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High Precision Relative Positioning and Slot Management for ad-hoc Networks as Examples for Traffic Applications of Galileo

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Abstract

For the new European satellite navigation system Galileo many new applications are envisaged using the enhanced features with the reliability and accuracy of the system. Most applications focus on the transport area where new approaches are dealing with increased traffic and road safety using Advanced Driver Assistance Systems (ADAS). The paper shows how this can be realised by means of procedures for a high precise relative positioning of vehicles vs. other vehicles or infrastructure (e.g. fixed obstacles). For that Galileo based technologies can primary be used being supplemented by additional onboard sensors. The acquired positioning raw data (satellite pseudo ranges, speed, acceleration, etc.), being subject of the same ionospheric interferences within a short range, will be exchanged with other vehicles where special algorithms can calculate the precise distances or velocities finally creating a virtual image of a vehicles surrounding with an extended visual horizon.

For the information exchange high amounts of data have to be transferred on dedicated frequencies with standardised procedures. The paper shows that future data communication for that high dynamic radio data traffic with permanent changing link partners needs highly enhanced protocols and access procedures (ad-hoc networks) where each participant gets a precise allocated time slot for transmitting own data. The synchronisation of such transmissions needs then a high accurate common time base which can be provided by the onboard Galileo receiver with services of guaranteed reliability and availability.

Introduction

Already at the end of the 1960th the US planned to deploy a new technological high developed global satellite navigation system - the later NAVSTAR GPS (Global Positioning System). This primary military system with enhanced performances enabled not only the US military forces for precise localisation at anytime and any location on the world but also generated a huge developing civil market for high end positioning and navigation systems from the 1980th up to now. This market is still growing with the greatest part in the transportation sector.

With Galileo the European contribution to GNSS-2 (Global Navigation Satellite System - 2nd generation) will be established in the near future as a supplement to the existing GPS offering several new features. Galileo shall serve the still increasing market by new systems and services inducing many new technological developments and jobs in Europe. In competition to GPS the future Galileo customer will benefit from additional services and added values including increased reliability and safety of the application. Most of conceivable GNSS applications of today can be served only by GPS as well. Thus the search for new applications using the special features of Galileo has been started. In this connection the authors have identified several Galileo applications with special emphasize on vehicle and road safety.

Transport efficiency and safety are currently high important issues which are more and more in the economical, political and ecological focus. New approaches using modern information, communication and localisation technologies shall solve the increasing demands in transport. Several international projects are targeting on co-operative traffic systems with the intention to develop and establish intelligent vehicles and infrastructures. When exchanging information with each other every

vehicle can ‘co-operate’ with other traffic partners by optimising own decisions with respect to safety and comfort when passing, turning, lane changing or approaching an intersection.

With existing communication & positioning technologies several new system concepts can be developed especially using GPS based sensors for an adequate reliability and accuracy. For selected safety related applications such as future cooperative traffic systems or advanced driver assistance systems (ADAS) a higher reliability and accuracy will be required which can up to now not only be performed only by GPS. Introducing Galileo as an extension with guaranteed services and integrity many conceivable applications or safety related positioning, information or surveillance services will be enabled. Some of them will be introduced below.

Current situation

All over the world the amount of traffic is increasing more and more. Especially the high developed countries are facing a challenge to meet the upcoming problems due to the permanent rising number of vehicles within a limited road space leading to more congestions, accidents (with material damages and personal injuries), environmental pollution and transport costs. The current traffic management is not able to exploit the available road space in an optimal way due to missing information and distribution possibilities. The introduction of telematics systems and services enables the specific acquisition and distribution of traffic and/or safety related information from and to the vehicles on the road.

Board autonomous safety systems can increase the vehicle and thus the road safety at all (e.g. ABS, distance warning, brake assistance, navigation, congestion warning or driver assistance and collective driving systems). For that the knowledge about the vehicles surrounding is necessary including obstacles, road and infrastructure characteristics as well as other vehicles with speed, trajectories and relative positions vs. the own vehicle. Current systems today use onboard sensors which are scanning the vicinity up to the next obstacle. To detect an other object a line of sight connection is needed from the sensor to the object. This can be performed by radar, ultrasonic or optical sensors such as infrared, laser or camera sensors. Here the optical camera systems use enhanced image processing procedures still under development and are more useful for object recognition (e.g. traffic sign or type of other vehicle) than for distance measurements. But independent from their advanced development phase all these sensors can not look beyond an ahead running truck or perceive an approaching vehicle behind a corner. Their detection range (sensor horizon) is limited by the line of sight.

