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LOcal interferenCe compensATion (LOCATe) for GNSS-based Lane-Specific Positioning of Vehicles

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***Abstract*—Precise traffic prediction and automated driving require accurate and reliable positioning information to be communicated to neighbouring vehicles as well as centralized traffic management centres. This paper proposes and evaluates the so-called Local Interference Compensation (LOCATe) method, which is a cloud-aided solution to provide lane-specific positioning information of vehicles. With LOCATe, location errors of satellite-based positioning systems caused by shadowing and multi-path fading of the environment are predicted, quantified and compensated by identifying those impacts with ray-tracing techniques applied to a 3D model of the environment. The paper introduces significant improvements of the original LOCATe approach which lead to both an enhanced accuracy and a reduction of the computation time to reach nearly real-time capability. Based on raw data gained with an open Software-Defined Radio implementation in a real-life environment, the efficiency of different LOCATe variants is evaluated and discussed. The results show, that the so-called real-time LOCATe provides significant improvements to the accuracy with only moderate additional CPU complexity/time compared to an ordinary GPS positioning estimation.**

I. Introduction

Capability and benefit of existing or future GNSS-based applications are directly correlated with their reliability. Especially when talking about safety-critical services, the accuracy of the corresponding positioning method is a key performance indicator. As stressed in [1], the use of positioning information like in traffic management or public transportation increases continuously. GNSS like GPS are excellent candidates because of their performance and the free of charge usability. However, one of the main drawbacks of GNSS is the unavailability of signals that occur in densely built areas, and the performance degradation caused by multipath or Non-Line of Sight (NLOS) signals. This reduces the capacity to reach the Required Navigation Performance (RNP) in terms of accuracy and availability [2]. In the former publications [3] and [4], the authors already discussed the most important influences on satellite navigation signals with an error of more than 1m.

To reach a better performance, many solutions are already available but misses the general applicability, e.g. *Differential GPS (DGPS)*. Despite the significant performance gain those systems are locally limited in their benefits. Using *Differential GPS (D-GPS)*, long distances to the reference station and/or direct shadowing or multipath effects directly affect the positioning algorithms within and hence, the corresponding accuracy of the *User Equipment (UE)*. With decreasing correlation of the system circumstances of the receiver and reference station, the correction signal benefit may also weaken. The same holds true for *Satellite-Based Augmentation Systems (SBAS)* like EGNOS, for example. Those systems may enhance accuracy, but suffers from poor availability in urban areas due to their low elevation angle in Europe [5] and will offer poor augmentations.

In contrast, the approach presented in this contribution, the *LOcal interferenCe compensATion (LOCATe)*, tries to predict, quantify and compensate the inevitable local impacts to the positioning accuracy using ordinary GPS/GNSS receivers. Using *LOCATe*, commercially available and resource-constrained one-frequency receivers outperform in terms of accuracy and integrity, which will be shown using an Advanced Software-Defined Radio (SDR) GNSS implementation.

In the following Section II will highlight an enumeration of existing and potential future countermeasures to enable a differentiation to *LOCATe*, which will be discussed in Section III. Afterwards, the gained results and a brief insight to the used validation setup will also presented in Section IV and wrapped up with a conclusion in Section V.

II. Related Research in Model-based Accuracy Enhancements

Model-based compensation methods to minimize local influences on satellite navigation signals have become an important research topic in the past years and their importance will even increase due to better communication protocols and improved computational performance. Cloud-based approaches even enable resource-constrained devices like navigation devices, to run or use complex functionality such as Ray-Tracing. Hence, other researchers are also facing a similar approach like the authors do with *LOCATe*, and is described in the following to allow a detailed differentiation to the idea of this paper.

