are estimated from the prior $p(\boldsymbol{x}_k|\boldsymbol{x}_{k-1})$ so this step is independent from the measurement vector Z_k.
The main advantage of this kind of filter is that the significant weights are easily accessed and therefore the pdf can be easily sampled.
The measurement z_k is used when weights of each particle are set:

$$w_k^i \propto p(\boldsymbol{z}_k|\boldsymbol{x}_k^i)$$

where index i expresses the i−th particle in the PF. The resampling phase is executed on each time step k.

C. Particle Filter receiver's behaviour estimator

The PF in the present paper aims to the position estimation of the receiver. In order to provide the PF a probability distribution, the measurements from the first day dataset were computed to find the deviation distribution of the receiver.
For both PF-Easting Estimator and PF-Northing Estimator the fitting values were a normal distribution with the mean value and sigma (σ) values describing the easting and northing behaviour of the receiver.
These values resulted from the deviation between the actual reference point from the antenna and the receiver's output from the first day dataset.
Based on Arulampalam et al. [6] a two part PF-based estimator was developed to be used in combination with the two quality control proposed approaches, as a reference frame for the receiver's behaviour. These two filters estimate easting and northing positions of the evaluated receiver.
As seen in Fig. 3 the inputs and outputs are:
Inputs: 1) Deviation distribution of the location of the antenna: this is calculated from the actual location of the antenna and the actual deviation value. Mean value and standard deviation are used for the deviation distribution. 2) Position data: the value for the position provided by the receiver.
Output: 1) Estimated reference: estimation based on provided deviation distribution. The used reference for the further quality control methodologies is the composition of both filters' outputs, and it will be referred as PF-Estimator for the rest of the paper.
Fig. 4 presents a short example of the PF adaptive period, showing the filter evolution of the Gauß-Krüger Northing part of the PF-Estimator.

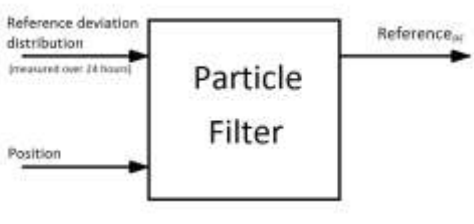

Fig. 3: Input-output diagram of PF.

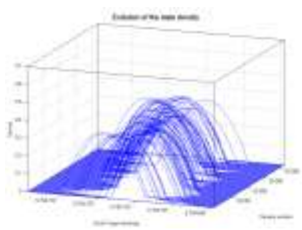

Fig. 4: Evolution.

Fig. 5 displays the improvement (in percentage of $LocAv_{1\sigma}$ added) for the MEF quality control methodology, with the PF-Estimator for different number of particles. Due to computational complexity of PF is affected by rising number of particles; a compromise relation had to be found with the improvement of the data for quality control approaches. For this purpose the selected number of particles for each component of the PF-Estimator was 400.
The MEF quality control methodology results and its improvements related to the usage of the PF-Estimator will be explained in detail in the section three of the present paper. Mathematically the PF-Estimator reference results in:

$$\boldsymbol{Reference_{PF} = Reference_{REAL} + deterministic\ error}$$

In Fig. 6 the resulting 777600 samples (i.e. nine days of estimated reference) used for the quality control methodologies comparison are presented. These are estimated by the PF-Estimator, after the one-day (19.05.2011) adaptation period composed by 86400 samples.
Using the PF-Estimator reference deviation can be studied as the direct function of the stochastic error of the receiver.
This is the selected characteristic for determining the quality of the receiver by means of uncertainty measurement.
The location provided by the receiver can be defined as:

$$\boldsymbol{Location = Reference_{PF} + stochastic\ error}$$

In section three the proposed quality control methodologies, based on SQC and MEF approaches, are compared using deviation calculated with and without the developed PF-Estimator.

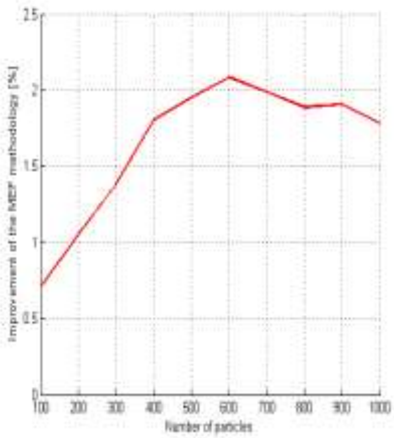

Fig. 5: MEF improvement.

