A Cooperative GNSS Positioning System for Accurate Vehicle Safety Application Development

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***Abstract*—Typical Global Navigation Satellite System (GNSS) receivers offer precision in the order of meters. This error margin is however excessive for different vehicular applications, such as forward collision warning, intersection collision warning, or hard braking sensing. This work develops a precision positioning system that uses Vehicle to Vehicle (V2V) and Vehicle to Infrastructure (V2I) communications to cooperatively improve the GNSS performance. To reach this goal, the proposed system executes a novel algorithm based on an empirical methodology, implemented by elliptical and spherical geometries to adjust the positions received from the GNSS. We evaluate the system performance carrying out real experiments using state-of-art vehicular communication equipments at the campus of the Federal University of Rio de Janeiro (UFRJ). The results show an accuracy level under 1.0 (where-in-lane) and 1.5 m (which-lane) for lane and road axis, respectively, achieved by the system using GNSS as unique positioning sensor. The proposed system meets vehicular safety applications requirements and reduces the amount of sensors to be installed in vehicles, and consequently decrease costs and avoids compatibility issues.**

***Index Terms*—Vehicular networks, where-in-lane, which-lane, cooperative positioning, GNSS, DSRC.**

I. Introduction

Research on Intelligent Transportation Systems (ITS) is currently a very hot topic, motivated by the potential to improve the quality of people daily lives. Having vehicles communicating with each other brings intelligence into scene. Vehicles equipped with built-in networking interfaces may exchange data in ad hoc mode or via an infrastructure installed alongside roads and streets. This work focuses safe driving applications, which rely on information about location, speed, and direction of vehicles, which can be obtained from Global Navigation Satellite System (GNSS) receivers. These applications, in addition to avoiding accidents by warning conductors about imminent risks, increase traffic law compliance, improve incident management, and facilitate crash investigations. Other than safe driving, applications which benefit from accurate vehicle positioning include autonomous vehicles, entertainment, and assisted driving [1]–[5]. Vehicle safety applications, particularly, require accurate positioning systems to improve vehicular navigation. This is the case of lane-level positioning or collision avoidance systems [4]. The accuracy of GNSS receivers, however, is affected by the multipath effect, caused by signal reflections in buildings or trees, and by non-line-of-sight reception, caused by satellite unavailability [6].

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Therefore, positioning systems like GNSS are typically prone to errors in the order of meters, which exceed the maximum acceptable for various safe driving applications. For example, in a forward collision warning application, errors of this magnitude can increase the risk of accidents, mainly if cars are moving at high speeds [7], [8]. As another example, considering that streets and road lanes have widths between 2.5 and 3.5 m, a lane-level positioning system using only an autonomous single carrier (L1) GNSS receiver would be unreliable since errors and lane widths are in the same order of magnitude. Even though GNSS techniques such as DGNSS (Differential Global Navigation Satellite System), PPP (Precise Point Positioning), or RTK (Real Time Kinematics) respectively provide meter, centimeter, and millimeter accuracy, their performance is also affected by the number of visible satellites and by multipath propagation [9]. One way to circumvent these issues is to deploy a positioning system based on multiple inputs coming from collaborative sources, to compensate for individual errors. Those collaborative sources include Vehicle to Vehicle (V2V) and Vehicle to Infrastructure (V2I) communications, in-vehicle sensors, Light Detection and Ranging (LIDAR), cameras, and digital maps [10]–[13]. Different solutions for vehicular positioning use subsets of those inputs. Nevertheless, the number of devices to coordinate and the costs involved are open issues.

Vehicle safety applications require positioning accuracy that is classified into three distinct levels: *which-road* (5.0 m), *which-lane* (1.5 m) and *where-in-lane* (under 1.0 m). The first one is only to know if the vehicles involved are in the same road. The second level of accuracy enables a vehicle to identify other vehicles that are traveling in the same or adjacent lanes, and the third one identify the vehicle positioning inside the lane. Electronic Emergency Brake Light (EEBL), Forward Collision Warning (FCW), and Lane Change Advisor (LCA) are examples of vehicle safety applications that require the above three accuracy levels [14].

This paper introduces the Cooperative GNSS Positioning System (CooPS), a system designed to provide *which-lane* accuracy. To achieve that goal, CooPS uses (i) V2V and V2I communications over the Dedicated Short Range Communications (DSRC) band in a cooperative way and (ii) a novel position computation method to overcome the low accuracy (of 10.0 m, typically) [15] of L1 GNSS receivers in Single Point Positioning (SPP) mode. One design requirement is to achieve accurate driving using only off-the-shelf GNSS receivers and, as a consequence, avoid compatibility issues imposed by additional sensors between vehicular equipment and the embedded GNSS. The proposed method combines the GNSS position of the vehicle, spherical and elliptical geometries, and ground-truth coordinates of fixed GNSS stations to correct positioning errors. The use of fewer sensors reduces direct and indirect costs, considering that sensors may require additional electrical wiring. Therefore, an important design goal of CooPS is to use as few as possible data sources. We evaluate CooPS performance by comparing the relative distance estimated with the proposed system and with ground truth geographic location of RSUs. We conduct experiments at the campus of Federal University of Rio de Janeiro (UFRJ) IEEE 802.11p communication devices, installed along the roadway and inside the vehicle. The experimental results show that CooPS improves the positioning accuracy in both road and lane axis. The results also show that CooPS achieves *where-in-lane* positioning accuracy with respect to lane axis and *which-lane* with respect to road axis using only a GNSS receiver as positioning input, avoiding the need of other sensors and providing a low-cost solution.

This work is organized as follows. Section II emphasizes CooPS contributions with respect to the related work. Section III introduces CooPS and provides an analysis of GNSS error sources. Section IV details the CooPS proposal, the empirical methodology, and the geometric model considered. Field experiments are described in Section V, as well as the results obtained in a real scenario, which serves as the proof of concept of CooPS. Finally, Section VI provides closing remarks and future work directions.

II. Related Work

Most of the works aim at achieving *where-in-lane* level for navigation and collision warning applications, using multiple sensors or cooperative approaches, as we will discuss below.