A. Model-based NLOS Prediction

As shown in [5] and [6], current scientific approaches try to predict and eliminate Non-Line-of-Sight (NLOS) and probably distorted signals, which lead to an increased positioning performance. Using a detailed 3D-model and the knowledge of direct surrounding area as well as the present satellite positions, a Ray-Tracing tool models the signal path from satellite to receiver and possible obstacles in between. Probably blocked but nevertheless received signals may be affected by multipath effects and will corrupt the positioning result. Hence, such signals are eliminated or at least lower weighted before the positioning estimation. But in case of challenging areas like urban canyons with a minor probability of a good satellite reception, it is important to not decrease the number of used satellites even more. In addition, a highly accurate knowledge of the own position is necessary to enable this kind of consideration between the receiver, the surrounding and the comparable far away orbiting satellite.

Another approach, the so-called *Intelligent Urban Positioning* [6], combines different methods like continuity testing and *Shadow matching* [7], which is a kind of NLOS detection to enhance the positioning accuracy. In combination with continuity surveillance, a kind of plausibility routine is added to the previous approach, but again, when an initial position estimation fails, this leads to a decreased overall accuracy.

B. Combination of Physical Measurements and Model-based Approaches

As shown in [8], another scientific approach is to detect signal strength breakdowns of each satellite due to high obstacles like buildings, trees or pylons with known positions close to highways or streets between receiver and satellite. Due to a distributed satellite constellation, these *signal shadows* are detectable in different angles on the street. Using multiple satellites in view, like every GNSS needs to, several *shadows* occur and are calculated by model-based approaches. Their distance to each other is then used to interpret the corresponding lane. In contrast to *LOCATe* or appropriate Ray-Tracing approaches, this related research is fully compatible with resource-constrained devices due to the comparable low complexity of the necessary calculations. But additionally to the fact that this approach requires highly accurate 3D-models (applied also to *LOCATe*), signal shadows especially of small pylons are not recognizable with commercially available GPS/GNSS receivers in fast moving objects like cars. Additionally, dynamic influences or modifications like lane changes between the two signal breakdowns, cannot be interpreted reliably and may lead to misinterpretations.

III. LOCATe - Local Interference Compensation for GNSS

As mentioned in Section II, model-based accuracy enhancement for GNSS positioning is already a current research topic and will become even more important due to increased requirements like reliability, accuracy and general applicability of positioning technologies. Hence, the upcoming section gives a brief overview of the main idea of the developed post-processing and model-based idea of *LOCATe*, which was already published in [4]. Afterwards, the paper focuses on the subsequent developed enhancements and gives a detailed insight to the used evaluation methods and formulas.

A. Main idea of LOCATe - Predict, Quantify, Compensate

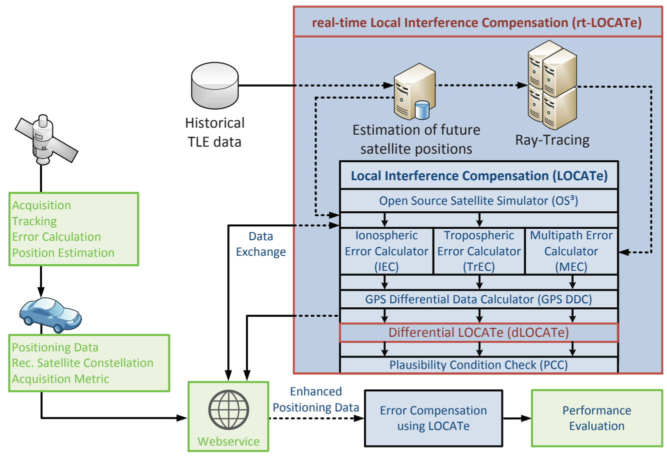

Fig. 1. Architecture of LOCATe and Extensions to reach real-time capabilities

As already introduced in [4] and shown in Figure 1 in the inner blue box, *LOCATe* is based on a satellite simulator combined with SiSNeT, UNB3 considerations and Ray-Tracing technology concerning to [9] and [10] to model all influences on navigation signals at a certain constellation respectively time combination resulting in an updated and *distorted* position including all impacts. To enable a compensation of the mentioned effects, the challenge is exactly the other way around. As input, *LOCATe* uses already distorted GNSS measurements and calculates the most probable real position on earth resulting in this kind of measurements after being influenced by all effects mentioned above. Hereby, the cloud-aided approach is used to circumvent the resource-limitations of mobile devices and leave the complex calculations (e.g. ray-tracing) to a backend without any resource-restrictions. Additionally, the communication delay and protocols are neglected in our considerations, due to the small amount of data for this kind of application per user equipment (cmp. [11]) and the existing permanent communication possibility in our time using smartphones. Summarized, the functionality of *LOCATe* is separated in the following three steps:

1) *Predict* all influences
2) *Quantify* the accruing shift
3) *Compensate* the overall error vector

The obtained significant performance gain in terms of accuracy, which was explained in detail in [4], motivated the authors to go even further and add several extensions, especially focused on reducing the CPU time and to potentially reach real-time capabilities for the specific given scenario. These extensions as well as the used evaluation methods are the focus of this publication and will be explained in the following paragraph.

B. Extensions to reach Real-Time Capability

Aiming for a real-time application in the future, manageable CPU workload despite the complex simulation chain within *LOCATe* has to be accomplished. Hence, the authors extend the already existing *LOCATe* framework to the so-called *real-time LOCATe* or *rt-LOCATe* as shown in Figure 1. Thereby, the basic approach from [4] was adapted by adding two further modules, *predictive LOCATe (pLOCATe)* to reach real-time capabilities and *differential LOCATe (dLOCATe)* to compensate the resulting errors. Both will be explained in detail in the following.

1) Time-Gain using 'predictive LOCATe': The first extension focuses on real-time capabilities. As already mentioned in Section III-A, *LOCATe* includes resource-intensive Ray-Tracing technology and is not applicable to any tasks, which rely on real-time capability. The basic idea of *pLOCATe* is to use the latest set of Two Line Elements (TLE) data to predict the satellite positions for a short period of time in future. Afterwards, the predicted positions are forwarded to Multipath Error Calculator (MEC) to start a Ray-Tracing analysis for future constellations and the results are stored in relational databases to replace the complex Ray-Tracing analysis by a simple database access during run-time. On the one hand, out-dated TLE data causes a higher inaccuracy of a satellite's [3] and beyond that of the receiver's position, but on the other hand, this increases the time-efficiency significantly by a dramatically decreased process time of *LOCATe*. As a consequence, the accuracy loss should be analyzed and preferably compensated using the second extension *dLOCATe* for instance.

2) Accuracy Gain using 'differential LOCATe' and Context-Sensitive Considerations: Based on the basic approach of Multiple Antenna GNSS, the idea of *dLOCATe* is to work with at least two antennas with an exactly known distance x to each other. Position measurements in parallel on both points will cause an unknown error $\Delta err_{1,2}$, hence the calculated distance y between these defective positions may differ to the real distance x. By shifting both calculated positions simultaneously with the same value, distance y can be set to x. Thus, the influence of $\Delta err_{1,2}$ can be reduced in average. Although this method may also corrupt some measurements, this effect will be limited to significantly uneven maldistribution between the two measured points. In addition, scenario-specific considerations may also increase the positioning accuracy, but they limit the degree of freedom for possible results. E.g. *LOCATe* is primarily designed for traffic scenarios, thus there are some restrictions to more easily detect and correct wrong position measurements. Like *MapMatching* approaches, accurate street maps are used to match position errors on the correct driving lane. This idea, of course, is only realizable based on detailed and up-to-date underlying map material, but it may result in a high performance gain. Because *MapMatching* is a well-known method in GNSS technology, e.g. in navigation devices, it is necessary to clarify the differences to this publication. Using *LOCATe*, defective GNSS measurements are getting more close to the real position and by using *MapMatching* afterwards, a correct solution is even more probable than without the accuracy gain of *LOCATe* in the forefront. Next to these extensions themselves, an evaluation of both as well as an classification of *LOCATe* in current research is necessary. Due to the explained scenario considerations, the necessary computing time consequently has also to be included, beside the accuracy gain in any kind of evaluation method. Hence, the next paragraph introduces a corresponding rating method in detail.