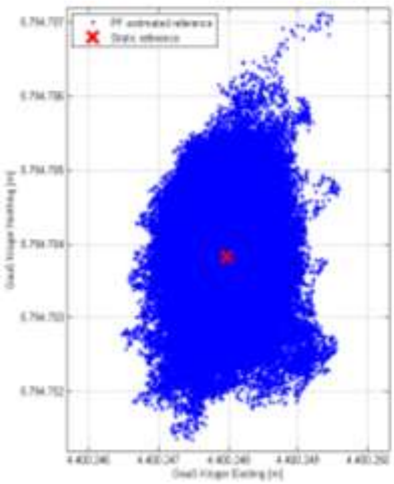

Fig. 6: Reference estimated by PF.

D. Statistical Approach

Statistical quality control (SQC) is a set of statistical tools used by quality professionals that can be divided into three categories according to Reid [10]:
1) Descriptive statistics; 2) Statistical process control (SPC); and 3) Acceptance sampling.
For the GNSS receiver accuracy-based quality control methodology developed in the present paper the proposed SQC approach focuses on descriptive statistics (description of quality characteristics and relationships by statistics measurements such as the mean, standard deviation and distribution of data) of the totality of the receivers' output dataset for further outliers' detection by means of deviation analysis. Two different trials are tested within this approach, focused on two separated calculations of the deviation. The first calculates the deviation by means of the Euclidean distance, and it's called module deviation calculation. And the second calculates the deviation in two separated components, called the easting northing (E/N) deviations calculation.

E. MEF approach

In order to achieve a meaningful description of the quality of a localisation system a new approach has been developed, in the frame of the extended accuracy-based evaluation developed in Grasso et al. [11] Mahalanobis Ellipses Filter (MEF) is a filtering technique that allows a better understanding of the nature of the deviation datasets, and therefore a better ground for GNSS data validation, based on Mahalanobis [12].
MEF methodology focuses on the finding of outliers from the deviation dataset while describing the behaviour of the system (composed by the GNSS-receiver and the reference system) by means of the resulting Mahalanobis ellipses.
MEFs provide not only a description of the bivariate (easting and northing) deviation, but also the resulting rotated ellipses describe the correlated behaviour of the deviation dataset. In Grasso et al. [11] it is proposed that quality control methods as well as validation procedures for certification of GNSS receivers can be performed by MEFs. In this paper the comparison between this new filter approach and the traditional SQC approach is conducted by means of outlier detection in the deviation resulting dataset. Results of this comparison and conclusions are presented in section three of the presented paper.

2 Dataset description

This section is focused on a short description of the used datasets for the quality control methodologies comparison, and their correspondent statistical analysis.

A. Measurement description

Using a receiver u-blox EVU-6H with EGNOS turn on, assembled with the antenna Novatel GPS-702-GG the location was determined geodetically on the roof of the Institut für Verkehrssicherheit und Automatisierungstechnik.

Fig. 7: Installed equipment and Google view of the reference.

Fig. 7 presents the picture of the installed equipment and the Google Maps reference. Measurements of 10 days were collected with a 1 Hz frequency in the period between 19.05.2011 and 01.06.2011, resulting in 864000 positions.

B. Statistical analysis of collected datasets

All 10 datasets present similar characteristics: Each one has 86400 samples over a period of 24 hours, with a number of visible satellites between 7 and 12 (average of 10) and a Horizontal Dilution of Precision (HDOP) value between 0.69 and 1.51 (average of 0.91). According to Ming [13], these characteristics describe the scenario as ideal. Table I shows the statistical analysis for the 10 datasets deviation analysis, referred to the PF-Estimator reference. The tenth dataset is a global dataset composed from the other 9 datasets. The first day (19.05.2011) dataset used for the PF adaptation period is not considered for the rest of the analysis.
In section three these distribution fittings will be used to calculate the limits for the QCC, as part of the SQC approach. Fig. 8 presents the fittings for the deviation between the PF-Estimator reference and the position measurements from the global dataset. Fig. 8A displays a lognormal distribution for the module deviation, while Fig. 8B and 8C display normal distributions for the E/N deviations, independently. This fitting evaluation presented in Fig. 8 has already been used as the basis for reliability margins definition in Grasso et al. [2].

3 Quality control process

This section focuses on the results for both SQC and MEF approaches. Both quality control methodologies are tested by three separated trials, using both the actual location of the receiver and the developed PF-Estimator, in order to conclude on its usefulness.

