DINGPOS: A Hybrid Indoor Navigation Platform for GPS and GALILEO

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BIOGRAPHY

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INTRODUCTION

In deep urban and indoor environments the direct reception of the satellite signal is very often obstructed, making necessary to turn to alternative positioning technologies to GNSS. The optimum solution to overcome the challenges of indoor positioning should take advantage of existing infrastructure, such as communication networks that already provide indoor coverage, or local or autonomous elements implemented within the user terminal. This field is now maturing and is producing interesting technological solutions at reasonably accessible prices. It is not far-fetched to envision a single portable platform capable of incorporating a GNSS receiver embedded in a cellular device incorporating A-GNSS, WiFi, DVB or UWB and local MEMS, and combining all this information to provide the best possible positioning service in all environments.

Indoor navigation will lead to a significant improvement in Location Based Services for personal and professional applications, which will imply also important social benefits. The logistical monitoring and deployment of search and rescue teams, police corps, etc., would be improved significantly given the capability to continuously track each asset, not to mention the benefits to other sectors such as the transport of goods or hazardous materials. Innovative new applications will arise as the price of this technology comes down and within range of the general public.

In response to the obvious benefits of indoor positioning, the DINGPOS Project has been launched by ESA to study, develop and test the most promising state-of-the-art indoor positioning techniques. The project is studying innovative ways to combine different wireless technologies (WiFi, UWB, cellular communication systems) and sensors (baro-altimeters, gyroscopes, accelerometers) with indoor GNSS and other methods, such as 3D indoor Map Matching algorithms. Special effort is being placed on the development of high sensitivity algorithms for GPS and Galileo signal acquisition and tracking in indoor environments capable also of mitigating multipath, interferences and cross-correlation effects, taking advantage of the innovative features of the Galileo signal (pilot one, etc.) and assessing the benefits to be had with Galileo. Advanced data fusion techniques are also being investigated to best hybridise the available data from GNSS, MEMS and Wireless sensors, so as to provide seamless positioning in different environments.

After a performance assessment and architecture trade-off, the most promising technologies and techniques will then be implemented in the DINGPOS demonstrator platform, which will be kept open to future evolutions of indoor navigation.

1. CHALLENGES FOR INDOOR NAVIGATION

1.1 Environment and Signal Reception/Acquisition quality

The difficulties in using GNSS for indoor positioning, come from the fact that GNSS have been designed and dimensioned for outdoor environments. The propagation from the satellite to indoors presents many deleterious effects and therefore, indoor GNSS receivers have to operate in conditions that are much more demanding than the ones assumed in the nominal design of the system. In short, the demand of providing location information everywhere has lead us to the need of designing GNSS receivers able to work in environments for which GNSS had not been designed. Moreover, these indoor GNSS receivers are aimed at being embedded mainly in mobile phone and PDAs, where cost and power consumption are of paramount importance. All these aspects give rise to many challenges at signal processing and other levels in the design of such receivers.

The interest on indoor positioning was mainly initiated as a result of the US FCC E911 mandate in 1996, followed by a similar European recommendation called E112. The mandate required the mobile communication operators to be compatible with location determination in the 95% of all sold handsets. This implied that mobile terminals should be able to report their position during an emergency call with accuracy on the order of 50 or 100 meters. As the previous requirement was independent of the location (either indoors or outdoors) of the terminal, and only restricted by the coverage area of the mobile operator, it immediately became a technical and economical challenge, and the entry-into-force date has been postponed year after year, until December 2005.

The most deleterious effect of indoor environments is obviously attenuation. Following to the results measurement campaigns, the conservative industry target is to receive GPS signals above a C/No of 20dBHz. Notwithstanding, in order to be able provide a positioning service with an unquestionable commercial appeal (i.e. with coverage in most building floors over the ground), reception down to C/No=10dBHz is pursued. The use of GNSS in this context has received the name of A-GNSS/A-GPS and HS-GNSS/HS-GPS, standing for Assisted or High Sensitivity GNSS/GPS.

Before proceeding any further, the plausibility of achieving the required position accuracy at these low C/No values has to be checked. In order to avoid implementation details in the receiver, the Cramér-Rao Bound (CRB) on the estimation error in τ_0 is used (expressed in meters). For GPS, the CRB of τ_0 for C/No=10dBHz is 30m [RD. 1]. If the dilution of precision is equal to four and all satellites in view have C/No=10dBHz (which is a very pessimistic assumption), the position standard deviation will be 120m, which is on the order of the requirement. Although the analysis cannot be conclusive because it is based on a lower bound and only considers thermal noise errors, the assessment is positive and indicates that positioning at that low C/No may be possible.

The immediate effect of those low power levels is that the bit energy to noise spectral density ratio, Eb/No, falls well below the Shannon's limit. Therefore, the navigation message cannot be recovered and the time stamps on the signal are missed. The availability of both the navigation message and the time stamps is essential for the computation of the position. The lack of the navigation message can be overcome with the use of the A-GPS concept, whereby the navigation message or equivalent information is sent to the GPS receiver by means of a terrestrial communication system, such as a cellular mobile system, a wireless local area network (WLAN), etc. The provision of the time stamps via the communication system is more problematic because it requires a very precise synchronization between the three parties involved: the navigation/communication receiver, the communication network and the GPS time. Although current (GSM) and third generation (CDMA2000 and UMTS) systems have the capability of providing this synchronization, it is a feature that is preferably not implemented because it increases complexity and cost of the network. In the absence of time stamps or synchronization with the network, the receiver can still compute the position as long a rough estimate of the position (on the order of kilometers) and the time (on the order of seconds) is available. The computation is more complex than in a conventional receiver and, as we will see below, the use of more sophisticated signal processing algorithm can simplify the position computation.

Although the navigation message cannot be detected, it is still possible to measure τ_0. Attenuation has clearly the effect of increasing the estimation error in τ_0, which eventually translates into larger position errors. Moreover, attenuation differences among the signals coming from different satellites also have detrimental effects. This effect is called *near-far* effect in reference to the differences in received signal power experienced in cellular communication systems. In these systems, the power differences are due to the differences in distance from the mobile to the base stations. On the contrary, in GNSS the power differences are caused by the different attenuation of the propagation paths; for instance, one signal may be received through the window and another signal through the ceiling. The near-far effect may cause that weak signals from satellites in view are not detected or they are detected but the measured pseudorange has a huge error. In a general case, the near-far effect may also make the receiver detect a satellite that is not in view. However, this type of error is not considered here because the list of satellites in view is transmitted along with the assisting information.