3) Efficiency Rating using Accuracy Gain versus CPU Time-Loss: Basically spoken, in time-relevant applications or services the CPU intensity is as important as the gained position accuracy and consequently has to be minimized. Thus, the authors suggest the usage of a Key Performance Indicator (KPI) called E to enable an efficiency rating of the developed processes P. To reach a reliable comparability, this KPI is normalized to the performance characteristics of the GPS reference measurements as follows:

$$E(P) = \frac{d(P_{GPS}) \cdot r(P_{GPS}) \cdot T(P_{GPS})}{d(P) \cdot r(P) \cdot T(P)}$$

Thereby, d is used for the median positioning error, r for the dispersion range of the measurement values to include all position outliers and T for the CPU Time, which is calculated as the difference between the quartiles $Q_{.75}$ and $Q_{.25}$ (interquartile range) to filter outliers caused by background processes of the operating system.

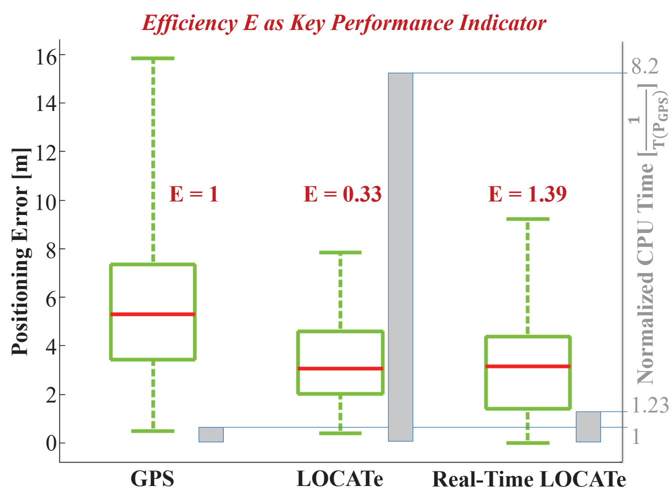

Fig. 2. Quantitative Accuracy Gain and corresponding CPU Time-Loss using LOCATe

IV. Accuracy Enhancement using LOCATe

The main objective during the development of *LOCATe* was to enable a lane-specific localization of traffic flow-objects, especially in challenging urban areas and/or canyons. After describing the main idea and the set-up of *LOCATe* in the upper sections, the following section faces the evaluation of the developed overall system as well as the quantitative comparison with other current scientific approaches.