A. SQC results

The results presented here are provided by both the real reference and the PF-Estimator reference regarding the deviation global dataset.

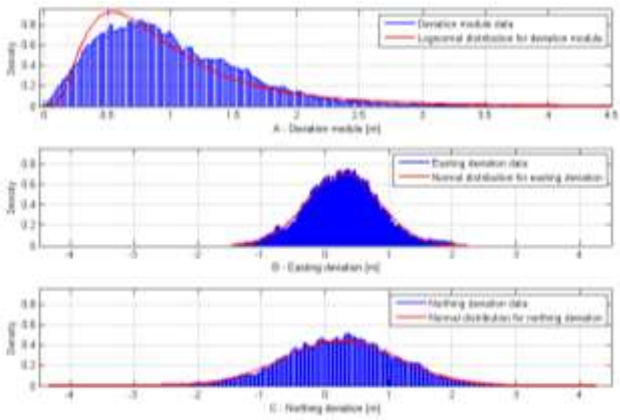

Fig. 8: Fitted distributions for global deviation analysis.

The first trial is focused using the SQC methodology with module deviation, while the second trial uses the E/N deviation.

B. SQC methodology with module deviation analysis

The control limits of the QCC for the module deviation analysis are calculated considering the lognormal distribution, as shown in set of equations (1).

$$\begin{aligned} UCL_M &= e^{\mu_M + nSigmas * \sigma_M} \\ CL_M &= e^{\mu_M} \\ LCL_M &= 0 \end{aligned} \qquad (1)$$

The fitting parameters presented in Table I for the global dataset are used and the control limits are calculated for 1σ result in:

$$LCL_M = 0,\ CL_M = 0.8218,\ UCL_M = 1.5782$$

Fig. 9 shows a QCC in the left side for the module deviation analysis, based on the lognormal distribution fitting. UCL_M separates accepted and rejected samples. Also Fig. 9 presents a in the right side a scatter-plot with the detailed marked limits. Using the limits from Table I from the lognormal distribution and the set of equations (1), the resulting location availability for 1-σ for the module deviation analysis is:

$$LocAv_{1\sigma M} = \frac{SQC\ module(1\sigma)\ filtered\ number\ of\ samples}{Total\ number\ of\ samples} * 100\%$$

The result without PF-Estimator is: $LocAv_{1\sigma M} = 86.0739\%$.
The result with PF-Estimator is: $LocAv_{1\sigma M} = 85.7486\%$.
This presents a decrease of the accuracy of the 1-σ filter of 0.3253 %.
The lognormal limits for QCC show that module deviation analysis is too permissive for the analysed dataset. And also the PF-Estimator proves that the estimated reference behaviour in the SQC approach spreads the acceptance threshold even outside the data cloud.

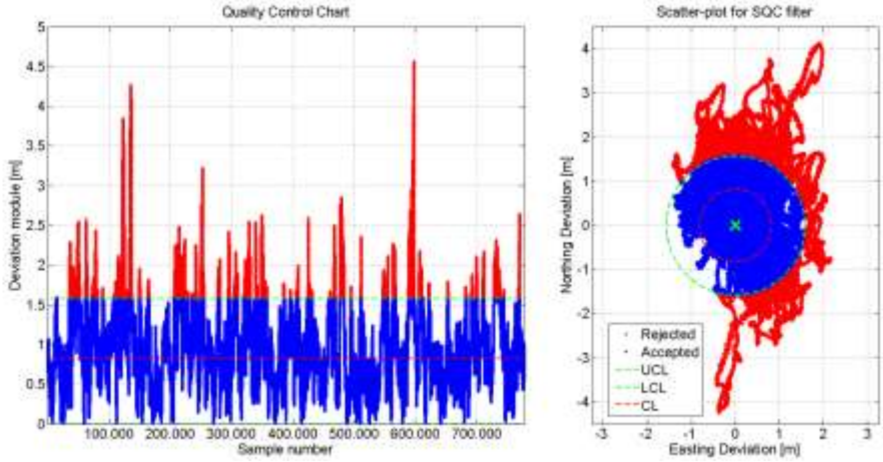

Fig. 9: QCC and Scatter-plot for 1σ SQC filter based deviation module.