The aspects conditioning GNSS-based indoor localization are not only arising from the propagation environment but also from the application requirements. First, the positioning receiver will most surely be included in a mobile phone or handheld, where the use of low-cost components is of paramount importance. Clocks used in this type of devices have stability on the other of 1ppm [RD. 2]. Note that 1ppm is equivalent to 1.5kHz in the L1 band. Second, as little additional hardware as possible should be needed for the navigation part of the receiver. Nowadays, there is the trend of using software-defined radio concepts for the implementation of the navigation functionality in the phone. Some manufacturers start to offer navigation receivers in which the signal processing is entirely executed in the processor (usually an ARM processor) already present in the phone. Next, mobile devices are power-constrained so the implementation of the navigation functionality has to be as power-efficient as possible. This fact leads to a snapshot or acquisition-only type of implementation. That is to say, the navigation receiver does not track the signals continuously, but only it processes them when a position fix is needed. The industry target is to consume less than 100mJ per position fix. Every time the position is to be computed, the receiver has to acquire or synchronize the received signals. This process has to be done as quickly as possible because the time-to-fix (TTF) is an important performance metric at application level, where a TTF smaller than 10 seconds is sought. The A-GNSS concept contributes towards this objective because the transmission rate of the navigation message is much faster than that of the navigation signal.

1.2 Limitations of sensor only navigation

Generally, users applications require to have navigation means with **in-door and out-door** coverage. Definitely GNSS is the most appropriate to provide out-door wide range navigation. For in-door environments, two families of location techniques exist, one based on local networks means (Wifi, ad hoc deployed UWB or DVB-H…), or inertial sensors. Inertial sensors are interesting since they do not need any infrastructure. Nonetheless they drift quickly with time in distance but also in heading, and provide a relative position only. For these reasons inertial sensors need to be combined/hybridised with GNSS or network based location techniques that provide absolute position.

2. STATE OF THE ART

2.1 Signal processing

The objective of the signal processing techniques is to address the main challenges posed by the indoor environment and described above: extremely low received signal energy, absence of time stamps and near-far problem.

It is clear that in order to be eventually able to detect weak signals, the signal power has to be accumulated during long time intervals. This is the so-called HS-GNSS principle. The correlation between the incoming signal and a local replica of the code for each of the satellites in view is computed for different trial values of the delay, τ, and frequency offset, f. The signal is correlated coherently during T_{coh}, and N_I values are non-coherently accumulated. The possible delay/frequency pairs where a signal may be present correspond to those values of total correlation that surpass a certain threshold. It is not convenient to select the maximum of those values as the correct location of the signal because a further processing to combat the near-far effect is in order. Moreover, experiments have shown that a different threshold for each value of f has to be used. The reason is that the effect of external interference and cross-correlation with other GNSS signals is frequency dependent, which results in different post-correlation noise-plus-interference power at different frequencies. In a practical case, the duration of the coherent correlation is limited by the presence of bits and/or the accuracy of the clock+Doppler frequency estimation. It is possible to replace the conventional squared non-coherent correlation with the multiplication of two successive coherent values, after having conjugated one of them. This approach is called differential correlation. Although it offers a sensitivity gain of 1.5dB at moderate and large C/No values, it does not bring any gain at low C/No values.

It might be argued that it should still be possible to attain the required sensitivity by increasing N_I as much as necessary. This argument is flawed because of some realworld implementation aspects that are generally overlooked in analytical derivations. The key point is that the accuracy in estimating the frequency shift must be on the order of the reciprocal of total correlation time, and not on the order of the reciprocal of the coherent integration time as it is usually assumed in communication systems. Therefore, increasing N_I has also a negative effect on complexity since a finer frequency grid must be used for the search of the maximum of correlation peak.

Even if the price of a finer frequency search is to be paid, the total integration time cannot be arbitrarily large because the frequency shift, $f_{d,0}$, cannot be considered as constant during that time due to the receiver clock drift. A varying frequency shift cannot be estimated with a single value, f, with the required accuracy no matter how fine the search is. In this case, methods to estimate the clock dynamics would be needed, but this kind of solutions are not feasible in a handheld receiver. Current clock technology limits the integration period to less than ten seconds, and it is recognized that the development of more accurate and cost-effective clocks will be a key technological enabler of indoor GNSS solution with increased sensitivity [RD. 2].

There are other effects that limit the maximum value of the total integration time. The satellites and possibly the receiver are moving during the correlation time. However, the result of processing the signals during the integration time is only one value of τ for each satellite. Using these values of τ and the positions of the satellites at a given instant, the receiver provides one position fix. There is an inherent ambiguity because the position fix does not correspond to the position at any particular instant, but it is a kind of average of the positions along the correlation time. The same type of ambiguity is applicable to the choice of which instant should be taken to compute the satellite positions. Furthermore, the longer the total correlation time, the more energy per position fix is consumed by the receiver.

The next desirable step is to increase the coherent integration beyond the bit duration. There are data-aided and blind approaches to achieve this goal. In the data-aided one, the bits of the navigation message are sent by the terrestrial communication system as part of the assisting information. Thus, the receiver can easily compensate for the bit changes in the navigation signal. However, this approach is not the preferred solution since it has many implications at system level. The communications system (regardless it is a cellular system or WLAN, etc.) has to transmit continuously the navigation messages of all satellites in view and, what is more restrictive, the receiver needs to have access to the communications system whenever it wants to compute the position. Moreover, the transmissions have to be synchronized with the navigation messages as received from the satellites signals. In the normal operation of A-GNSS, the receiver can obtain the assisting information and use it later on to compute the position even if at that instant it has not access to the communications system.

The existence of pilot signals in Galileo should seemingly make the extension of the coherent integration easier because all the signal components are perfectly known at the receiver. However, this is not so straightforward in reality because the receiver needs to find out the timing of the secondary code

If correlation is computed using the FFT, the selection of the sampling frequency is a key aspect. The sampling frequency has to be incommensurate with the chip rate and, at the same time, provide a number of samples per code period close to a power of two.

The worst-case cross-correlation between GPS signals is 24dB if there is no bandwidth limitation, but this value decreases to 20dB or even less due to the small bandwidth of handheld receivers. The power differences found in the indoor environment may reach 30dB, so the inherent robustness of GPS signals is not enough to withstand the near-far (NF) effect indoors.

The result of coarse acquisition is a matrix of correlation values in a time-frequency grid. This matrix allows for a detailed analysis of the signal characteristics, and this analysis is not possible in the subsequent stages of the receiver, which only process a small part of the matrix. Therefore, near-far detection must be performed after coarse acquisition and its main goal is to discriminate the peaks that are due to near-far interference from the one (if it exists) that corresponds to the desired signal. If the near-far detector is not able to distinguish the correct peak, it is possible to apply a near-far mitigation technique, and coarse acquisition can be repeated again. From the user point of view, detection is much more important than mitigation. If the near-far interference on one signal turns out to be undetected, the error in the pseudorange and, hence, on the position will be extremely large (e.g. tens of kilometers). If the near-far interference is detected but not mitigated, the satellite will be declared unavailable.