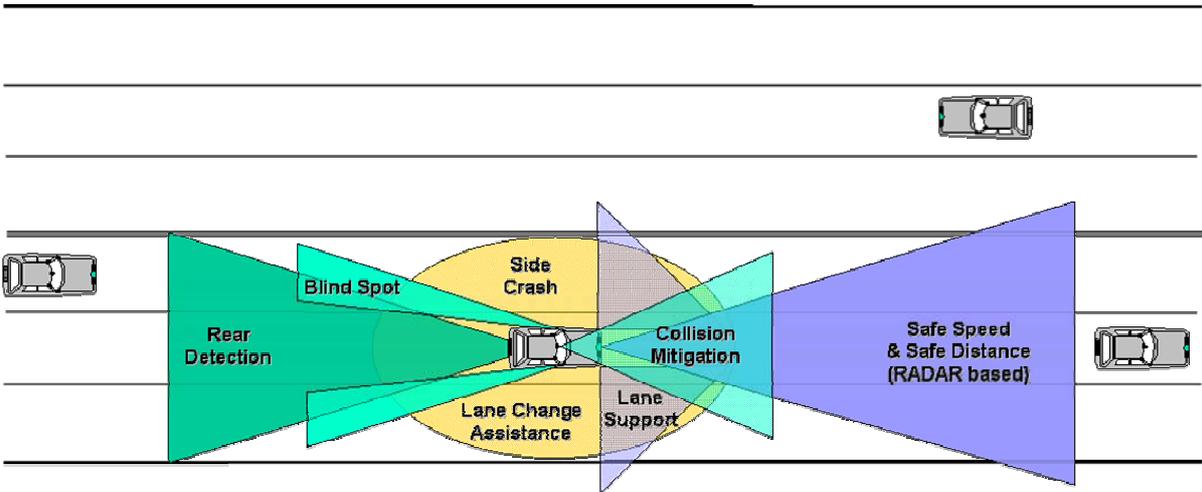


Figure 1: Intelligent vehicle for increased safety

Within the aviation sector this problem can be solved using airspace surveillance radar to provide an overview of air traffic within a large range of airspace to an air traffic controller. This long existing radar technology is also available onboard of ships where the crew gets an image of their surrounding with infrastructure, shore lines and other vehicles on an electronic screen. Thus the detection horizon can be extended beyond the visual horizon or other objects as far as the radar antenna is mounted on a higher lookout point than the obscuring objects. However, such protruding systems are obviously not very useful for the relative small road vehicles, not even for large trucks.

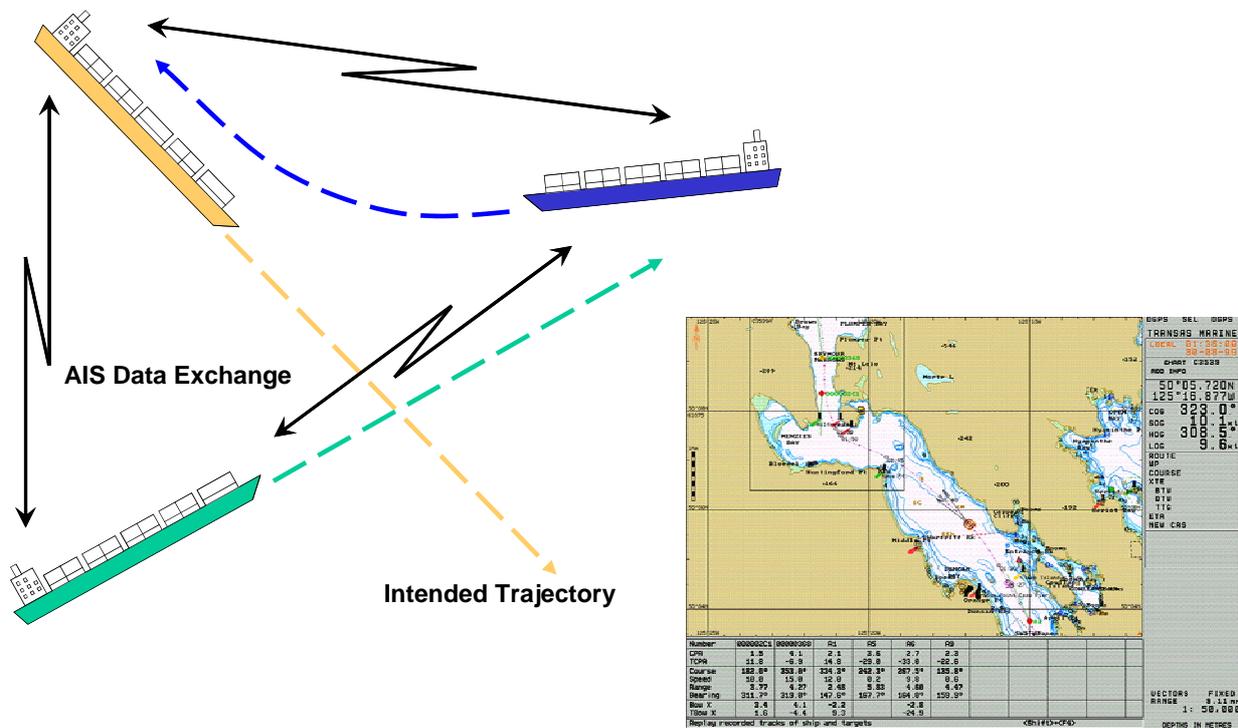


Figure 2: AIS principle function and AIS display integrated in electronic nautical charts

An other technology for maritime application is just in an introduction phase. The recently global standardised 'Automatic Identification System' (AIS) shall provide more safety in maritime traffic by exchanging information between each sea craft up from a defined minimum size. This lower limit will be decreased from year to year so that one time every ship worldwide will be equipped with AIS. The system transmits data from a ship for instance the name, type, size, cargo, GPS position, speed, direction, origin and destination to all other ships within the transmission range. The data of each ship are transferred through a well defined protocol to avoid data collision and interferences. With the received information an onboard computer can generate a virtual image of the vehicle surrounding to be displayed on a screen, similar to a radar screen but with much larger range and accuracy since the position information are GPS supported. Thus the AIS is not board autonomous but more a kind of co-operating system where each participant can be warned of other traffic and dangerous situations such as an upcoming collision.