C. SQC methodology with easting-northing deviation analysis

The control limits of the QCC for the E/N deviation analysis are calculated considering the normal distribution, as shown in set of equations (2).

$$\begin{aligned} UCL_E &= \mu_E + nSigmas * \sigma_E \\ CL_E &= \mu_E \\ LCL_E &= \mu_E - nSigmas * \sigma_E \\ UCL_N &= \mu_N + nSigmas * \sigma_N \\ CL_N &= \mu_N \\ LCL_N &= \mu_N - nSigmas * \sigma_N \end{aligned} \qquad (2)$$

The fitting parameters presented in Table I for the global dataset are used and the control limits are calculated for 1σ resulting in:

LCL_E = -0.2842, CL_E = 0.2831, UCL_E = 0.8503
LCL_N = -0.6555, CL_N = 0.2533, UCL_N = 1.1620

Fig. 10 shows in the left side two QCCs for the E/N deviations, based on the normal distribution fittings. Also Fig. 10 presents in the right side a scatter-plot with the detailed marked limits.
Using the limits from Table I from the normal distribution and the set of equations (2), the resulting location availability value for 1-σ for the E/N deviation analysis is:

$$LocAv_{1\sigma EN} = \frac{SQC\ E/N(1\sigma)\ filtered\ number\ of\ samples}{Total\ number\ of\ samples} * 100\%$$

The result without PF-Estimator is: $LocAv_{1\sigma EN}$ = 49.4520%.
The result with PF-Estimator is: $LocAv_{1\sigma EN}$ = 50.9816%.
This presents an improvement of the accuracy of the 1-σ filter of 1.5296 %.

TABLE I: STATISTIC ANALYSIS OF THE DATASET

Dataset date	Trueness Module [cm]	Deviation Module Lognormal Fitting		Easting Deviation Normal Fitting		Northing Deviation Normal Fitting	
		μ_M	σ_M	μ_E [m]	σ_E [m]	μ_N [m]	σ_N [m]
23.05	51.1417	-0.1591	0.6491	0.3124	0.5140	0.4049	0.8691
24.05	37.4525	-0.0512	0.6771	0.0763	0.5310	0.3667	1.1880
25.05	44.5379	-0.1277	0.6587	0.1331	0.6841	0.4250	0.8676
26.05	51.8165	-0.1668	0.5992	0.2969	0.5940	0.4247	0.7660
28.05	41.5153	-0.2046	0.6285	0.1621	0.4599	0.3822	0.8786
29.05	30.8001	-0.2979	0.6666	0.3069	0.4852	0.0256	0.9118
30.05	31.3785	-0.2955	0.7471	0.2811	0.5390	0.1394	1.0128
31.05	33.0559	-0.3721	0.5855	0.2459	0.4700	0.2210	0.6875
01.06	74.1256	-0.0919	0.5743	0.7331	0.5342	-0.1099	0.7181
Global	37.9860	-0.1963	0.6526	0.2831	0.5673	0.2533	0.9088

E/N deviation analysis proves to be better than the module deviation analysis, due to the consideration of the deviation on each component of the horizontal position plane independently. Also the increase of the percentage of the $LocAv_{1\sigma EN}$ with PF-Estimator results from the reduction of stochastic error in the deviation calculation, making the quality control analysis based only on the stochastic error of the receiver.

D. MEF results

Since the Mahalanobis distance measures the number of sigmas that separate all samples from the rest of the group, the MEF 1-σ filter provides the number of samples within 1-σ of Mahalanobis distance related to the group.
Therefore, the location availability for 1-σ with the MEF Methodology is:

$$LocAv_{1\sigma MEF} = \frac{MEF(1\sigma)\ filtered\ number\ of\ samples}{Total\ number\ of\ samples} * 100\%$$

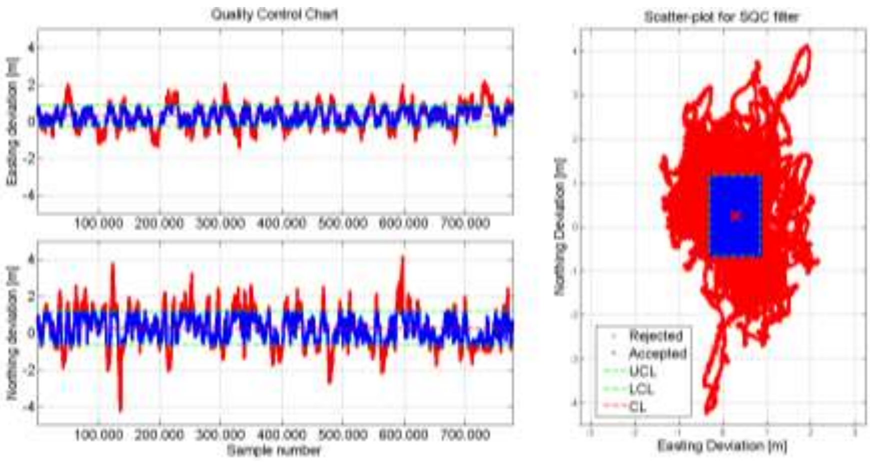

Fig.10: QCC and Scatter-plot for 1σ SQC filter based on easting and northing.