Galileo employs longer PN codes and, as a consequence, it offers between 6dB and 30dB of increased NF protection. The range is so wide because it depends on which signal component is considered and on whether the coherent correlation extends to the complete secondary code or only to the primary one. It is anticipated for that reason that NF will be much less of a problem in Galileo, although this needs to be corroborated by experiments with real signals. Note, however, that this gain is obtained at the price of a more complex coarse acquisition

The measurement of the C/No is not only important if NF mitigation is applied, but it is an integral part of any receiver because it is used for signal quality monitoring. The quality of the signals is employed in the position computation, where each delay measurement is weighted by square root of the corresponding C/No to improve position accuracy. C/No estimators used in outdoor receivers fail in indoor receivers working in acquisition-only mode and need to be adapted.

Finally, it is worth mentioning that all the signal processing steps addressed above must be applied according to a state machine that takes into account the variety of situations found in a real scenario. The logic underlying this state machine is as important as the quality of each individual step.

2.2 Assistance Information

The DINGPOS platform includes assisted–GNSS capabilities that are used in connection with Thales Alenia Space Location server providing the necessary assistance data.

These data are consistent with the 3GPP defined RRLP protocol, and are exchanged within OMA defined SUPL transactions. They consist of:

- ✓ Reference Time
- ✓ Reference Location
- ✓ DGPS corrections
- ✓ Navigation Model (Ephemeris data)
- ✓ Ionospheric Model
- ✓ UTC Model
- ✓ Almanac
- ✓ Acquisition Assistance data
- ✓ Real Time integrity

It must be noted that DGPS corrections are computed as Local Differential corrections, or as EGNOS Differential corrections, depending on the distance of the User receiver to the Location Server reference GNSS receiver.

2.3 Wifi

During the last few years, Wireless LANs have experience a huge growth in popularity, mainly due to widely available low cost standardized commercial solutions, interoperability between equipment manufacturers, easy installation and maintenance and freedom to access data anytime, anywhere.
The Wifi positioning technology takes benefit of this development together with mobile network location technologies. Most of the Wifi-based positioning techniques relies on Cell Identification (CI), Received Signal Strength (RSS), Wifi Time of Arrival (TOA), Wifi Time Difference of Arrival (TDOA). Angle of Arrival (AOA) techniques are not really applicable as highly directional antennas are not used in Wifi equipments.

2.4 UWB

UWB technology is an excellent candidate for precise positioning in indoor environments. The fundamentals of this technology are based on the emission of subnanosecond pulses with spectral occupancies on the order of several GHz. Thus, an unprecedented precise time resolution can be achieved compared to traditional narrowband systems. The impulsive nature of UWB signals is also an important feature. As it has been recently found, this particular transmission format is optimal for radio transmission under the low-SNR regime [RD. 3] (e.g. indoor scenarios).

Except for this physical layer advantage, positioning algorithms for UWB signals do follow the same reasoning as for conventional narrowband positioning systems [RD. 4]. This allows UWB measurements to be easily coupled and hybridized with other technologies, but also to share many of the traditional positioning approaches. That is, signal strength measurements [RD. 6], time-of-arrival, or combinations of both [RD. 7]. For the latter, significant enhancements have been reported with respect to the case where only SS measurements or only TOA measurements are used.

2.5 Sensors

Using sensors as an augmentation to GNSS-based positioning systems is all the more interesting as their integration into consumer products is constantly increasing since a couple of years. Single-die sensors capable of providing measurements along three orthogonal axes can now be found in large volume (as for instance accelerometers [RD. 8], magnetometers [RD. 9]), whereas other sensors are likely to follow (currently two-axis gyroscope into one single-die [RD. 10]).

Sensor-based positioning methods have been widely studied. Traditional navigation algorithms may have very different performance in terms of accuracy depending on the quality of the sensors embedded in the measurements unit. Two typical mechanizations can be used to navigate, namely the Inertial Navigation System mechanization [RD. 21] or the Pedestrian Navigation System mechanization [RD. 11], [RD. 12].

2.6 Map-Matching

Map matching is a process that identifies the correct route of a user's navigation by associating the estimated positioning data of the user to the network map data. In many enhanced map matching algorithms, the user's location on the identified route can be determined. Mainly, the two essential components that impact the performance of a map matching algorithm are user's positioning and network data. Taking the example of vehicles localisation, their navigation solutions have some special attributes from the fact that vehicles are mostly travelling on roads. This property can be used to impose constraints on the position solution. The Map matching can also be defined as the process of imposing such constraints.

From a general point of view, MM algorithms can be grouped into two distinct families, the geometric based and the topological based. The first one uses geometric information of the network. The algorithms use geometric elements such as the shape of the segments of a route, and not the ways in which these are connected [RD. 11]. Generally, the geometric based approach can be categorized by point-to-point matching, point-to-curve matching and curve-to-curve matching. In point-to-point matching, an estimated location is matched to the nearest shape point (or node) of the network. A fundamental approach to determine the nearest distance between the estimated location and the shape point is through the Euclidean distance [RD. 11]. In point-to-curve matching, an estimated location is matched to the nearest arc in the network. The most common approach to identify the nearest arc is to use the minimum distance from the estimated location to the arc. As most of the arc can be modelled as piecewise linear curves, it is fairly simple to find the minimum distance from an estimated point to a curve [RD. 11]. The third approach, curve-to-curve matching, would be much better for non-straight routes as it consider several estimated positions simultaneously by matching the arc formed by these estimated positions to the closest curves of the network.

The performance of a geometric based map matching algorithm can be improved if geometric and topological information are used. Topological information refers to connectivity, proximity and contiguity of the network. Subsequently, when the geometry of the points/arcs as well as the connectivity, proximity and contiguity of the points/arcs within the network are considered, limitations present in geometric based algorithm can be compensated. Moreover, searches can be done in relation to the previously established matches and the context of the network, the result of the map matching is likely to be improved [RD. 11].

2.7. Filtering and hybridisation techniques

Position estimation combining measurements from different sensors can be made using snapshot Least Squares Estimation (LSE), where each epoch measurements are processed independently. However the estimation accuracy can be highly improved considering past measurements and the user dynamics behaviour. When the user dynamics is not well known recursive Kalman Filtering is the classical approach.