New approaches on road safety

The functional principle of the maritime AIS could also be useful for the road traffic. A system where all vehicles are communicating with each other can also exchange essential information between traffic participants on roads and also to information and control centres via the infrastructure. For future Advanced Driver Assistance Systems (ADAS) the extension of the visible range of the onboard sensors (electronic ADAS horizon) has to be extended to look beyond the vehicles and obstacles of the direct neighbourhood. However, the AIS can not be directly transferred to the road sector with the existing properties. The road traffic is much more dynamic with quick changing speeds and directions

of each participant. The traffic space is much more limited to one dimensional roads and the distances between vehicles can decrease to less than one meter (lateral from lane to lane or longitudinal on congested roads).

Furthermore the number of vehicles entering or leaving a data exchange area (which is determined at least by the range of the applied radio link) is much higher than on the sea. Thus the communication links between the partners have to be established and disconnected very quick and very often per time interval. A similar approach using this principle for road application needs an other communication link with other frequencies, data rates, protocols etc. as well as enhanced positioning functionalities with an accuracy better than one decimetre and with an update rate of at least ten samples per second. However, the required position information is primary needed relative to other vehicles or to the local infrastructure.

But anyhow previous solutions or approaches are covering functionalities for example to warn the following vehicles when braking via a short range radio signal (electronic brake light) to avoid rear-end collisions. For more efficient road safety systems a seamless information exchange between all concerned mobile or fixed stations via a vehicle-to-vehicle (V2V) or a vehicle-to-infrastructure (V2I) communication is a precondition with high performance ad-hoc radio networks and high accurate relative position and trajectory data from each vehicle. These features will enable real co-operative traffic systems which are now called from the European Commission and is reflected within the recently closed e-Safety call for Co-operative Systems (IST 4).

The intention is to develop and standardise a system concept where finally all vehicles on a road are equipped with intelligent units for the exchange of the mentioned data via short range communication. This concept can enable not only procedures for more road safety and efficiency but can also generate important supra-regional data for traffic information, route optimisation, congestion warning and even for high dynamic update of local dynamic map data bases.

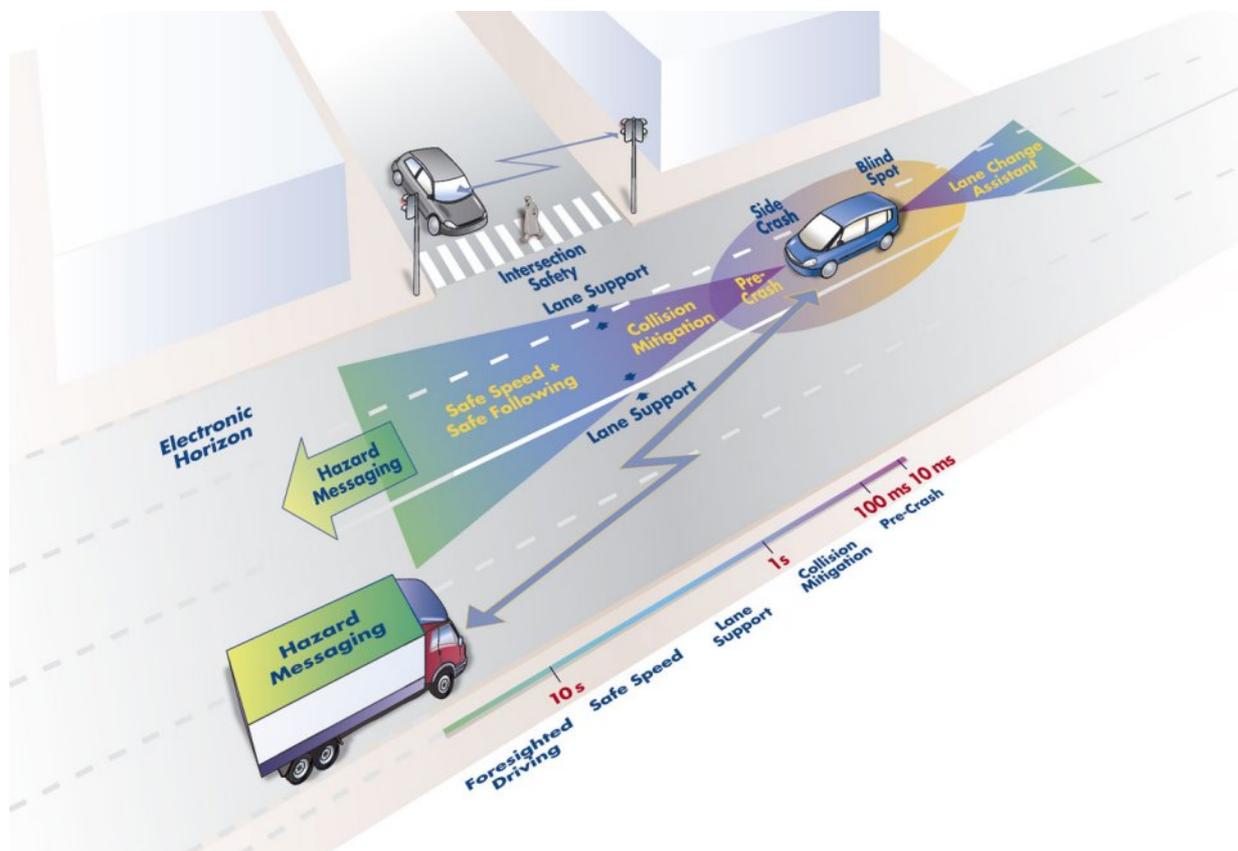


Figure 3: Principle function of future co-operative systems (www.prevent-ip.org)

One idea for a co-operative system component now is to collect relative position and other onboard data of the surrounding vehicles via permanently connected and disconnected local ad-hoc networks. Using these data an onboard computer can calculate relative short-term trajectories of each vehicle comparing the data with own onboard measurement data and creating a virtual image of the direct surrounding of the own vehicle. This image can now include the movement behaviour of the other vehicles using their relative positions, speeds, directions and accelerations (e.g. ahead running, following, passing, meeting or stopping) as well as the probably intended next manoeuvres. This can help to assist or warn the driver during his own decisions.