Positioning systems using multiple data sources have been investigated in the literature. Different works consider the joint utilization of digital maps, GNSS, Inertial Measurement Units (IMU) and data acquired directly from the CAN bus of the vehicle [16]. Tsai *et al.* [17] propose a cooperative system that combines an autonomous GPS and a camera to improve the accuracy of relative positioning in urban environments. This system, called IPC (Improving Positioning in real City environments), runs an algorithm that relies on V2V communications and a camera, in addition to the GPS, to determine the position of a vehicle relative to its neighbors. In case of GPS failure, IPC relies on the camera and V2V communications to perform navigation. Conversely, if the camera becomes inactive, GPS is used, performing mutual compensation between the navigation modes. IPC is a complete solution for relative positioning, nonetheless, it relies on the existence of a camera, V2V communications, and a GPS. CooPS on the other hand relies only on V2V and V2I communications, and a GPS to achieve accuracy below 1.5 m. Even considering that an additional camera does not add much complexity to the system, the reduction of 15% with respect to the raw GPS positioning error achieved by IPC yields an error greater than 4 m. This performance does not meet the requirements of vehicular safety applications.

Ansari *et al.* [18] propose a cooperative network architecture that is used to distribute differential corrections using the standard Radio Technical Commission for Maritime Services (RTCM) message format [19] and V2I communications. The Road Side Unit (RSU) receives geographic positions from an embedded GPS receiver, compatible with the RTK technique, and performs corrections using the data received from the nearest Continuous Operating Reference Station (CORS). The communication between the CORS and the RSU goes through the 3G cellular network that carries the correction messages using the Networked Transport of RTCM via Internet Protocol (NTRIP). This data is received at the OBUs also using the NTRIP protocol, which, in turn, allows the correction of the OBUs positions.

The authors call this architecture Real-time Relative Positioning (RRP) and claim that it guarantees relative positioning of vehicles with centimeter precision, according to the experimental analysis carried out against various traffic scenarios. The proposal presents an accurate positioning system which meets the requirements of vehicular safety applications. Nevertheless, the use of GPS-RTK is prohibitive due to the high cost of RTK GPS equipment and the need for a permanent communication with a CORS. In contrast, CooPS does not require permanent connection with a CORS and uses an off-the-shelf GNSS receiver.

Roth *et al.* [20] propose a collaborative positioning system designed to reduce the number of sensors using an autonomous single carrier GPS installed in each vehicle, as a unique positioning sensor, and V2V communications to perform vehicle self-localization. The distance between each satellite and the Earth (pseudoranges) received by the vehicles in range are shared and, in case a GPS receiver of a vehicle fails due to lack of satellite availability, the neighboring vehicles can act as sources of satellite data. The proposed Advanced Shared Pseudorange Algorithm (ASP) uses a least squares position estimation and the shared information to improve positioning accuracy, mitigating the problem of satellite unavailability in urban environments. ASP shares with CooPS low hardware cost and high degree of compatibility. Nevertheless, the accuracy achieved by ASP does not meet the requirement of vehicular safety applications.

Huang and Lin [21] propose a collision warning system based on three inputs: speed variation, direction change, and position interruption. The latter is defined as the time the system stays in the same position, which is equal to the GPS update period, for practical reasons. The proposed Vector Cooperative Collision Warning (VCCW) system evaluates the collision risk by considering a vehicle and all of its neighbors within the same coverage area, once per second. If there is risk of collision, a subsystem actuates to calculate the safe braking distance and the time needed to reach this distance. The simulation of VCCW has shown safe braking distance errors below 3 cm. The work improves collision warning algorithms by also considering speed and direction variations, and position interruption over time. To accomplish that, VCCW takes

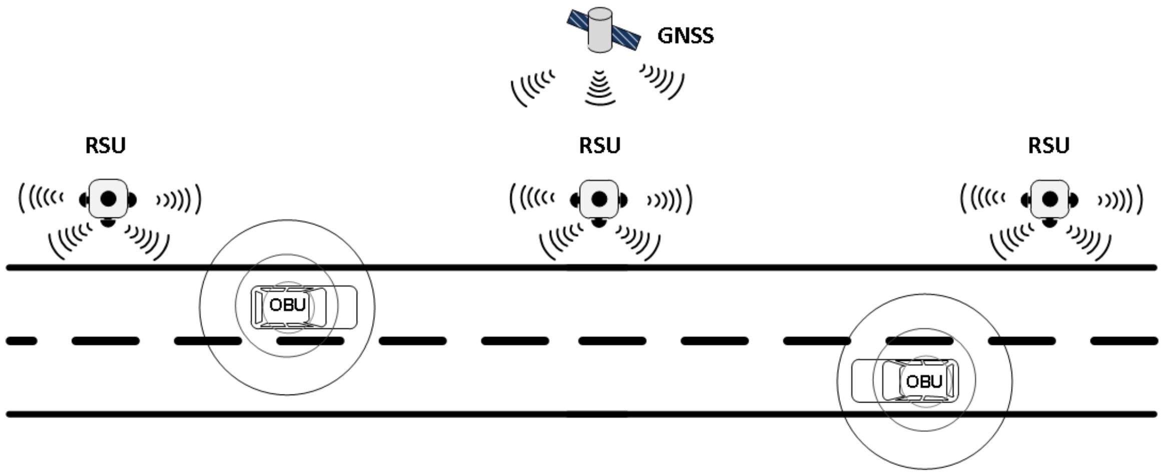


Fig. 1: Application scenario of CooPS where the Road Side Units, deployed along the road, broadcast their ground truth geographic position to the On-Board Units. These location informations are used by the system embedded in the OBUs to determine vehicles relative distance.

into account the acceleration influence on the speed and the utilization of a vector-based algorithm to avoid collision even if vehicles change the course in a curve. These contributions are important for increasing accuracy in straight and curved roads. Moreover, VCCW compensates for the time between two GPS acquisitions by adding an estimated distance traveled by the vehicle to its position. It also increases the accuracy with respect to errors introduced by the GNSS update rate. The performance of VCCW meets the requirements of vehicular safety applications: it is one of the few works that tackle GNSS update rate issue. The main difference to the present work is that CooPS uses a novel geometric model, based on empirical results, to estimate the relative distance between vehicles. In that sense CooPS is simpler because it does not require coordinates transformation. Moreover, CooPS provides better accuracy by using an external reference (the RSU location) compared with VCCW, which directly computes the distance between vehicles based on GPS coordinates from each one. CooPS uses V2V and V2I communication in a cooperative way, instead of V2V only, as used by VCCW. We validate our proposal through real experiments.