The Extended Kalman Filter (EKF), is the approach usually applied, linearizing the measurements and the state vector dynamics around the last epoch. This is the case of indoor navigation where the user motion is not deterministic, where the outputs of sensors like an IMU are not lineal, and where the geometry of reception of the signal based measurements (either GNSS, Wifi, Bluetooth UWB or any other signal based mechanisms) changes with the time or the user motion.

Depending on the application there are different strategies to combine or hybridise the measurements with Kalman type filters:

- Loose coupling, where the Kalman filter uses as inputs the positioning or state vector estimation by each sensor. This approach is simple, robust, not more accurate than each sensor and has as major drawback that a sensor can not be used when lacks measurements for an stand alone position estimation.
- Tight coupling, where the Kalman filter uses as inputs raw measurements from each sensor. The redundancy of sensors allows estimating positions in conditions of few measurements. However the conditions of use of the different measurements have to be carefully managed to avoid filter divergences
- Ultra-tight or deep coupling. This is a tight coupling filter where the output state vector and covariance is provided as feedback to the GNSS sensor to support its estimations of the expected next measurements.

Two implementations are possible regarding each integration strategy: open-loop or closed-loop mode.

In open-loop mode the Kalman filter errors estimations are used to correct the sensors outputs, without feedback to the sensors. Without feedback, the mechanisation error grows rapidly, and thus can introduce large errors into the integrated system.

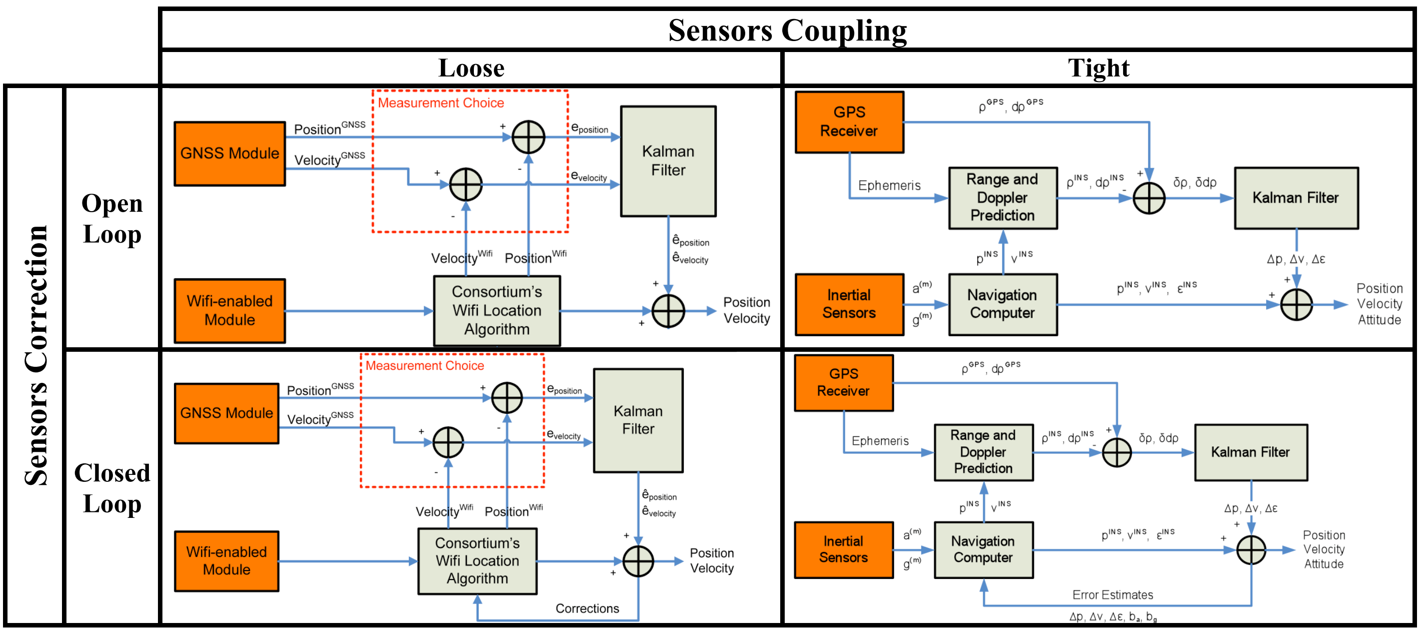

Figure 1. Sensors coupling and feedback alternative architectures.

In a closed loop integration scheme, a feedback loop is used to correct the raw sensors outputs and other mechanisation parameters using the error estimates obtained from the Kalman filter. Sensors mechanization outputs are kept with small errors and outliers are more likely to be detected.

The user model is one key element to consider in indoor applications. A usual approach is the Complementary Kalman Filter (several nested filters at different frequencies) where the user model is used for process noise definition and for errors calibration, but the state vector prediction step in the filter is directly taken from the dead-reckoning sensors. In indoor applications these are the Pedestrian Navigation System combining IMU, heading and a bar altimeter sensors.

Another major problem in hybrid navigation is the management of the environment conditions. Levels, walls and doors impose constraints in the feasible motion and positioning solutions. The introduction of these domain considerations seems difficult to be introduced in a generic approach in the classical EKF and has driven the search of other algorithms. New alternatives recently introduced are the unscented filters (UFs) (see [RD. 12] and [RD. 13]), also known as sigma-point filters, and the particle filters (see [RD. 14] and [RD. 15]) which are being postulated recently for positioning estimation in indoor navigation (e.g. [RD. 16], [RD. 17]) thanks to its suitability to manage the environment constraints.

3. DINGPOS PLATFORM ARCHITECTURE

The architecture selected for the DINGPOS platform is depicted in the figure below:

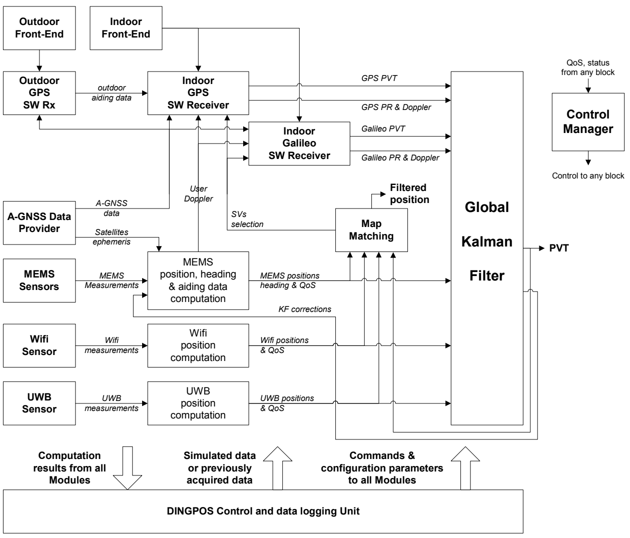

Figure 2. DINGPOS architecture.