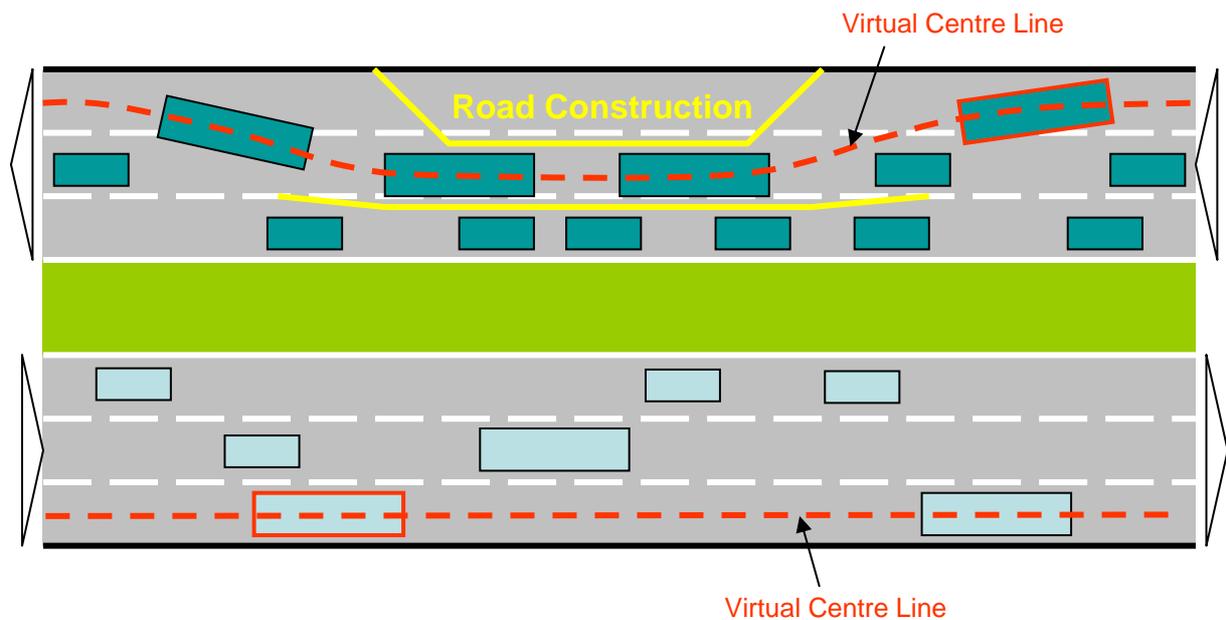


Figure 4: Example for a virtual image of a vehicle's surrounding through co-operative monitoring

Furthermore the currently used road lanes can be detected by a statistical evaluation of the trajectories of the other vehicles. This includes important information such as their occupation, course or appearing shortens (e.g. caused by road constructions), the lane function (e.g. lanes for parking or driving up or down a highway) or active speed limits as well as other interesting information. The virtual image of the surrounding created in this manner can then deliver a kind of local digital map data to be collected, improved and redistributed via local information centres on the one hand or global service provider for digital map data on the other hand. The collection of latest traffic information for a supra-regional broadcasting and traffic management can be an additional benefit.

GNSS-based relative positioning

This scenario primary needs two basic technologies: The high dynamic and high precision relative positioning of vehicles plus high performance ad-hoc networks between vehicles. For that purpose there are several technologies and type of sensors available in principle. Relative position sensing can be performed by radar, optical or ultrasonic sensors for instance. But as mentioned above all their ranges are limited by the line of sight. And inertial based relative positioning is not precise enough to meet the specific requirements for the mentioned application. To increase the electronic (ADAS) horizon and to measure the relative positions between vehicles navigation satellite signals can be used. Satellite positioning is primary used for absolute positioning within a global defined earth related coordinate system. In this case a user's receiver needs at least four satellites in view for a 3D position determination. The fourth satellite is needed to determine the unknown clock error of the receiver (which has no atomic clock inside). When using more than four satellites for the position solution it is

over-determined but this can increase the reliability and the accuracy of the result. The mean accuracy of GPS positions ranges between 10 and 20 meters depending on the satellite constellation but can also reach better values. Galileo is asserted to reach about 4 meter accuracy with the open service.

For an absolute positioning with a higher accuracy in the sub-meter range a second frequency band and a differential mode with special receiver is needed. A precise surveyed reference receiver station compares the measured pseudo-ranges with its own position and distributes it's calculated differential correction data to other moving receiver (e.g. via a radio link). With that technology DGPS services can reach an accuracy in a centimetre range but always needs a stationary local reference station. An other new approach is the exchange of unprocessed raw measurement data (mainly pseudo-ranges between a vehicle and the received satellites).

