SARHA – DEVELOPMENT OF A SENSOR-AUGMENTED GPS/EGNOS/GALILEO RECEIVER FOR URBAN AND INDOOR ENVIRONMENTS

Franz Weimann[(1)], Phillip Tomé[(2)], Adrian Waegli[(2)], Klaus Aichhorn[(1)], Okan Yalak[(2)], Bernhard Hofmann-Wellenhof[(1,3)]

[(1)]*TeleConsult Austria GmbH*
Schwarzbauerweg 3, A-8043 Graz, Austria

[(2)] *Geodetic Engineering Laboratory (TOPO), École Polytechnique Fédérale de Lausanne (EPFL)*
Bâtiment GC, Station 18, CH-1015 Lausanne, Switzerland

[(3)] *Institute of Navigation and Satellite Geodesy, Graz University of Technology*
Steyrergasse 30, A-8010 Graz, Austria

Keywords: GNSS, GPS, EGNOS, Galileo, Pedestrian navigation, Autonomous sensors, Step detection, Transponder.

Abstract

The main objective of the project 'SARHA - Sensor-Augmented EGNOS/Galileo Receiver for Handheld Applications in Urban and Indoor Environments' is the development of a modern satellite navigation receiver with autonomous sensor augmentation. Additionally, the hybrid navigation system will be enhanced by a transponder capable of receiving absolute position updates from transmitters installed inside buildings. The transponder will allow the SARHA system to significantly increase reliability and accuracy of the positioning solutions indoors. The hybrid navigation software is split up into two parts. The first one will be implemented directly on the GPS receiver, whereas the second part will run on a microcontroller. Thus, a small, low-performance microcontroller can be used, representing the first step towards the reduction of size, weight and power consumption of the mobile system.

This paper provides an overview on personal mobility and typical applications related to the system, describes the system architecture and the hybrid navigation software in detail. Furthermore, emphasis is laid on a comparison of different step detection algorithms, showing their advantages and disadvantages. Based on the Galileo signal definition, additional analysis set up to explore the signal characteristics in comparison to the GPS signals, are provided. Improvements due to the Galileo signal availability in urban and indoor environments are assessed and will later ensure seamless integration of enhanced technologies into the continuous developments.

1 Introduction

In the personal mobility sector, in dense urban, indoor and outdoor environments, nearly all of the current applications rely on satellite navigation, sometimes also exploiting regional or local augmentations to improve positioning accuracy. As applications move into safety-critical and other domains, where service reliability is of major concern, users and service providers are becoming aware of the importance of positioning accuracy, availability and service quality. In pedestrian user environments, like dense urban canyons or indoors, the GNSS positioning performance reaches well-known technological limits. These limitations can be overcome by adding additional sources of information to the system.

In the near future, small and portable devices will combine seamless communication, navigation, and geo-information capabilities in a highly integrated hardware. The devices will be offered at reasonable cost with high positioning performance regarding accuracy and availability. The global market will be influenced by the simplicity of the system, its size and weight, robustness and performance.

The objective of the project 'SARHA - Sensor-Augmented EGNOS/Galileo Receiver for Handheld Applications in Urban and Indoor Environments' is to combine a modern satellite navigation receiver with augmentation sensors. The hybrid navigation software is split up into two parts. The first part will be implemented directly on the GPS receiver and the second part on a small microcontroller. Thus, a low-performance microcontroller can be used, representing the first step towards the reduction of size, weight and power consumption of the mobile system. SARHA is a one-year project that has started in February 2006 and is managed by the Galileo Joint Undertaking (GJU) through EU 6FP funds. The project consortium is lead by TeleConsult Austria GmbH

(Austria), being responsible for user requirements and software development. OECON GmbH (Germany) is in charge of hardware integration, u-blox AG (Switzerland) for the GPS receiver hardware, and Dynatronics AG (Switzerland) is responsible for the transponder development. The Geodetic Engineering Laboratory of EPFL (Switzerland) contributes with a study which analyses the impact of Galileo on handheld applications.

2 Objectives

The global market forecast for the annual net turnovers for satellite navigation products in general forecasts a growth from about € 4 billion in 2000 to about € 24 billion in the year 2025. The share of the personal mobility on the global net turnovers by application will grow from ~2% in 2001 up to more than a third of the market in 2015. The number of GNSS users is estimated to reach more than 700 million in 2010, and expected 2500 million in 2020. These numbers and forecasts are based on [1] and [2], and although they have been revised to lower numbers in updated market studies (i.e. [3]), the market potential is still expected to be tremendous. The conclusion to be drawn is that within the next years the need for navigation products supporting personal mobility and the related services will increase significantly. Incremental benefit will arise with new applications and services as already mentioned in [4].