Although most of the systems described above provide accuracy levels that meet *where-in-lane* requirements, their deployment is relevant mainly when GNSS fails to provide a reliable position. Thus, the main difference compared with CooPS is the utilization of only GNSS as positioning device in conditions where other systems would need additional sensors to achieve *where-in-lane* accuracy level. On the other hand, CooPS depends on a GNSS system and then, whenever it fails, e.g., as a consequence of vehicle navigation through street canyons, tunnels, and dense forests, the navigation may face interruptions. In this case, dead reckoning positioning techniques [22], [23] can be used as an alternative whenever GNSS satellites are not visible. Dead reckoning techniques do not require additional sensors and can operate using only data from available built-in sensors, such as wheel speed or steering angle sensors.

III. Accurate Positioning Problem for Safe Driving Applications

Fig. 1 shows the application scenario considered in this paper. The idea is to combine information received from the GNSS with information received from other vehicles to accurately estimate the current position of the vehicle. To accomplish that, On-Board Units (OBUs), the mobile communication devices inside the vehicles, receive positioning information from fixed Road Side Units (RSUs), which we assume as *identified* base stations installed along a roadway. On the one hand, RSUs broadcast ground-truth geographic coordinates acquired at the time of their installation along the road, whereas OBUs acquire geographic coordinates from their embedded GNSS receivers. To achieve high precision for the RSU geographic location (centimeter accuracy), the Differential Global Navigation Satellite System (DGNSS) technique is used to set the coordinates at the moment of RSU installation. DGNSS services providers, like International GNSS Service (IGS), a voluntary federation, use a reference station to transmit navigation correction messages including ephemeris and satellite clock errors to the user GNSS receivers [24].

After receiving information from the RSUs through V2I communications, the application running in an OBU, is able to find the ego-vehicle localization and, furthermore, the relative position in the current road stretch. To this end, CooPS must calculate, for every new position delivered by the embedded GNSS receiver, the distances from its current position to the RSUs, which have absolute coordinates. Note that, as consider mathematical operations over geographic coordinates, a suitable Earth model must be chosen. Three such Earth models are used for most purposes: the real world model, the ellipsoidal model, and the spherical model. The real world model is based on a solid called a *geoid* which represents the relief features of the Earth: it is frequently used on maps and is ideal for measuring heights. The ellipsoidal model is based on a solid called an ellipsoid, which is generated by the revolution of an ellipse and is used by the GNSS to calculate latitude and longitude coordinates [9]. Finally, the spherical model is based on a sphere: it is less accurate than the other two models, but does not require complex calculations. The difference of accuracy between the real world and the ellipsoidal model is very small. Nevertheless, the accuracy difference between the ellipsoidal and spherical models is about 3 m per kilometer [25]. Thus, some assumptions about the performance of GNSS receivers and new techniques to evaluate the relative distance between OBUs must be used, which will be the focus of CooPS. We first overview all possible sources of errors of a GNSS receiver for accurate positioning and then present some experiments to assess the impact of those error sources over GNSS receiver performance in Single Point Positioning (SPP) mode.

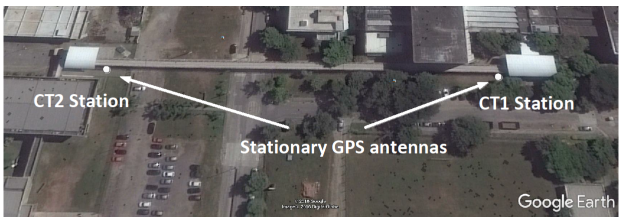


Fig. 2: CT1 and CT2 GPS Stations.

A. GNSS error sources

GNSS is based on a constellation of satellites that send their orbital positions to receivers on Earth, providing geographic position and high precision time. Basically, GNSS receivers calculate positions estimating the distance between the satellite and the Earth (pseudoranges). The position accuracy varies depending on weather conditions, visibility, and satellite availability, as well as on signal reflections. More specifically, GNSS ranging errors can be caused by the variation of the speed of signal propagation (an effect of the ionosphere); pressure, temperature and humidity, which change the speed of light (troposphere effects); satellite orbit (ephemeris) data errors; satellite clock errors; intrinsic errors of the receivers; and multipath propagation [24]. Currently, four GNSS navigation systems are operational: the American GPS, Russian GLONASS, European GALILEO, and Chinese BeiDou. In this work, we employ GPS equipment. Thus, hereinafter we use the term GPS instead of GNSS.

TABLE I: Sources of GNSS positioning errors and their typical magnitude (source: [9]).