If a mobile receiver can detect its position by measuring pseudo-ranges to several GNSS satellites than it can also output the unprocessed pseudo-ranges \mathbf{r}_i with a high precise time stamp from the satellite system time. This time reference is the processed result additional to the position wherefore four satellites are needed. If an onboard computer gets the received data of an other receiver in the near vicinity (pseudo ranges \mathbf{r}_i'), regardless whether this receiver is mounted in the same or another vehicle, then the pseudo-ranges of both receivers can be compared to each other and a range difference $\Delta\mathbf{r}_i$ to every satellite (no. i) can be determined. The projection of the searched relative position vector \mathbf{d} (from the own antenna to the other one) on the range vector \mathbf{r}_i is just the difference vector $\Delta\mathbf{r}_i$ for every received satellite. With three difference vectors $\Delta\mathbf{r}_{1,2,3}$ the 3D relative position vector \mathbf{d} can now be determined.

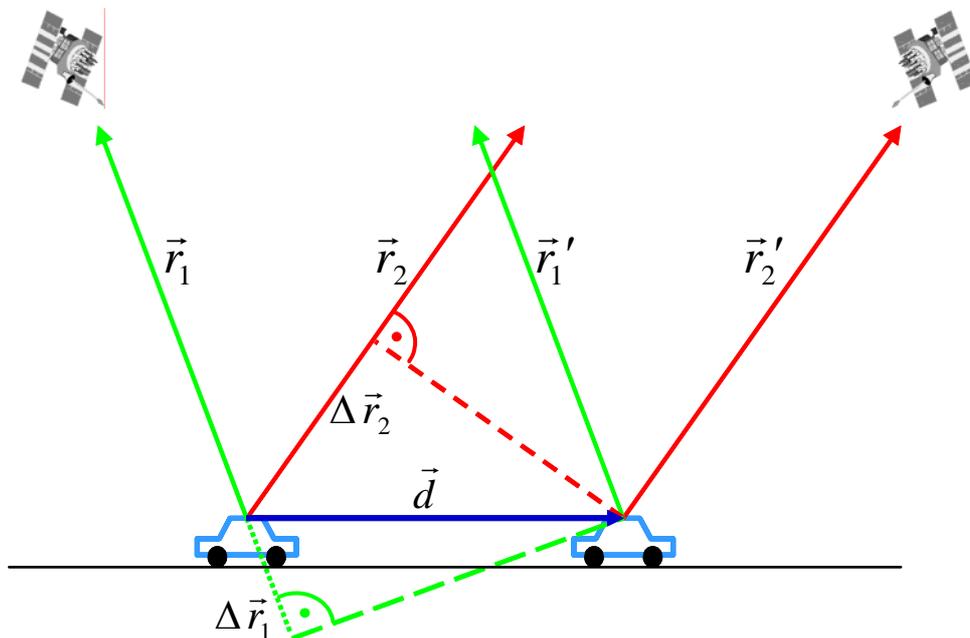


Figure 5: Relative positioning through satellite pseudo-range differences

\mathbf{r}_i = pseudo-range vector from the own vehicle to the satellite no. i

\mathbf{r}_i' = pseudo-range vector from the other vehicle to the satellite no. i (quasi parallel to \mathbf{r}_i)

$\Delta\mathbf{r}_i$ = pseudo-range difference between both vehicles to the satellite no. i

\mathbf{d} = relative position vector from the own vehicle (antenna) to the other one

For the measurements it will be assumed that the pseudo-range vectors \mathbf{r}_i and \mathbf{r}_i' from the reception antennas of each vehicle to a satellites are quasi parallel even if the vectors are fractured within the ionosphere. The angular difference of the reception signals at each location within a small vicinity can be disregarded. Furthermore both signals are following almost the same path and will be influenced by the same effects. Thus the absolute pseudo-range errors through ionospheric signal refraction will not effect the result of the pseudo-range differences used for the calculation of the relative position vector \mathbf{d} .

Whereas other effects appearing at the surface can result in different reception conditions. These effects can be the signal shadowing by buildings, vehicles or vegetation or the signal reflection at any kind of object. Using signals at different receiver locations (e.g. at two vehicle positions) at the same time from the same satellites it has to be assured that the conditions for the reception at either location is identical. Only the uninfluenced pseudo ranges can be compared for the difference. If one signal is shadowed or reflected this would cause a large error in the calculation of the pseudo range differences and thus in the relative position result. For that the signals in each receiver have to be analysed in respect of their signal quality (signal strength or the S/N ratio and bit error rate). This value has to be considered for each pseudo-range comparison of each vehicle as well to exclude diverse signals from further processing.

But using only satellite signals for the determination of absolute or relative vehicle positions has several disadvantages. The high frequency radio signals coming from orbiting satellites can be shadowed any time as mentioned before by moving or fixed obstacles of any kind. This will lead to an interruption of the position determination process and to gaps or leaps in the resulting trajectory. Furthermore the vehicle movement on a road is a high dynamical process with sudden accelerations, brake actions or direction changes. To cover this vehicle path a similarly dynamic measurement process has to be applied to capture all waypoints with the required position accuracy. But satellite navigation data can at most be provided several times per second from a high performance receiver. Regular mass market receiver provide a complete data set at most once per second.

To close the appearing gaps in the satellite navigation data due to limited dynamic or shadowing and signal interruption it is recommended to combine GNSS receiver with other high dynamic onboard sensors for relative positioning. These sensors are often present in today's vehicles with navigation systems or only for vehicle safety and driver assistance functions. Such onboard systems are using odometer, accelerometers, gyros or compass sensors to fulfil there different tasks. An onboard sensor fusion with a GNSS receiver is already state-of-the-art technology and should be maintained also for a relative positioning application.