The DINGPOS Platform comprises a PC with a number of USB interfaces to connect the different sensors: two GNSS RF Front Ends, the MEMS, Wifi and UWB sensors. The platform is connected to the Location server via an Ethernet interface and an IP router.

From a software point of view, the different algorithms are controlled via a Control and Data Logging Unit. Each sensor is associated to a dedicated algorithms block that provides the corresponding standalone PVT solution. These PVT solutions also feed an extended Kalman filter in charge of elaborating the PVT for the different hybridization modes. Finally, a specific map matching algorithm enhances the performance of the different PVT computation modes.

The achievement of real-time operation is one major challenges for the indoor platform stem from both hardware and software design choices.

4. PRELIMINARY PERFORMANCES

4.1 HS acquisition of GNSS signals

Reliable code acquisition for HS-GNSS is one of the main problems to be faced within this project. Because of the presence of severe attenuation and phase/frequency uncertainties in the received signal, coherent integration during code acquisition must be restricted to just a limited time window. Since this short coherent integration is not enough for reliable detection, the receiver is forced to implement noncoherent post-detection integration. By doing so, the overall correlation interval can be extended far beyond the bit interval and signal detection can be accomplished for C/N0 values below 25 dBHz.

In order to efficiently implement the HS-GNSS acquisition module, the double-FFT method [RD. 5] has been selected in the DINGPOS project. This method can be understood as the optimal implementation of the time-frequency matched filter to the received signal. Two are the main advantages of this scheme. First, it makes extensive use of FFT processors for efficiently implementing both the input correlation and fine frequency search. Second, it performs the maximum possible coherent integration in the absence of bit assistance. That is, one whole bit period of 20ms. The result is an acquisition architecture with superior performance compared to traditional schemes.

A flow diagram is shown in Figure 3 to describe the behaviour of the DINGPOS HS-GNSS acquisition module. The core of this module is based on the double-FFT method which takes inputs from the incoming digitized samples and assistance information from the Thales-Alenia location server. A basic set of assistance parameters are requested: the list of visible satellites, their corresponding Doppler error and ephemeris for enabling the user’s position determination. In principle, code phase information is not exploited to avoid possible mismatches due to delays in the server access.

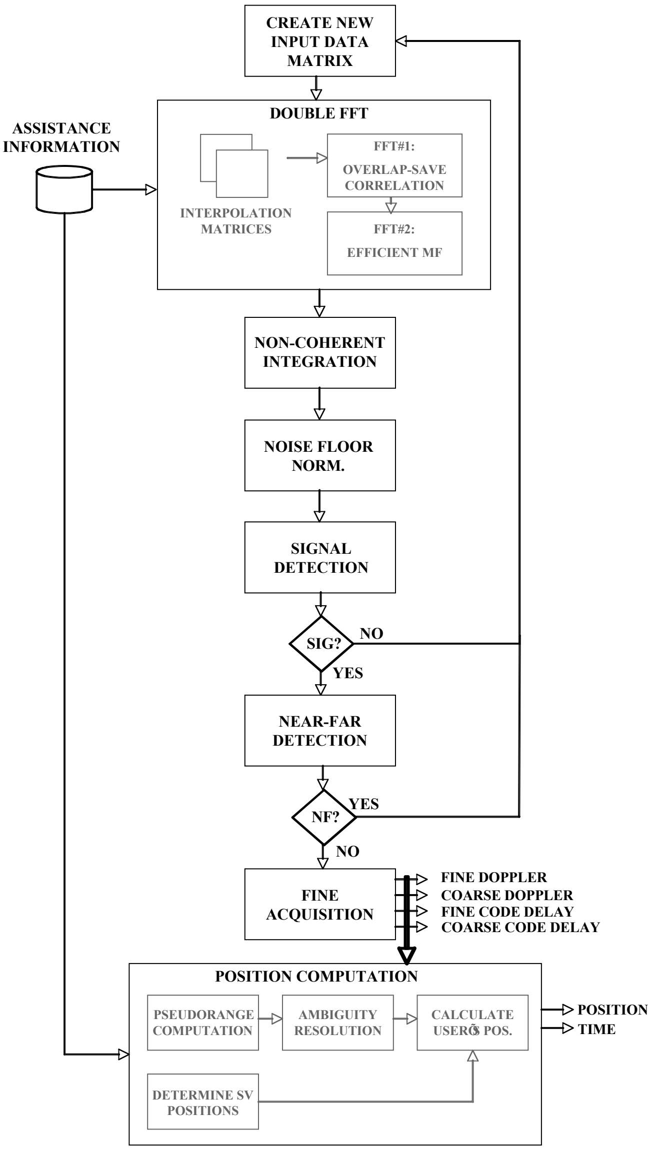

Figure 3. Flow diagram of the HS-GNSS acquisition architecture.

With the assistance information, the double-FFT method performs correlation with the input samples and fine frequency search around the assisted Doppler value. This fine search comprises a range of +/- 500Hz and uses 40 frequency bins with 25 Hz resolution. Once the time-frequency processing is finished, the results are stored in a three-dimensional matrix. Each dimension corresponds to the number of samples per code, the number of fine frequency bins and the number of possible bit transition hypotheses, respectively. This matrix is then noncoherently integrated with the aim of extending the overall correlation interval without being degraded by unknown bit transitions. This noncoherent integration is performed by using the absolute value of the time-frequency correlation samples. This is in contrast with traditional approaches where the squared value is adopted instead. The advantage of using the absolute value is a small increase in the probability of detection, especially for those working scenarios with severe noise and/or in the presence of outliers or interfering signals.

Once noncoherent integration is finished, noise floor normalization is required to ensure that all frequency bins share the same level of noise spectral density. Otherwise, different noise levels would lead to an increase in probability of false alarm when evaluating the signal detection threshold. Next, signal detection is required to determine whether the desired satellite is present or not. In case of failure, acquisition is restarted for a new satellite. In case of success, a final test must be undergone to ensure that signal detection was really caused by the presence of the desired satellite and not because of the presence of another satellite with stronger signal power. This near-far validation is carried out by taking into consideration the different statistics when near-far is present or not. Finally, and assuming that no near-far is present, some refinements are performed onto the output acquisition data. These refinements consist on resampling the input signal with the estimated fine Doppler and bit-level code phase error. Then, five correlation points are re-calculated around the maximum correlation peak. These points serve as the basis for interpolating a more accurate code phase value and thus, provide precise pseudoranges to the position determination module.