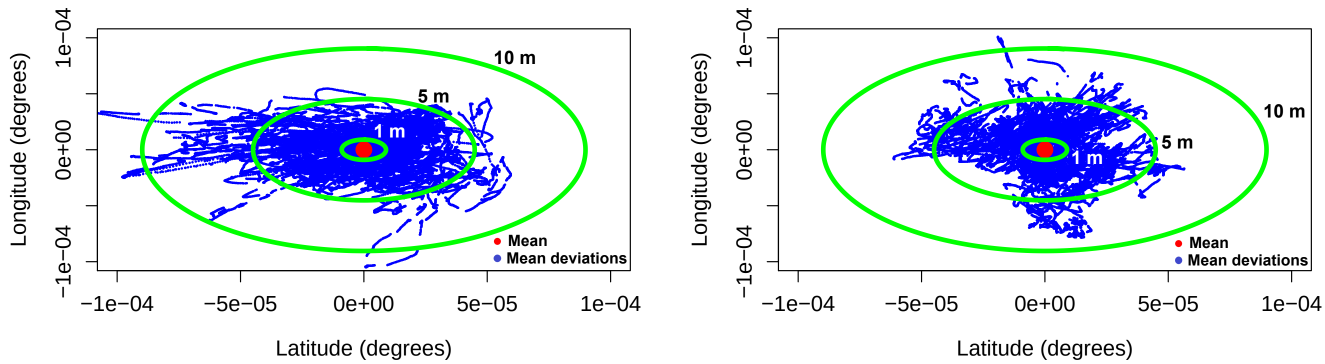
Source	**Typical Error (m)**
Ephemeris data	1.5
Satellite clocks	1.5
Effect of the ionosphere	3.0
Effect of the troposphere	0.7
Multipath reception	1.0
Effect of receiver	0.5

The geographic coordinates of any point around the globe can be determined by a single receiver (SPP mode) or by two GPS receivers working in differential mode (DGPS). The former, under ideal conditions, provides accuracy around 10.0 m; whereas the latter, with the support of a reference ground station, can achieve millimeter accuracy [14]. A detailed analysis of the poor accuracy of GPS receivers working in SPP mode reveals an assortment of error sources, as seen in Table I. Grewal *et al.* [24] analyze these error sources and point out that ephemeris and satellite clock errors slowly vary in time, but are more significant over long time intervals, such as hours. They also conclude that if two GPS receivers are close enough, i.e. less than 100 km apart, the errors caused by the effect of the ionosphere and of the troposphere are highly correlated. Under this condition, the differential error of GPS receivers related to the ionosphere and the troposphere is very small (under 1 m). Considering the vehicular communication scenario, a driving safety application is typically concerned with events that occur in seconds or few minutes. Moreover, the distances between RSUs should be less than 1 km, assuming the use of IEEE 802.11p wireless devices [26]. Hence, we assume that the relevant GPS error sources are multipath propagation and errors intrinsic to the GPS receivers.

B. Experiments using GPS receivers in SPP mode

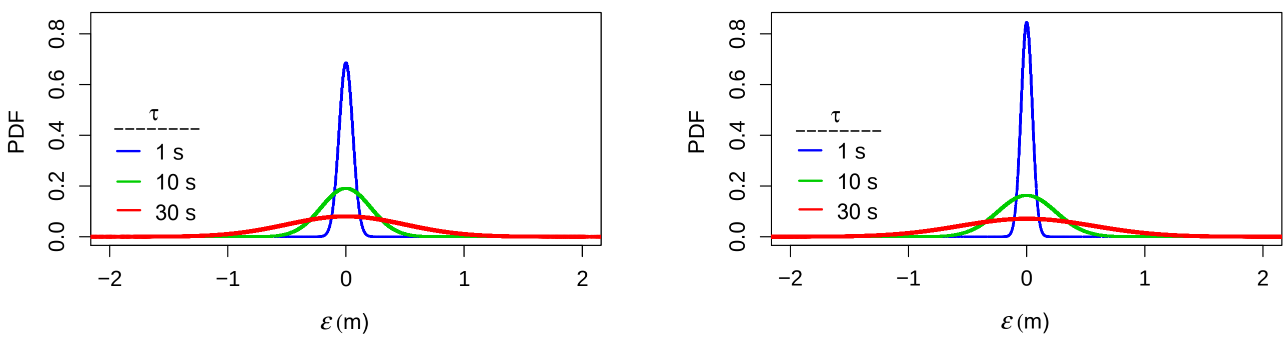
Our first empirical experiments at the campus of UFRJ confirm that obtaining sub-metric positioning errors using GPS receivers operating in SPP mode is a challenge. The experiments were carried out at experimental line of MagLev-Cobra project, a magnetic levitation train developed at the Laboratory of Applied Superconductivity of UFRJ. We collect and analyze data from two GPS stationary stations separated by 160 meters, shown in Fig. 2, one located at the Technology Center I (CT1 Station) and another at the Technology Center II (CT2 Station). CT1 and CT2 Stations have single carrier (L1) autonomous GPS receivers with an accuracy of 2.5 m in 50% of the measurements taken in a time interval of 24 hours. Measurements were taken at both stations at a rate of one sample per second during 24 h. Figs. 3a and 3b show the differences of acquired geographical coordinates (blue dots), in degrees from their mean (full red dot), denoted herein by *deviations* taking into account that the mean may not be the exact real value. The inner, intermediate and outer green ellipsis represent boundaries corresponding to the distances of 1, 5 and 10 m from the mean. We can observe that deviations greater than 10 m from the mean are more frequent at CT1 Station, as a consequence of its proximity to tall buildings (Fig. 2), which increases multipath reception errors and reduces the number of visible satellites.

The deviations shown in Figs. 3a and 3b enforce the hypothesis that GPS receivers working in SPP mode do not meet the requirements of vehicular safety applications. Nevertheless, such deviations occurred in a time interval of 24 hours, which is prone to all error sources described in Section III-A; and they are all computed as the distance to a fixed coordinate reference. Considering that vehicular safety applications are related to events that occur at short time intervals, we can consider the difference between consecutive measurements instead of the absolute value between the GPS pseudoranges and its 24-hour mean. This is equivalent to the use of the last measurement as coordinate reference, which reduces the



(a) CT1 Station. (b) CT2 Station.

Fig. 3: Mean deviations (errors) of coordinates acquired from GPS receiver stations during a 24-hour period. Green ellipses enclose deviations smaller than 1, 5, or 10 meters.



(a) Distribution of errors related to the position of CT1 Station. (b) Distribution of errors related to the position of CT2 Station.