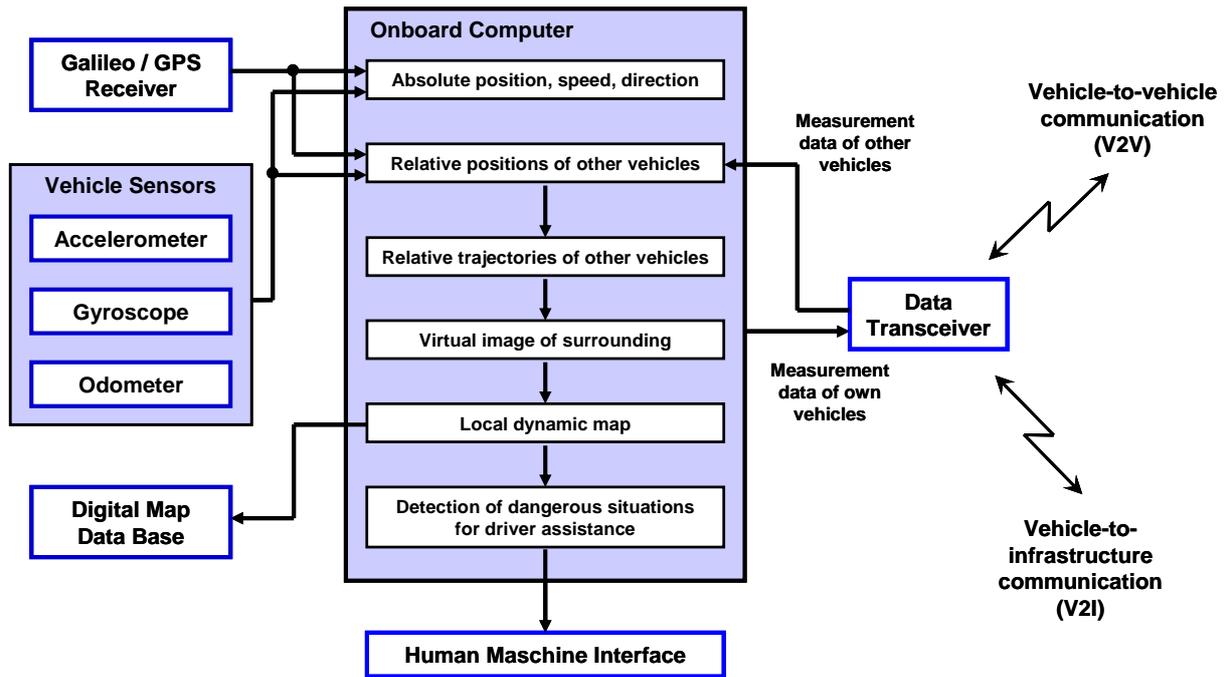


Figure 6: Block diagram of an onboard platform for relative positioning with sensor fusion

Benefits from Galileo

To ensure the reception of at least three satellites without signal interferences at several vehicle locations at the same time the number of visible satellites has to be as high as possible. Thus more satellites in orbit will lead to a higher probability for the reception of enough satellites on the ground even within critical areas such as urban or mountain areas for instance. Fig. 7 shows an example for the satellite availability in Berlin during 24 hours with an assumed simplified elevation mask at 45 degree due to urban buildings. It will be obvious that only GPS-based 2D- or 3D navigation can not be performed under these conditions (green line). Using the additional Galileo satellites the critical threshold of visible navigation satellites required for 2D- (at least 3 sats) and even for 3D-navigation (at least 4 sats) will almost always be exceeded regardless whether for the absolute or relative positioning (blue line).