After signal acquisition, determination of the user's position is obtained by using the Petterson method [RD. 5]. This is a two-step procedure where, first, the position of the acquired satellites is calculated and second, the user's position is determined by linearizing the pseudoranges variation. At this second step, information regarding the satellites velocities is also included to overcome the pseudorange ambiguity.

The results can be observed in Figure 4 for the case GPS L1 in a static scenario with C/N0=25 dBHz. Different integration intervals are represented for 300ms, 600ms and 1000ms, corresponding to 15, 30 and 50 noncoherent integrations of one bit period. As expected, increasing the integration interval reduces the spread of position fixes.

Figure 4. HS-GNSS position fixes for a static scenario at C/N0=25dBHz.

In order to determine the user's positions, one of the parameters that is required to be estimated is the GPS time-of-week (TOW). This time is required to determine the transmit time of the received signals and thus, determine the satellites position. An example of the TOW estimation error is shown in Figure 5 for a static scenario with C/N0=15 dBHz. Because of the severe noise of this scenario, long correlation intervals must be adopted. In this figure, these intervals range from 3 to 7 seconds. It is interesting to observe that for the longest correlation interval, estimation errors start with a rather reduced jitter (lower than 25 ms) but as time goes by, the estimation degrades exhibiting a drift with increased jitter. This degradation is due to the fact that TOW estimates are obtained independently from snapshot to snapshot and no correction is made to subsequent snapshots based on the estimated TOW on previous snapshots. As a result, the possible drift in the user's clock accumulates over time.

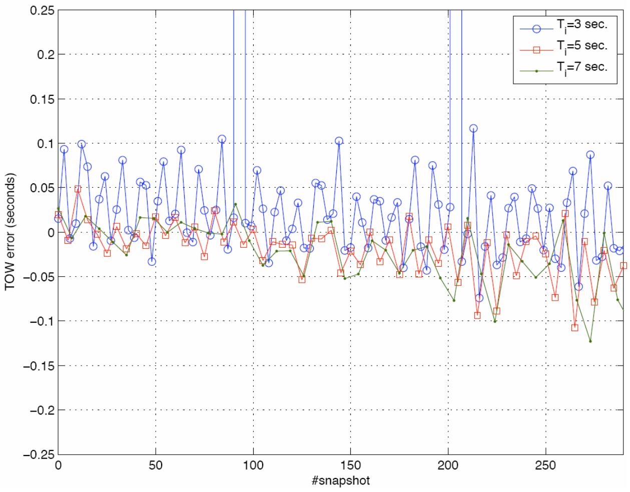

Figure 5. HS-GNSS estimation error in time-of-week (TOW) at C/N0=15 dBHz.

Finally, some results are also presented in Figure 6 for the HS-GNSS acquisition module in a dynamic scenario.

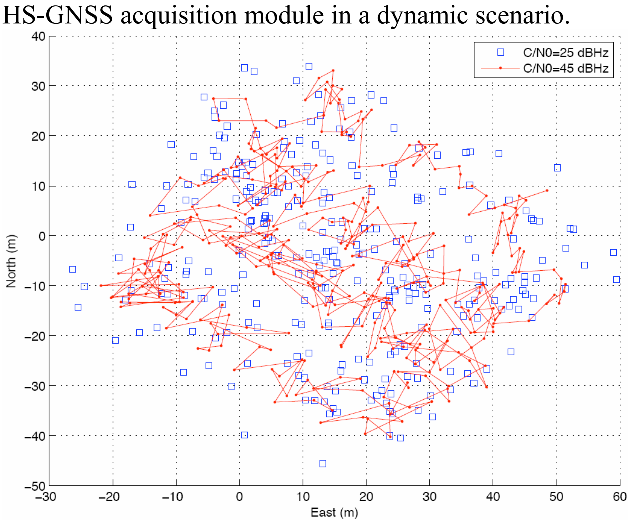

Figure 6. HS-GNSS position fixes for a dynamic scenario following the reference trajectory.

The results correspond to an outdoor scenario with C/N0=45dBHz and an equivalent indoor scenario with C/N0=25dBHz. As it can be observed, even in the presence of a 20dB attenuation, the receiver is still able to follow the trajectory. Clearly, the jitter of position fixes is larger for the indoor scenario. However, as it will be shown later on, these positions fixes are still able to provide valuable information for the hybridization with the rest of sensors.

4.2 MEMS performance

The DINGPOS platform comprises a PNS module based on [RD. 22]. Accelerometer and gyroscope measurements are fed in a Pedestrian Navigation System to produce dead reckoning measurements. The PNS module is initialized off-line (initial position, initial heading) and the regression coefficients of the velocity model [RD. 22] are loaded before the test. These coefficients are taken from a previous test, which was conducted with another pedestrian in others conditions.

Figure 7 shows the resulting test trajectories of the PNS module. The blue plot is the trajectory computed with the reference GPS receiver. The red trajectory is the resulting trajectory computed with the PNS module. The heading drift is clearly observable. To provide a more accurate reference, a PNS-like trajectory is also computed, but taking into account GPS measurements: both heading and pedestrian velocity are computed based on the measurements of the reference GPS receiver. Following the PNS algorithm, the trajectory is computed and shown in green. It provides a more relevant reference trajectory to compare with the PNS one.

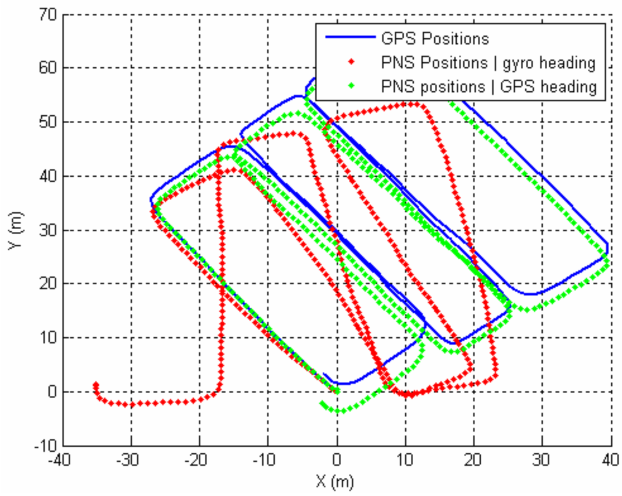

Figure 7. GPS and standalone PNS trajectories.

Figure 8 shows the PNS heading error (drift) with respect to the reference (GPS), as well as the curvilinear upper bound error. In red is shown a theoretical error model as given below. The model fits the real error pretty well. The model implements a heading drift of 0.13 deg/s, and was initialised to zero at the beginning of the test. Note that the heading error at the beginning and at the end of the test is not relevant as the pedestrian is not moving, making the GPS reference not valid.

$$\sigma^k_{heading} = \sum_{n=1}^{k} d_n \cdot \sin\left(\int_{t_1}^{t_n} \dot{\alpha}_{\max} dt\right)$$

where $\dot{\alpha}_{\max}$ is the maximum heading drift and d_n is the true step length at epoch n.