Fig. 4: Probability Distribution Function of the error (ϵ) between consecutive location measurements. These measurements are acquired by the GPS station receivers from a fixed coordinate at sample intervals of 1, 10, and 30 s.

deviation as consecutive measurements are expected to vary more smoothly. Let $p_0, p_1, ..., p_n$ be a sequence of geographic locations acquired from a GPS receiver every τ seconds and $d_0, d_1, ..., d_n$ the distances from these points to a fixed reference location p_{ref}. Denoting ϵ_k as the error of the distances measured at time intervals t_k and t_{k+1}, we have:

$$\epsilon_k = d_{k+1} - d_k, \tag{1}$$

where $p_{ref} \neq p_{k+1}$,p_k and $t_{k+1} = t_k + \tau$.

We can safely assume that $d_k > \epsilon_k$, as the distance between consecutive measurements is varies smoothly. In the long term, e.g., 24 h, we can further expect that $\max(d_k) \gg \max(\epsilon_k)$, which motivated the utilization of consecutive measurements technique as the base of our proposal. Figs. 4a and 4b plot the Probability Density Function (PDF) of ϵ for the CT1 and CT2 Stations, respectively. We plot three PDFs in each figure to evaluate the impact of consecutive measurements taken at different sampling intervals (τ): 1, 10, and 30 s. The results confirm very small differences between consecutive measurements, mainly for $\tau = 1$, for both CT1 and CT2 stations over 24 hours. Table II shows the mean, the standard deviation, and the absolute value of 95% confidence interval for all sampling intervals τ and stations. Note that the results are presented in millimeters due to the small distances found. According to Figs. 4a and 4b, and to Table II, the smaller the sampling time, the greater the accuracy. Moreover, even for the highest τ values (30 s), the accuracy is acceptable.

TABLE II: Statistics data of the distance error (ϵ) between consecutive location measurements at sample intervals (τ) of 1, 10, and 30 s.

τ (s)	Mean (mm)		Sdev (mm)		Conf. Int. (mm)	
	CT1	CT2	CT1	CT2	CT1	CT2
1	0.17	0.46	58.18	47.23	-0.43-0.46	-0.31-0.40
10	-2.36	4.60	208.97	244.57	-1.84-1.36	-1.42-2.33
30	-9.32	13.17	496.44	561.69	-4.74-2.88	-2.30-5.63

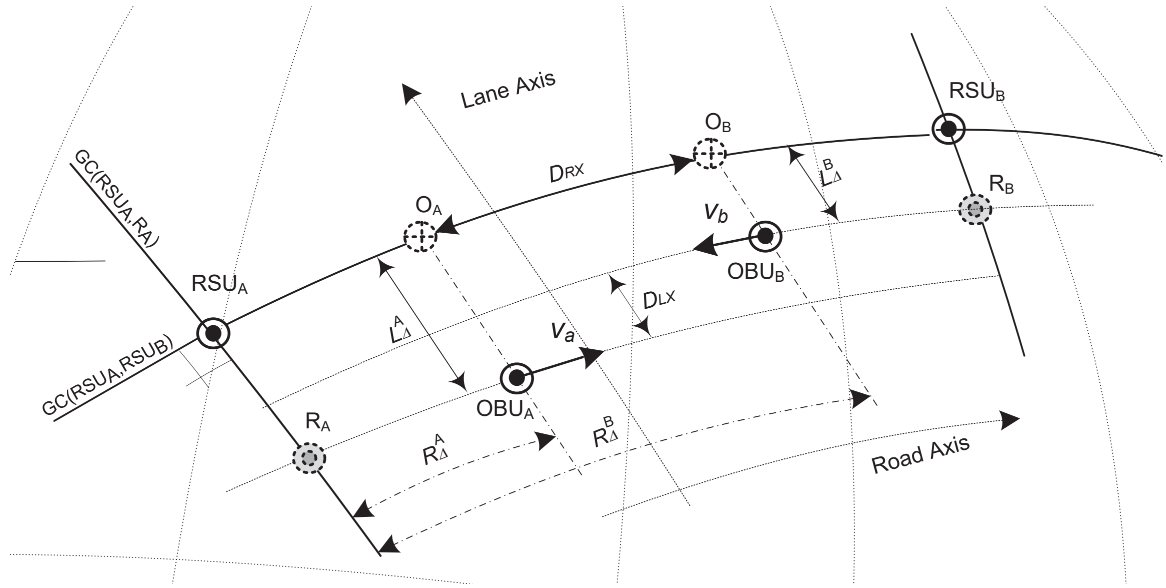


Fig. 5: Geometric model used by CooPS to determine the relative distances D_{RX} and D_{LX} between the OBUs with respect to road and lane axes, respectively. OBU_A and OBU_B represent vehicles traveling in different lanes at v_a and v_b speeds, respectively. OBU_A and OBU_B are in the same road stretch, delimited by the road-side units RSU_A and RSU_B. The arcs R^A_Δ, R^B_Δ, L^A_Δ, and L^B_Δ represent the road and lane axes displacement projections over their respective great circles (GCs).

IV. CooPS: A Cooperative GNSS Positioning System

The main goal of CooPS is to provide *where-in-lane* accurate positioning, required by vehicle safety applications. The experiments of Section III-B show that this accuracy level is not guaranteed when computing the distance between fixed RSUs and mobile OBUs inside vehicles. Nevertheless, we argue that if the difference between *consecutive* distance measurements is computed, it is possible to achieve *where-in-lane* accurate positioning. Computing the distance between consecutive measurements, nevertheless, involves vector arithmetic. As a consequence, CooPS considers the distance between the fixed RSU and the OBU embedded in the vehicle as a vector, and computes its projections over the road axis (R_Δ) and the lane axis (L_Δ), for each new location received.

Fig. 5 illustrates the projection of the straight line between OBU_A and RSU_A over the road, R^A_Δ, and over the lane axis, L^A_Δ. Similarly, the projection of the vector between OBU$_B$ and the RSU$_B$ produces the vectors R^B_Δ and L^B_Δ over the road and lane axis, respectively. Thus, CooPS combines the benefit of road and lane axis utilization which permits the computation of relative errors for each lane separately; the closeness of the GNSS and the fact that smaller intervals to compute the relative distance between two vehicles taken from a common reference coordinate produces greater accuracy.