TABLE II: MEF DEVIATION ANALYSIS

Ellipses Center [m]	**Easting**	0.2533
	Northing	0.2831
Semi-radii [m]	**A**	0.529
	b	0.9316
Rotation	**[deg]**	15.497
LocAv 1σ	**with PF**	**44.0213**
LocAv 1σ	**without PF**	**42.2172**

Fig. 11 shows the Mahalanobis distance for each sample in the left side. The 1σ distance is marked by the UCL, separating the rejected samples from the accepted.

Fig. 11 presents as well a scatter-plot in the right side with the detailed marked limits. The deviation mean value is marked in Fig. 11 as the intersection between semi axes. Also the rotation of those axes with respect to the coordinate system describes the degree of correlation between E/N deviations. These characteristics are numerically presented in Table II.

The Mahalanobis distance is a descriptive statistic that provides a scale independent measurement of the distance of each sample with respect to the entire dataset, normalised with respect to σ. Therefore UCL_{MEF} for 1σ corresponds to a unitary Mahalanobis distance.

The Euclidean distance that is used in the SQC module deviation analysis and presented in Fig. 9, is not a descriptive statistic and is not scale-invariant. It measures the distance of independent position samples with respect to the reference.

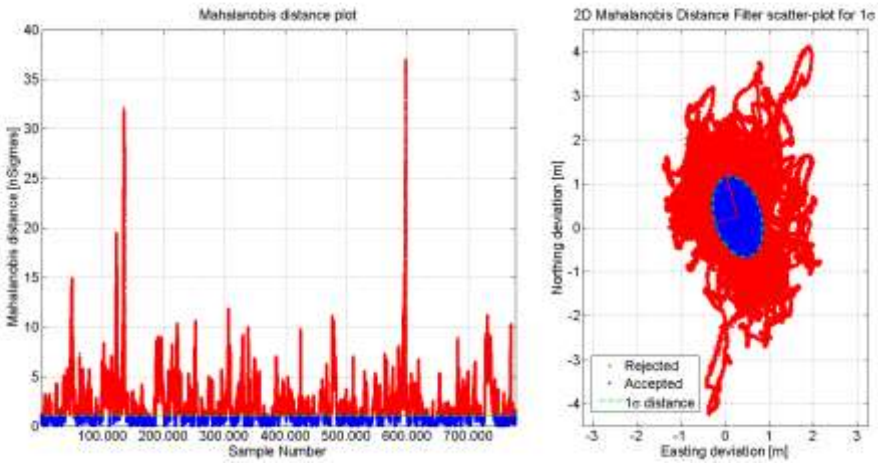

Fig. 11: Mahalanobis distance plot and Scatter-plot for 1σ MEF filter.

TABLE III: SUMMARY OF QUALITY CONTROL METHODOLOGIES

SQC Module	**LocAv 1S (with PF)**	***85.7486***
	LocAv 1S (without PF)	86.0739
SQC E/N	**LocAv 1S (with PF)**	***50.9816***
	LocAv 1S (without PF)	49.452
MEF	**LocAv 1S (with PF)**	***44.0213***
	LocAv 1S (without PF)	42.2172

This distance is fitted to a lognormal distribution in order to perform a statistical analysis of the samples, and the UCL_M for 1σ depends on the parameters of the fitted distribution.
Table II shows the characteristics of the produced Mahalanobis Ellipse of 1-σ and also the location availability for 1-σ with and without PF-Estimator. The increase of the 1.8041% with PF-Estimator results from the reduction of stochastic error in the deviation calculation.