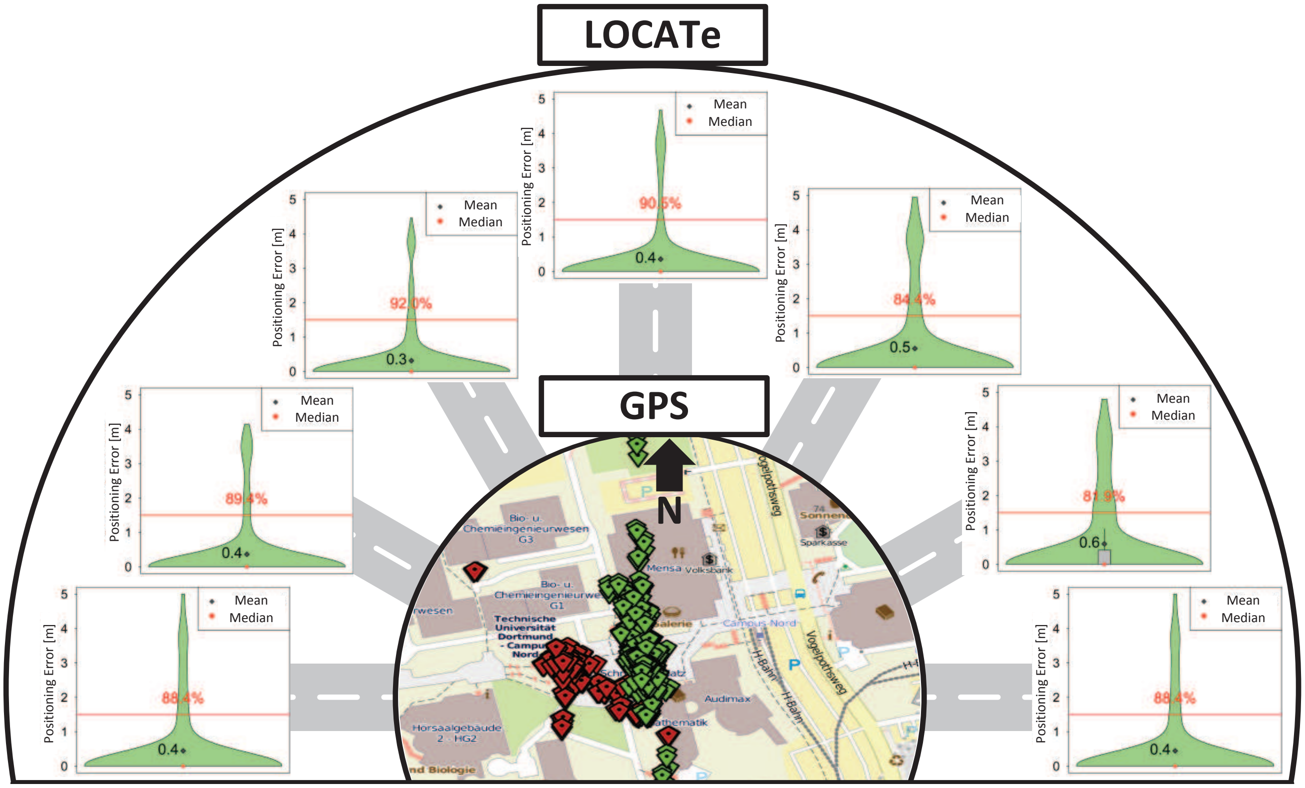

Fig. 3. Accuracy Gain using real-time LOCATe on defective GPS measurements using different virtual Highway directions

A. Performance Gain using LOCATe

First of all, an evaluation of the achieved accuracy gain using the basic *LOCATe* idea without any extensions is illuminated. Thereby the authors used a developed *Advanced Software-Defined GNSS receiver (ASDR)* published in [12] to enable a *White Box*-analyses as well as a commercial GPS receiver from u-blox. As shown in Figure 2, the basic *LOCATe* idea increases the accuracy by an average of 45% in comparison with stand-alone GPS position measurements. In addition, and for some applications even more important, the maximum error can be reduced by 9m, which results in an overall improvement of more than 87% for all position values. However, the corresponding time-loss referring to the increased computing complexity reduces the overall efficiency using the introduced KPI E_{REL}. By combining *predictive and differential LOCATe* to the so-called *real-time LOCATe (rt-LOCATe)*, the median of both error values shows approximately the same level facing only the accuracy of both systems. This is caused by Ray-Tracing results with predicted and less accurate satellite positions (cmp. Section III-B1). But taking the CPU intensity of each task into account, the normalized key performance indicator E_{REL} of 1 (in case of GPS) can be significantly increased to 2,08 (*rt-LOCATe*), which implies at least an enhancement of $\approx 110\%$. Especially the inclusion of CPU usage clarifies the possible benefit of using *LOCATe* even for time-relevant application scenarios. The significant accuracy gain in combination with the negligible time-loss through extra CPU time clearly enables further applications to take huge advantages using this approach.

Nevertheless, the gained results also show that, up to this point, the main objective has failed: the lane-specific positioning. Although *LOCATe* as well as *rt-LOCATe* increases the amount of lane-specific geo-locations by more than three times (from 9% to 28% and 31% respectively), Figure 2 visualizes still more than 60% of non-lane-specific ones. Consequently, the next paragraphs face the usage of the gained improved localization results in combination with the introduced *Map-Matching* after a short comparison between the performance of *LOCATe* so far with another current research project in this scientific area.