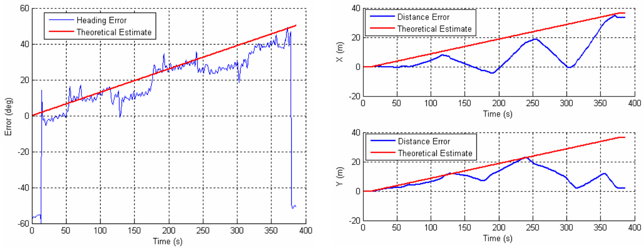

Figure 8. PNS heading and curvilinear distance upper bound error with respect to GPS heading.

4.3 Map matching performance

Within the DINGPOS project, two MM algorithms are developed: one for relative positioning system (PNS) and one for absolute positioning systems (Wifi, GPS). Both algorithms were tested on the data set generated for the integration test phase. Each MM algorithm uses a common diagram, built from the reference GPS measurements used to generate the reference trajectory. The nodes of the diagram are shown as the red squares in Figure 9. In this figure, the blue plot is the raw PNS positions where the heading drift of 0.13 deg/s is clearly observable. The filtered positions appear in green, with a good heading correction thanks to Map-Matching process.

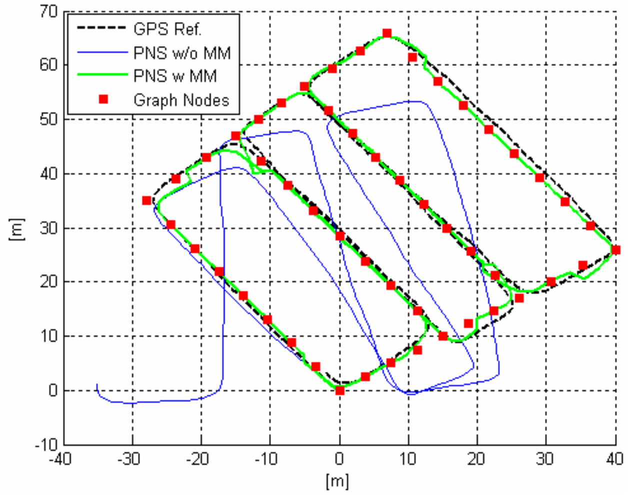

Figure 9. MM results on PN positions.

Figure 10 shows the error computed with respect to GPS positions (and not the graph used for MM). It thus includes the error of the graph positions w.r.t. the GPS trajectory. The 2D error is restrained to the distance-to-the-graph threshold for heading and position correction in the Map-Matching algorithm, i.e. 3 metres.

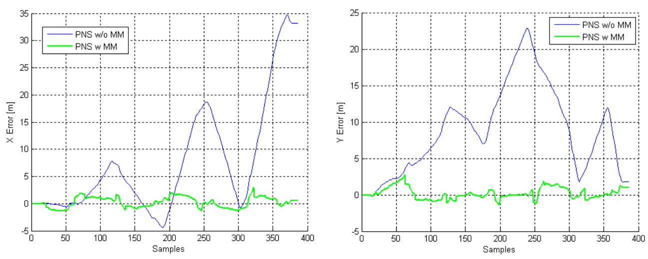

Figure 10. MM error – X and Y axis – PNS case.

Figure 11 presents the Map-Matching results over WiFi positions. The WIFI positions are generated from the GPS reference trajectory on which a uniform distributed noise is added (5 m upper bound error). WiFi positions are very noisy and the Map-Matching filter enables to restrain these positions to the diagram. However, this not necessarily means that the accuracy is improved.

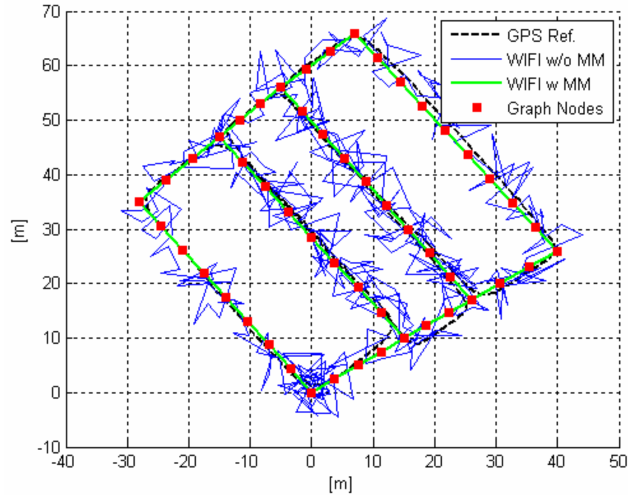

Figure 11. MM result on Wifi positions.

Indeed, Figure 12 shows the error computed with respect to GPS positions (and not the graph). As the positions given by the Map-Matching process are restrained to the nodes of the diagram, the filtered position can be either early or late in comparison to the reference trajectory. The accuracy improvement is not that obvious in this test, even if the overall MM position error standard deviation is smaller than raw WiFi positions.

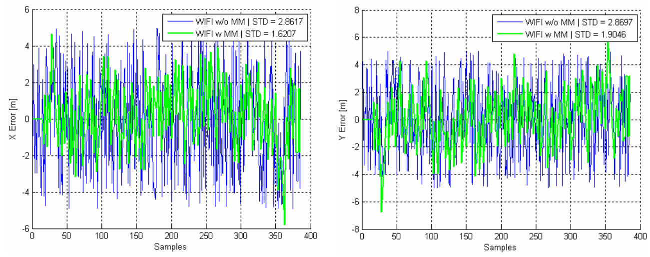

Figure 12. MM error-X and Y axis-Wifi case.

4.4 Hybridized solution: GNSS, MEMS, Wifi

Among the alternatives of sensor processing and hybridation techniques described above in the State of the Art description, the approach finally considered in DINGPOS as the baseline case is a tight coupling navigation in closed loop which will process as input measurements HS-GNSS pseudorange and Doppler observables, Wifi and/or UWB positions and heading and velocity observations from a PNS model processing IMU MEMS raw data. Tight coupling navigation is fully necessary because under indoor conditions the probability of not receiving HS-GNSS measurements is very high due to their attenuation and degraded measurement error, with a total loss of measurements in deep indoor environments.

The closed loop approach is also necessary when the system is designed based on "low cost" sensors (e.g. the IMU) whose error grows rapidly in a matter of a few seconds or minutes.