As for the coordinate system, CooPS is based on the datum World Geodesic System 1984 (WGS84) reference ellipsoid to compute long distances for geographic coordinates (notation: $\phi = Latitude$, $\lambda = Longitude$). For some specific functions which operate over short distances, we use the spherical model in CooPS, despite the small loss of accuracy, since it greatly simplifies the computation of geographic coordinates distances. In Fig. 5, points RSU_A and RSU_B represent two consecutive Road Side Units, located at geographic coordinates (ϕ_{RSU_A}, λ_{RSU_A}) and (ϕ_{RSU_B}, λ_{RSU_B}), respectively. OBU_A and OBU_B points represent the OBUs carried by two vehicles, currently located at the geographic coordinates ($\phi_{OBU_A}, \lambda_{OBU_A}$) and ($\phi_{OBU_B}, \lambda_{OBU_B}$), respectively. Note that the geographic coordinates of the vehicles are informed by the GPS receivers of the OBUs. OBU_A and OBU_B travel at speeds v_a and v_b, respectively. The road axis, parallel to the great circle (GC) formed by RSU_A and RSU_B, is used to determine D_{RX}, the relative distance of vehicles regarding the traveling direction, whereas lane axis is used to determine D_{LX}, the relative distance regarding to the lateral direction.

These relative distances can be calculated through the OBU's projections O_A, O_B, R_A, and R_B. Using V2I communications, the RSUs periodically send their ground-truth geographic coordinates to the OBUs. Rather than applying the simple difference to make positioning corrections, CooPS calculates the angular distance related to the projections of the acquired GPS positions over two orthogonal great circles (GCs), as represented in Fig. 5. These angular distances are used by CooPS to correct the OBUs positions in a simple and efficient way, avoiding computational effort of coordinate transformations.

A. CooPS Positioning Algorithm

To obtain the distance between the two vehicles, CooPS first calculates the distances of the projections along the road axis defined by the GC that connects points RSU_A and RSU_B, denoted as GC(RSU_A, RSU_B). Then, it executes the same procedure regarding the lane axis, defined by the GC which is orthogonal to the first one, denoted by GC(RSU_A, R_A). Considering OBU_A, the system calculates, for each position informed by the GPS, the angular distances L_Δ and R_Δ

from the points OBU_A and OBU_B to the GC(RSU_A, R_A). As Fig. 5 illustrates, these distances are the same as the $\overline{RSU_A O_A}$ and $\overline{RSU_B O_B}$ projections of the given points over GC(RSU_A, RSU_B). Therefore, the road axis relative distance D_{RX} between the OBUs is calculated as:

$$D_{RX} = |R_\Delta^A - R_\Delta^B|. \tag{2}$$

Similarly, with respect to the lane axis, CooPS calculates the angular distances L_Δ^A and L_Δ^B from the OBU_A and OBU_B points to the circle GC(RSU_A, RSU_B). Hence, the lane axis relative distance D_{LX} among the OBUs is calculated as:

$$D_{LX} = |L_\Delta^A - L_\Delta^B|. \tag{3}$$

CooPS can also be used to determine the absolute position of the OBUs. The procedure is similar except that there must be an external trigger, for example, a sensor on the vehicle, to establish a reference to correct the position with respect to both axes of the road.

CooPS assumes that there is a communication between RSUs and OBUs along the road stretch and the maximum distance between RSUs is smaller the wireless network range. We only describe the procedure for determining of the relative distance for OBU$_A$, since it is identical for OBU$_B$. Thus, three steps are performed before calculating L_Δ and R_Δ:

Step 1) *Compute the initial Azimuth between RSU$_A$ and RSU$_B$.*

Using the elliptical model implemented by Vincenty solution [27] enhanced by Karney [28], the initial azimuth (bearing) β_{AB} from RSU_A at (ϕ_{RSU_A}, λ_{RSU_A}) to RSU_B at (ϕ_{RSU_B}, λ_{RSU_B}) can be computed as:

$$\beta_{AB} = \arctan 2(a, b), \tag{4}$$

where $a = \sin(\Delta_\lambda) \cdot cos(\phi_{RSU_B})$, $b = \cos(\phi_{RSU_A}) \cdot sin(\phi_{RSU_B}) - sin(\phi_{RSU_A}) \cdot cos(\phi_{RSU_B}) \cdot cos(\Delta_\lambda)$, and $\Delta_\lambda = \lambda_{RSU_B} - \lambda_{RSU_A}$.

Step 2) *Compute the initial Azimuth between RSU$_A$ and OBU$_A$.*

Using Equation 4, the initial azimuth β_{AA} is obtained from RSU_A at ($\phi_{RSU_A}, \lambda_{RSU_A}$) to OBU_A at ($\phi_{OBU_A}, \lambda_{OBU_A}$).

Step 3) *Compute the distance between RSU$_A$ and OBU$_A$.*

The angular distance d_{AA} between points RSU_A at (ϕ_{RSU_A}, λ_{RSU_A}) and OBU_A at (ϕ_{OBU_A}, λ_{OBU_A}) can be obtained by using the haversine formula [29], a spherical model, as:

$$d_{AA} = 2 \cdot atan2(\sqrt{c}/\sqrt{1-c}), \tag{5}$$

where $c = sin^2(\Delta\phi/2) + cos(\phi_{RSU_A}) \cdot cos(\phi_{OBU_A}) \cdot sin^2(\Delta_\lambda/2)$, $\Delta\phi = \phi_{RSU_A} - \phi_{OBU_A}$, and $\Delta_\lambda = \lambda_{OBU_A} - \lambda_{RSU_A}$.

We have now two GCs that intersect at point RSU_A, as required to determine the angular distances R_Δ^A and L_Δ^A, as shown in Fig. 6. Note that these projections over the respective GCs have a sign rule, given by the position of the point with respect to the GC. For example, if the point is on the right side of GC(RSU_A, R_A), like OBU_A, then R_Δ^A is negative. Otherwise, it is positive. The same occurs for GC(RSU_B, R_B).