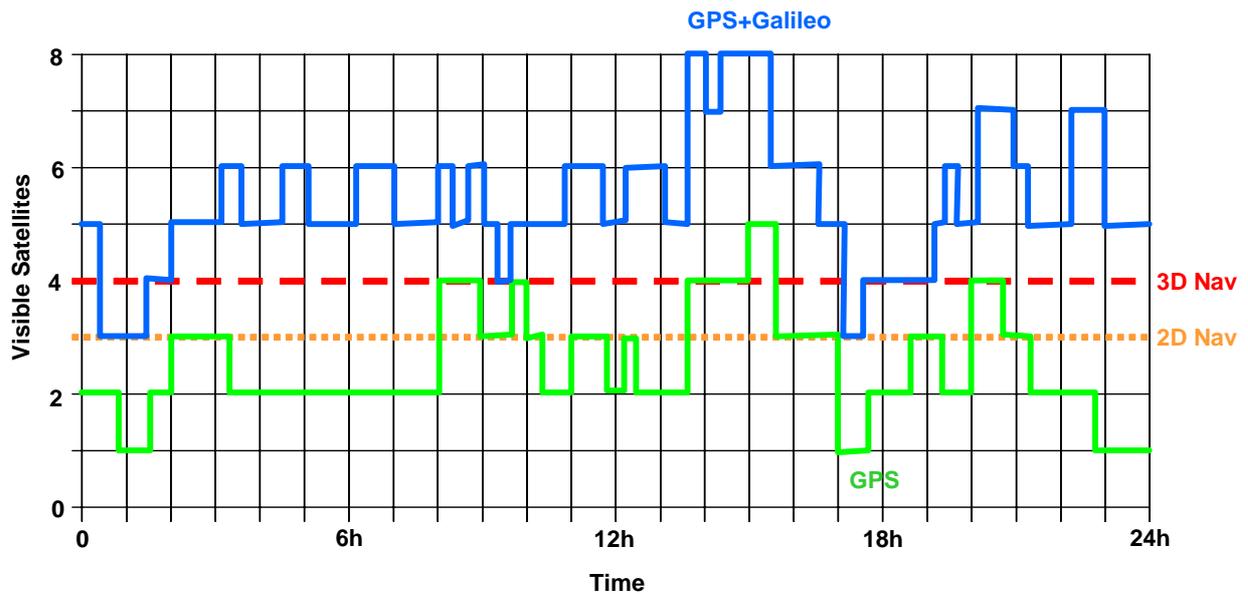


Figure 7: Simulated GNSS satellite availability in Berlin for 24 hours with a 45 degree elevation mask angle

Other benefits from using Galileo are already well mentioned within the user community. Not only the higher availability due to more orbiting satellites but also a higher signal quality respectively a higher positional accuracy and service reliability can be achieved with Galileo as well as service guarantees for Safety-of-Life services (SoL). This can be of important interest if absolute or relative positioning technologies will be applied for driver assistance, vehicle safety or road safety applications, where the positional information from every vehicle is of vital importance. The safety and reliability aspect is also close connected with the integrity monitoring functions for Galileo. The permanently monitored satellite signals enable the creation of information about the signal condition of each satellite and the calculated position resulting from the utilisation of a dedicated signal. When a signal is interrupted or degraded this information can be provided to any user.

Furthermore Galileo provides more frequency bands than GPS and can thus reach a higher basic accuracy for absolute positioning due to a better measurement of the ionospheric refraction and a better resolution in the code and carrier phase measurement. The Open Service (OS) of Galileo will be provided free of charge with two usable frequencies which can support basically a higher resolution in satellite pseudo-range measurements with code and carrier phase evaluation. A third frequency can additionally be used for a maximum precision especially for the measurement of range differences to the satellites needed for the high precision relative positioning. Thus Galileo or the combination of Galileo and GPS will be much more efficient, available and accurate than only GPS.

But one problem for satellite navigation applications which can appear on urban roads with high buildings and north-bound direction is the missing appearance of any navigation satellite within a large celestial region around the north pole (Fig. 8). This black out area is caused by the inclination of the satellite orbits which do not overfly latitudes higher than the orbit inclination (55° for GPS, 56° for Galileo). This fact can result in a poor coverage within north-south road canyons regardless whether using GPS, Glonass or Galileo since it does not depend from the number of orbiting satellites but only from the orbit inclinations.

When driving through such a road canyon only a small window of the southern sky can provide usable satellites (as far as not shadowed by additional buildings or own vehicle components) while east and west directions are shadowed by buildings and the north is 'empty'. This can corrupt an absolute as well as a relative positioning result due to too few satellites.

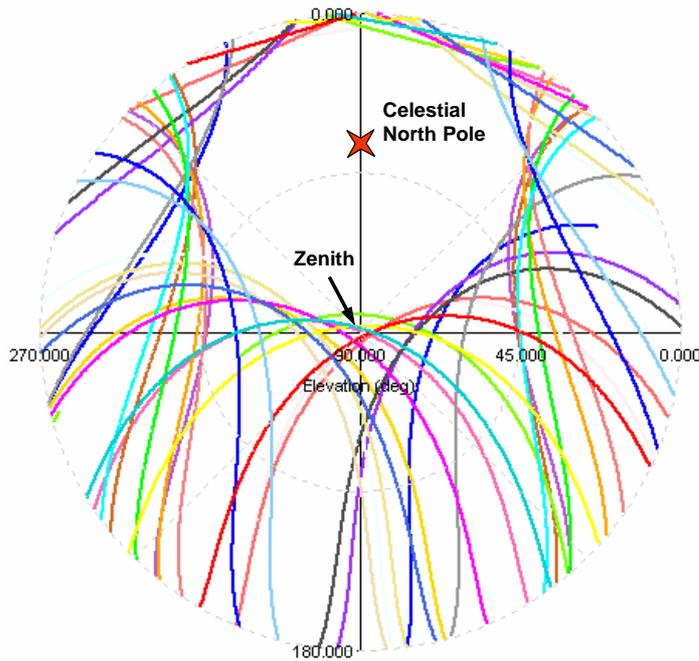


Figure 8: Celestial polar diagram of GPS overflights over Berlin for 24 hours

While absolute 3D-positioning needs at least four received satellites the relative 3D-positioning procedure mentioned above only needs three satellites. But a valid navigation result is necessary any way because a high precise time stamp coming from the navigation result has to be provided with the measured pseudo-ranges from each vehicle to be comparable with the measured pseudo-ranges of an other vehicle. Thus this procedure needs four satellites as well. This has to be considered when designing or using satellite based positioning sensors which should be augmented by additional sensors any way (as mentioned before).

Ad-hoc communication

The exchange of measurement data between vehicles of a dedicated area needs a special communication procedure. One approach which is commonly made is the application of ad-hoc networks to be established by the participating vehicles. Such networks which are just under development in numerous institutions and projects need a complex access procedure where a precise time slot will be allocated to each subscriber. Since the number of appearing subscribers respectively vehicles can be very high with frequently changing links to be established and terminated a well defined slot management has to be applied using a precise common time base.