Under this overall approach, the EKF state vector corresponds to a system dynamic model composed of the user model and sensor measurement error models along with the calibration parameters. The user model considered is based on a horizontal motion at constant velocity, maintaining a level altitude, with configurable uncertainty. This model intends to be a compromise between the unpredictability of pedestrian motion (which would be considered in the velocity uncertainty) and good knowledge of such motion having PNS outputs at 50 Hz. The modelled measurement errors are the GNSS clock bias and drift terms that appear in the GNSS pseudorange and Doppler measurements, and PNS output errors, the residuals after the PNS mechanisation implementation described above: a heading error second order model and a speed bias, with uncertainty in heading error acceleration and in speed bias respectively. Finally, Wifi measurements do not consider any error model.

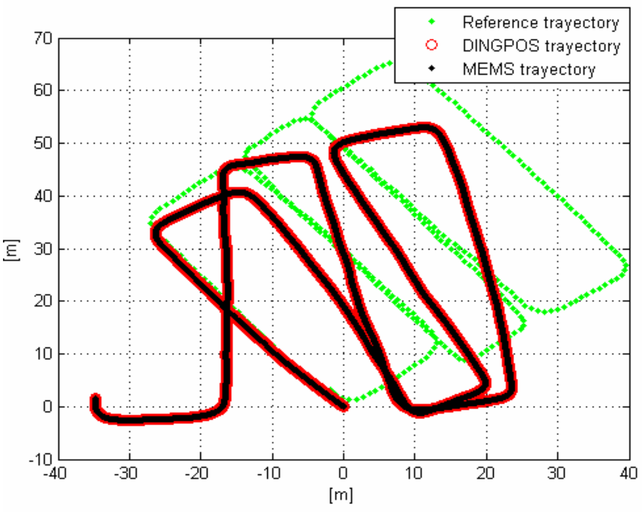

Figure 13. DINGPOS hybrid and MEMS sensor trajectories comparison.

The hybrid filter processes one, several, or all the sensors, each of them with different output rates. In this project phase the tuning of the EKF parameters (measurement noises and system dynamics uncertainty) has aimed to define a single configuration valid for any combination of input sensors. With this approach the solution of the hybrid filter for the generic MEMS/WiFi/GNSS case has come out very close to the corresponding specific stand alone sensor filter solution (see MEMS example in Figure 13) each time the measurements are processed (see in Figure 14 how the user model propagation at 50 Hz is updated close to MEMS positions at 1 Hz.)

The fully integrated hybrid case, with HS-GNSS, Wifi and MEMS measurements is shown below in Figure 15. As expected, it is remarkable that Wifi and HS-GNSS measurements allow the successful estimation of the PNS model calibration, so that the integrated solution is a very smooth HS-GNSS or Wifi trajectory.

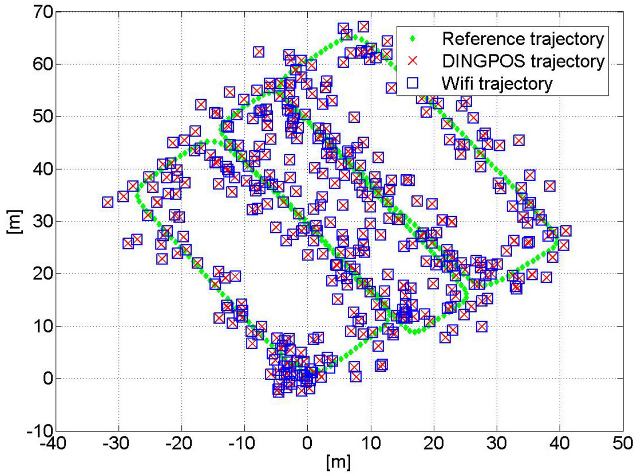

Figure 14. DINGPOS hybrid and WIFI sensor trajectories comparison.

Quality control of the estimation state has been implemented by means of a snapshot Chi-squared test on the final measurement residuals after the state estimation update with the given measurements. In this phase the objective of this test has been only Failure Detection (FD) of epochs showing a questionable solution. An exclusion capability will be implemented in further project phases.

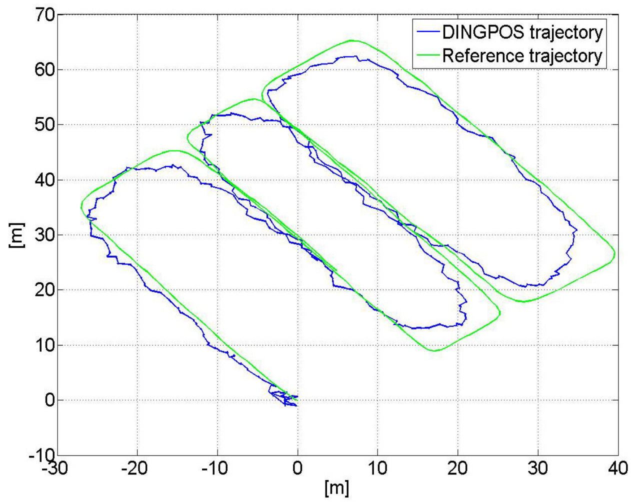

Figure 15. Full integrated DINGPOS hybrid trajectory in Soft Indoor Dynamic Scenario.

In order to assess the hybrid navigation filter performance several scenarios are considered. Such scenarios cover a broad range of conditions where the DINGPOS system is required to perform providing an exact and reliable position.

In a preliminar stage, these scenarios are addressing basically three different environments: soft indoor, urban and outdoor conditions. Deep indoor scenarios are to be considered in a subsequent stage by means of an outdoor-aided version of the HS-GNSS receiver. The environmental conditions are defined and characterized in terms of the signal-to-noise ratio. Both static and dynamic cases are considered for all environments. The following table summarizes the different use cases considered:

	Outdoor	Urban	Soft indoor
Static	36 dBHz	25 dBHz	15 dBHz
Dynamic	45 dBHz	25 dBHz	15 dBHz

Table 1: Different scenarios considered

The main conclusion of the implemented hybrid navigation filter is that this case corresponds to low, although unpredictable, user dynamics when compared to the rate of availability of measurements from any of the considered sensors. In these conditions, the state observability is always high and satisfactory results can be obtained with a single EKF parameter configuration. This aspect is quantified by the "manoeuvre index" proportional to the ratio between the motion uncertainty over a sampling interval and the corresponding measurement uncertainty (see reference [RD. 20]). In the case where the different sensors were converging to qualitatively different manoeuvre indexes, a single EKF configuration would not have been possible and a federated Kalman filter approach with different implementations and tuning would have been required.

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