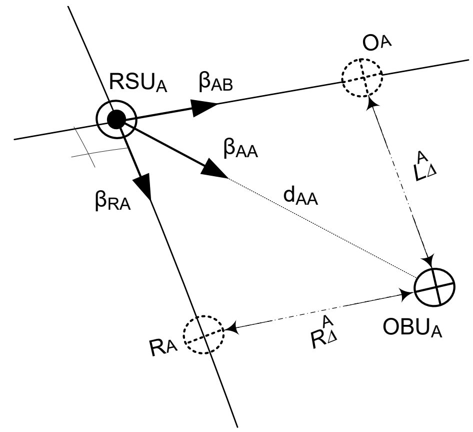


Fig. 6: Calculation of the projections R_Δ and L_Δ over the GC(RSU_A,RSU_B) and GC(RSU_A,R_A) using spherical trigonometric relations. R_Δ and L_Δ are function of distance and bearing between RSU_A and OBU_A and bearing of their corresponding GC projection.

Denoting the azimuth $\beta_{RA} = \beta_{AB} + \pi/2$, the angular distance R_Δ^A from point OBU_A at ($\phi_{OBU_A}, \lambda_{OBU_A}$) to GC($RSU_A, R_A$) can be calculated, given the initial azimuth β_{AA}, the angular distance d_{AA}, and the initial azimuth β_{RA}, using spherical trigonometry [30], as:

$$R_\Delta^A = \arcsin(d_{AA}) \cdot sin(\beta_{AA} - \beta_{RA})). \tag{6}$$

Similarly, the angular distance L_Δ^A from point OBU_A at ($\phi_{OBU_A}, \lambda_{OBU_A}$) to the GC($RSU_A$,$RSU_B$) can be calculated, given the initial azimuth β_{AA}, the angular distance d_{AA}, and the initial azimuth β_{AB}, as:

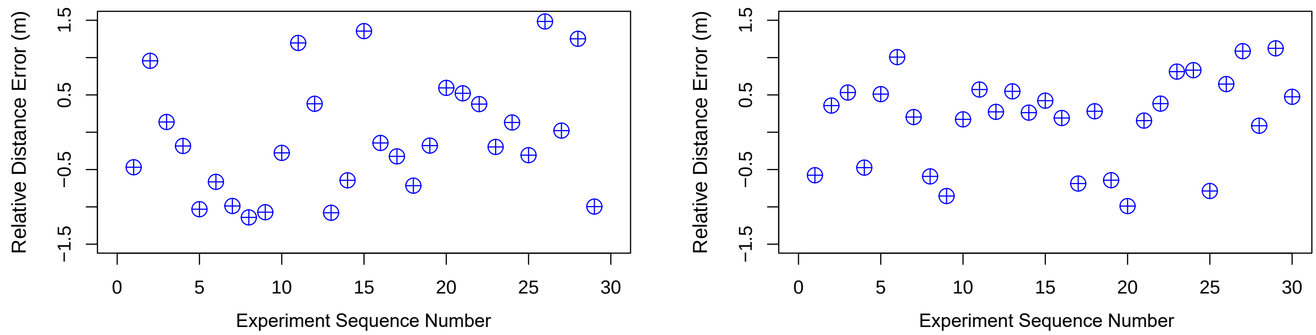
$$L_\Delta^A = \arcsin(d_{AA}) \cdot sin(\beta_{AA} - \beta_{AB})). \tag{7}$$

R_Δ and L_Δ are calculated for every new position acquired from the GPS receiver and correspond to the distances to the respective GCs, the fixed references. These distances are obtained as well as the distances to a fixed point and used in the empirical methodology described in the previous section.

Fig. 7: Experimental scenario used for CooPS evaluation performance. Three separate road stretches were used, Lanes 1A, 1B, and 2. We used two fixed road-side units: RSU_A and RSU_B (figure produced using Google Earth).

V. Performance Evaluation

The performance of CooPS was evaluated through real experiments conducted at a two-way street in the campus of UFRJ. Fig. 7 shows the experimental scenario. The two



(a) Lane 1A Relative Distance Error.

(b) Lane 1B Relative Distance Error.

Fig. 8: CooPS Road Axis Performance to estimate the distance between RSU$_A$ and RSU$_B$.

RSUs were installed at a height of 1.5 m, separated by a ground distance of 407.64 m. The geographic coordinates of the RSUs ($\phi = Latitude$, $\lambda = Longitude$) were extracted from landmarks on the Google Earth map (a vertical white line for RSU_A and a light pole for RSU_B), their values are:

$$RSU_A: \quad (\phi_{RSU_A} = -22.862084, \lambda_{RSU_A} = -43.22487),$$
$$RSU_B: \quad (\phi_{RSU_B} = -22.860038, \lambda_{RSU_B} = -43.221572).$$

To evaluate the accuracy of CooPS regarding to the road axis, Lanes 1A and 1B were used whereas for the lane axis, Lanes 1A and 2 (Fig. 7). The distances from the RSUs to the center of Lanes 1A, 1B, and 2 are 2.68, 12.60, and 6.20 m, respectively. A vehicle with an embedded OBU traveled 15 times on Lane 1A, 15 times on Lane 2, and 30 times on Lane 1B at speeds between 20 and 60 km/h. The hardware used in the experiments is listed in Table III. The CooPS elliptical geometry model was implemented using *GeographicLib* [31]. The RSUs and OBUs are equipped with single carrier GPS receivers operating at 5 Hz update rate and two IEEE 802.11p radios used for V2V and V2I communications over the DSRC band, working at the power level of 23 dBm. Messages between RSUs and OBU were sent on DSRC channel 178.

TABLE III: Hardware used in the experiments.