B. LOCATe with Scenario-specific Considerations

As mentioned above, traffic scenarios allow context-aware plausibility checks to match unrealistic position measurements to the nearest traffic lane. Because *LOCATe* is still under development and the testing equipment is not smooth-running, the authors use the campus of the university and its detailed 3D-model to create virtual lanes in direction of the widest dispersion to generate a first indication of the possible additional benefit in using these kind of considerations. Figure 3 shows the first results. Hereby, all measurements recorded on two highly accurate surveyed reference points are shown on a map in the middle, circuited by different virtual two-lane highways with 2.9m width each, and the gained *rt-LOCATe* results including *MapMatching*. It is obvious that the result depends on the used angle but also shows a significant accuracy gain. The lane-specific content increases to a value between 82% and 91% of the position measurements, which means an immense accuracy gain. Especially, the direct comparison to GPS only and *MapMatching* shows the correct assumption introduced in Section III-B2. Without increasing the accuracy before the *MapMatching* routine using *LOCATe*, only 64% of the gained measurements were allocated correctly, and by that may be count as lane-specific. Just the combination with the ideas presented in this paper increases the performance in a way, that nearly 90% of all improved measurements are mapped to the right lane.

C. Classification of LOCATe

As mentioned in the previous paragraphs, *LOCATe* shows a better performance than current research projects, especially in challenging scenarios. In addition, it is applicable and performs independently from the amount of satellites, location and time. Summarized, Figure 4 shows a direct

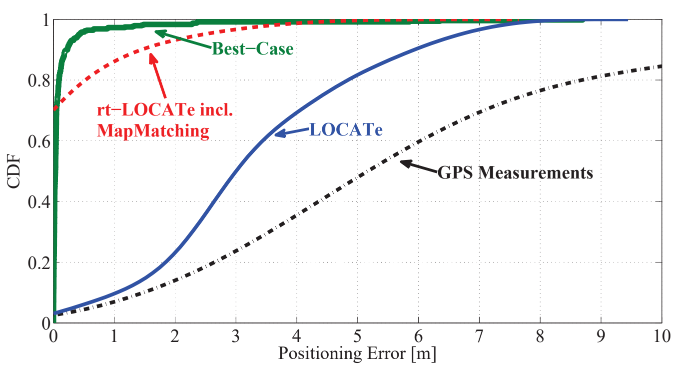

Fig. 4. Classification of Accuracy Gain using LOCATe

comparison of ordinary GPS measurements with *LOCATE*, *rt-LOCATe* including *MapMatching* and the theoretical maximum determined in [7] after compensating all atmospheric and local influences and just let noise, clock biases and some galactic impairments behind. The extensions of *rt-LOCATe* show comparable position results with significantly decreased execution time in comparison with *LOCATe*, which are pretty close to the overall best-case maximum and the high benefit in using this approach for future applications with the demand of highly accurate positioning.

V. Conclusion

This paper provides the conceptional design, architecture and performance evaluation of the consistent further developed *Local Interference Compensation (LOCATe)* for GNSS to increase the accuracy especially for lane-specific applications in urban areas observing roughly real-time capabilities (*rt-LOCATe*). Using this post-processing approach, the authors identified certain accuracy enhancements using the three steps: Predict, quantify and compensate all influences on satellite signals at a specific point on earth. Hereby, a possible accuracy gain of more than 45% is detectable in consideration of the real-time capabilities and the constrained resources in the mobile devices using the cloud-based approach. By combining *LOCATe* with existing ideas like *MapMatching*, the accuracy gain increases even more and allows a lane-specific positioning with a probability of up to 90% by using GPS only. All results and models were evaluated with a prototypical implementation on a SDR, underlining the applicability of the presented approach.

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