E. Comparison of results

Table III and Fig. 12 present the results of the comparison between the three analysed quality control trials for both SQC and MEF methodologies.
SQC Module, SQC E/N and MEF results are presented by percentages values of the 1-σ outlier detection function with and without PF-Estimator as reference.
The SQC Module filter test considers only the module of the deviation. It does not discriminate the deviation direction of the location samples, resulting in a high $LocAv_{1\sigma}$ that does not describe accurately the behaviour of the receiver.
The SQC E/N filter test considers an independent evaluation of easting and northing deviations. It discriminates between two main deviation direction components, resulting in a lower $LocAv_{1\sigma}$ that represents better the receiver's behaviour when low correlation between easting and northing deviation is present.
Finally the MEF test performs a simultaneous evaluation of easting and northing deviations, taking into account the deviation correlation. The MEF approach also works considering all possible deviation directions by means of the normalised Mahalanobis distance; resulting in a lower $LocAv_{1\sigma}$ that represents better than the SQC E/N filter the receivers' behaviour.

Further work and conclusions

As seen in Fig. 12, the SQC approach is separated in two trials: SQC module trial, testing the trueness and precision, regarding the receiver's deviation; and SQC E/N trial that solves the trueness problem while improves the precision, although it is still not able to discriminate borderline outliers.
On the other hand the MEF approach proves to be the best filter for the receiver's deviation datasets, according to the receiver's behaviour and coinciding with the theorised ellipse, described in Kaplan and Hegarty [14].

The presented LocAv$_{1\sigma}$ comparison of outliers' detection for GNSS-receiver quality control proves that the MEF methodology is better than SQC methodology for the three following reasons: 1) Even though the SQC E/N test was a better description than SQC module, only MEF approach has a simultaneous evaluation of easting and northing deviations, while considering their correlation. 2) Also the MEF approach is the only one from the tested approaches considering all possible deviation directions by means of the normalised Mahalanobis distance. 3) The MEF methodology follows the elliptic behaviour predicted theoretically for accuracy evaluation. In the accuracy metrics section of Kaplan and Hegarty [14] the probability of a measurement to be in the 1-σ ellipse is defined as 39 %; while the probability of being in the 2-σ ellipse is 86 %. These theoretical values are calculated in contrast to the one-dimensional Gaussian result of the probability of being within ±1-σ of the mean value being 68 %.

Based on these theoretical values proposed by Kaplan and Hegarty [14] the MEF methodology is proven to be a sufficient representation of the receiver's behaviour and enough for validating the quality of the receiver tested in the present paper (both with and without the developed PF-Estimator).

Also it has been proven that the usage of a PF-Estimator as estimated reference is effective for stochastic error reduction of the receiver.

The results with 400 particles for the presented static case, in the 1-σ MEF case proves to improve up to 1.8041 % the inclusiveness of the location.

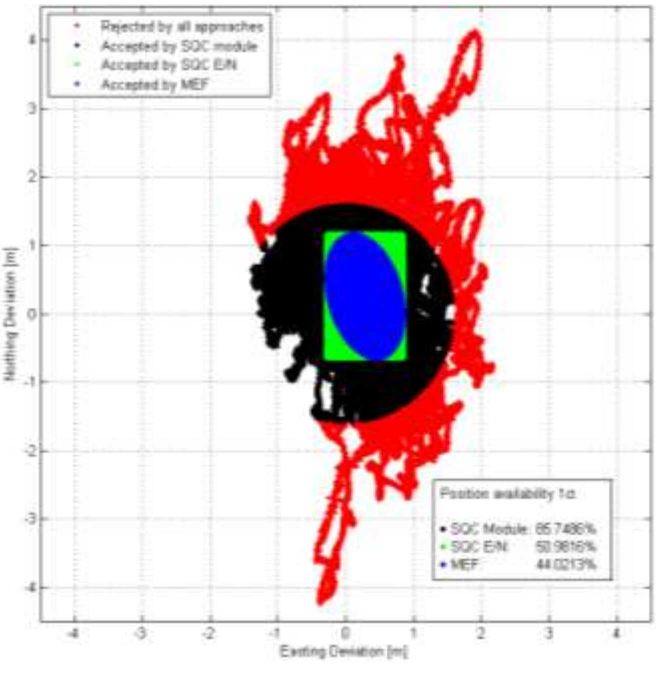

Fig. 12: Comparison between all approaches with 1σ filters.

It is suggested as further work to test the PF-Estimator for dynamic cases. In dynamic scenarios the actual reference value must be calculated from an on-board independent reference.

The developed PF-Estimator approach will be a necessary part of quality control processes, as well as further validation and certification processes for static and dynamic reference system. Finally, as a general conclusion of the present paper, the combination of the MEF methodology and the developed PF-Estimator approach seems to be the best representation of the behaviour of the GNSS-Receiver, and therefore the best base for its quality description.

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