Hardware	**Description**
RSU	Cohda Wireless model MK5-RSU
OBU	Cohda Wireless model MK5-OBU
DSRC Antenna	2 x 5.9 GHz MobileMarkECO6-5500e
GNSS Antenna	1 x WELL-HOPE GPS/GLON-09B
Vehicle	2015 Peugeot 408

A. Results

In our experiments, we collect the values of R_Δ, L_Δ every time the vehicle travels the road stretch from RSU_A to RSU_B and from RSU_B to RSU_B. During that time, the vehicle speed and geographic coordinates provided by the GPS receiver of the OBU are also collected. To evaluate the precision of CooPS to estimate the relative distance relative to the road axis, we compute the values of R_Δ taking into account the vehicle traveling direction. When the vehicle goes from RSU_A to RSU_B (Lane 1A), R_Δ is computed from the RSU_A coordinates, until the vehicle passes by RSU_B. This event is detected at the moment the vehicle crosses GC(RSU_B, R_B), as shown in Fig. 5). Similarly for Lane 1B, R_Δ is computed from the RSU_B coordinates until the vehicle passes by RSU_A.

These values are compared with the distance between RSUs, calculated using absolute coordinates. Nevertheless, due to the GPS update rate combined with the vehicle speed, the signal changing detection of R_Δ happens after a random time interval, resulting in an additional distance, d_{cr}, given by:

$$d_{cr} = v_{cr} \cdot t_{cr}, \tag{8}$$

where v_{cr} is the vehicle speed when it crosses the GC, and t_{cr} is a random fraction of the GPS update period. Assuming that t_{cr} is a random discrete variable with uniform distribution over [0,200 ms] interval, where 200 ms is the update period of the used GPS, the expected value of d_{cr} is:

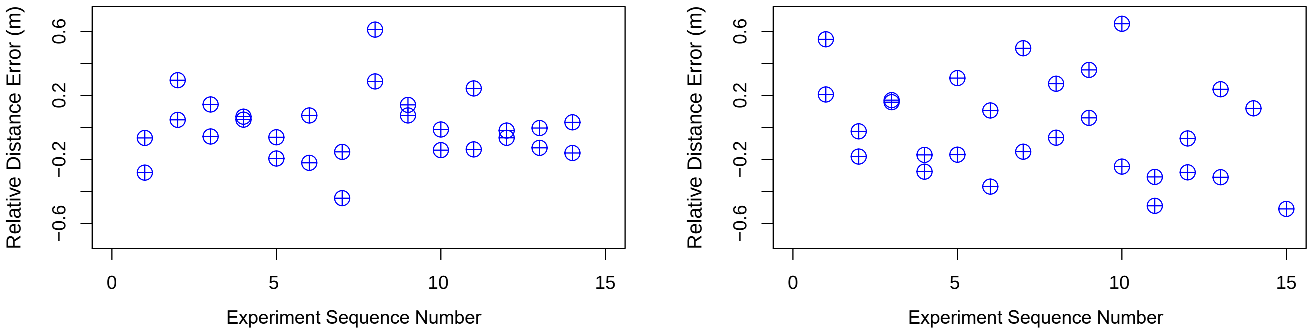
$$E(d_{cr}) = E(v_{cr}) \cdot E(t_{cr}). \tag{9}$$

Therefore, after extracting outliers and subtracting the corresponding expected values of d_{cr}, CooPS performance with respect to the road axis positioning error is shown in Fig. 8. Negative values mean an estimated distance shorter than the reference distance between the RSUs.

Note that the performance of CooPS with respect to the road axis meets *which-lane* requirements. A better performance is observed for Lane 1B (Fig. 8b which can be assigned by an average speed of experiment sequences lower than Lane 1A. This fact is confirmed by the numbers of Table IV, that shows smaller standard deviation and confidence interval for the experiments over Lane 1B.

TABLE IV: Statistical data of road axis CooPS performance.

	Mean (m)	**Sdev (m)**	**Conf. Int. (m)**
Lane 1A	-0.06	0.78	-0.36-0.23
Lane 1B	0.17	0.60	-0.04-0.40



(a) Lane 1A.

(b) Lane 2.

Fig. 9: CooPS Lane Axis Error Evaluation.

Assuming a negligible lateral displacement of the vehicle during the experiments, CooPS performance evaluation with respect to the lane axis was performed by calculating for each lane (1A and 2), the difference of the values of L_Δ at beginning (RSU_A) and at the end (RSU_B) of every experiment sequence, i.e. this difference must be zero, otherwise we have an error. Since lateral speed is zero, L_Δ has no additional distance at the end of sequence. Thus, after extracting outliers, the relative distance errors with respect to lane axis are shown in Fig. 8. We note a similar behavior of relative distance error for both experiment sequences, with a performance slightly better for Lane 1A, confirmed by the statistical data of Table V. These values mean that CooPS outperforms *which-lane* requirements and provides *where-in-lane* accuracy level.

TABLE V: Statistical data of lane axis CooPS performance.

	Mean (m)	**Sdev (m)**	**Conf. Int. (m)**
Lane 1A	0.00	0.21	-0.08-0.07
Lane 2	0.00	0.31	-0.11-0.12

VI. Conclusion

This work presented CooPS, a cooperative positioning system that meets vehicle safety applications accuracy levels requirements. To achieve these requirements, CooPS employs IEEE 802.11p V2I and V2V communications by Vehicles and road-side units cooperatively. CooPS calculate the relative distance among vehicles combining Spherical and elliptical geometry and the fixed ground-truth coordinates of the RSUs. The development of CooPS involved the analysis of GNSS receiver error sources and an experimental evaluation campaign that collected consecutive position errors over 24 hours, acquired at variable sample periods (1, 10, and 30 s). CooPS design was based on the results of this preliminary study and the assumption that the vehicular environment inside of OBUs radio coverage area is stable, considering the short time in which vehicle interactions occur. We have implemented CooPS using commercial IEEE 802.11p OBUs and RSUs. The system performance is confirmed by the results of the conducted field experiments that have shown a relative distance accuracy level under 1.5 m with respect to the road axis and under 1.0 m with respect to the lane axis. Despite adopting a single carrier GNSS as unique positioning device, CooPS was able to provide positioning accuracy sufficient to deploy safety applications in vehicular environments, with a minimal number of devices, low cost hardware, and ease of installation. As future work we will enable CooPS to use vehicle factory assembled sensors data to overcome GNSS unavailability due to urban canyons, dense forest canopies, and tunnels.

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