For a first rough estimation of the required data network performance the following scenario will be assumed: Each vehicle shall receive data from other vehicles within a circle of 500 metre radius. On a highway junction with three lanes in four directions there are a 12 lanes each with 1000 m length (500 m in each direction from the present position of a dedicated vehicle). If each lane carries one vehicle every 100 m there will 120 vehicles appear within a 500 m radius around the junction. Every vehicle can broadcast a data set of 1 kByte (or 10 kBit) containing the absolute position, direction, speed, acceleration and a historical set of raw measurement data with pseudo-ranges, inertial, odometer or gyro data for instance.

Thus a permanent number of several hundred vehicles (120 in the present scenario) could to be served while moving with speeds up to 200 km/h or more (only some of them). With an assumed exchange rate of 10 data sets per second from each vehicle (to detect also the quick changing directions or brake actions) every vehicle would transmit 100 kBit of data every second. Within the assumed area this would produce a netto data amount of 12 MBit with 1200 connections and disconnections per second. Assuming an efficiency of 10% due to data overhead for the link protocol, data formats and access procedure the amount would increase up to over 100 MBit/s with a bit length of 10 nanoseconds respectively corresponding with 3 m of covered distance for a radio signal.

Assumed Scenario	Highway junction
Number of lanes per direction	3
Number of total lanes	$4 \times 3 = 12$
Radio range of ad-hoc network	500 m
=> Concerned road space	$2 \times 12 \times 500 \text{ m} = 12000 \text{ m}$
Traffic density	1 vehicle / 100 m of road lane
=> Total number of vehicles in range	$12000 \text{ m} / 100 \text{ m} = 120 \text{ vehicles}$
Data block length of each vehicle	10 kBit
Update rate	10 blocks/s
=> Required netto data rate per vehicle	100 kBit/s
=> Required total netto data rate	$120 \times 100 \text{ kBit/s} = 12 \text{ MBit/s}$
Protocol efficiency	10 %
=> Req. total brutto data rate (physical)	$10 \times 12 \text{ Mbit/s} > 100 \text{ Mbit/s}$
=> Bit length	$10 \text{ ns} \hat{=} 3 \text{ m}$

Table 1: Assumed scenario for vehicle data exchange via an ad-hoc network

But the quick increasing or decreasing distances between communicating vehicles will shift the used time slot relative to each other. If the allocated access time slot accuracy for each subscriber is one bit length then it represents a required distance accuracy of 3 metre to be known when the time slot will be allocated. With an assumed speed of 200 km/h this distance will be covered within 54 msec by a vehicle. To ensure an undisturbed data exchange between all vehicles within the dedicated range the precise measurement of the vehicles relative positions, speeds and directions has to be performed as well as the provision of a high accurate common time base of at least $10 \text{ nsec} = 10^{-8} \text{ sec.}$ accuracy. These information can only be provided by very expensive dual-frequency GPS receiver used for military or survey applications or by multi-frequency but low-cost GPS/Galileo receiver to be new developed in the near future for a mass market like road and traffic safety. Finally the provided service guarantees of Galileo for the Commercial (CS) or Safety-of-Life (SoL) Services can enable these special functions where not only a high precise position and time information is needed but also a high reliability to ensure the finally intended safety related services. These quality of service (QoS) will not be provided by GPS.

Within this short examination the type of radio link, frequency band, data exchange and access protocol or coding scheme have not been considered. For the mentioned purpose of high speed short range mobile communication and the high dynamic exchange of small data packets there are already some technologies such as WLAN, Bluetooth or cellular networks envisaged. But also cellular radio networks (e.g. GSM, UMTS, 3G) may be considered for similar scenarios which will not be investigated here since the main idea is the use of Galileo for traffic applications. In the future every communication transceiver will probably be equipped with an additional GNSS receiver component which will be useful for future location based services and therefore will be part of future mobile phones and transceiver any way. Thus an additional added value for road safety related aspects should be proposed.

Conclusion

For the mentioned technology of precise relative vehicle positioning there are arising applications e.g. in co-operative systems for increased road safety and efficiency. Within these new developments the relative positioning procedure could supply an important core technology since the knowledge of the vehicle locations vs. each other is more safety relevant than the absolute position. The current traffic flow and behaviour as well as the condition of the used infrastructure can be better analysed and evaluated using this information from all vehicles of a dedicated road sector.

But such a system can even provide actual traffic and infrastructure data for traffic information and control as well as for digital map updating. The collected onboard data of each participating vehicle can be downloaded on special exchange points (e.g. petrol station) with the appropriate communication components. Thus this system can have twice benefits, one for real time driving safety and one for long term traffic and map data support.

All in all this technology are conceivable for several transport applications. Some of them are listed below and do not only cover the road traffic sector:

Road traffic:

- Track control assistance,
- Break support when traffic is jamming
- Warning of curves, obstacles or shortages
- Speed dependent distance warning of road construction, break-down or accident points
- Separation support to ahead running, following or approaching vehicles or to contrary lanes
- Mutual warning of intersecting road and rail traffic (e.g. tram)
- Clearance warning for passing or lane changing vehicles
- Trailer surveillance
- Convoy surveillance
- Warning of roadbed for visually handicapped pedestrians

Air Traffic:

- Collision avoidance of service vehicles, airplanes and other obstacles in airport apron areas

Railroad:

- Train completeness monitoring
- Speed dependant train separation and obstacle clearance warning
- Rail track separation and control
- Shunting support