Handheld applications in particular require flexible navigation techniques that are not restricted to places with unobstructed view to the sky. This is important especially for urban or indoor situations. Following [5], possible fields of applications for handheld or pedestrian navigation systems include:

- Military operations
- Safety of life operations (police, fire fighters, rescue services, etc.)
- Route guidance for pedestrian
- Tourism
- Services for people suffering from visual impairment
- Lone workers

For user acceptance, easy handling, high automation, robustness, and reliability are besides the navigation parameters, the stringent requirements under severe service conditions for indoor and outdoor applications. High integration and reduction of complexity will further reduce size and weight of the system.

The first prototypes and products of pedestrian navigation systems according to [6] and [7] have already been developed and demonstrated in various field tests with very promising results. However, due to current system complexity, size, weight, reliability and, last but not least, high cost, a handheld positioning system for urban and indoor applications will not be available for the consumer mass market in the short term. Beside navigation improvements, the integration of communication capabilities into the system is of main importance to control the overall process. This requires a communication link to a Service Centre, as well as a seamless integration of the technology into service concepts and management processes.

3 System Architecture

The majority of existing pedestrian systems are based on the integration of GPS with some kind of Dead Reckoning (DR) approach, measuring distance travelled and direction. In case of GPS outages, the DR component is responsible for positioning. However, extended periods of limited GPS visibility are problematic due to the drift effects inherent to DR [8]. Nevertheless, the achieved position results are much better compared to the classical GPS-INS approach, where position computation is done by simple double integration of accelerations [9]. Therefore, also the SARHA system architecture follows the concept of pedestrian navigation.

To increase position accuracy and availability, especially in difficult environments, the SARHA system incorporates beside a u-blox GPS/EGNOS receiver, a magnetometer and a gyroscope for heading information, and accelerometers for speed determination based on the principle of step detection and speed modelling. For extension to 3D positions, the system contains a barometric altimeter providing pressure and temperature information (Figure 1).

Additionally, the hybrid navigation system will be enhanced by a transponder receiver, which communicates with transmitters installed inside buildings. When passing nearby a transmitter, the transponder reader receives an absolute position update, which will allow the SARHA system to increase reliability and accuracy of the computed position indoors. In the absence of GNSS signals, especially indoors, the position accuracy will degrade caused by the drift behaviour of the autonomous sensors. Therefore, the indoor transponder position updates will improve the position results significantly.

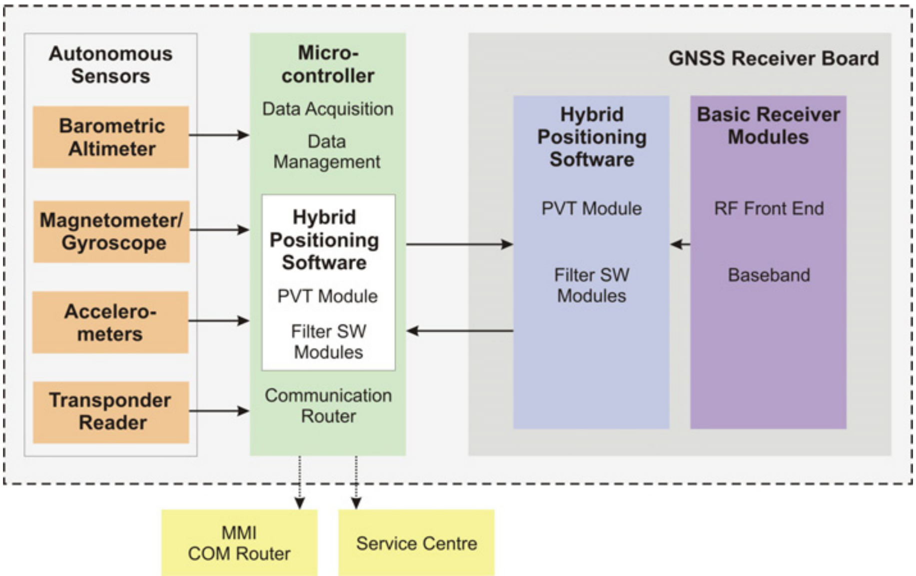

Figure 1: SARHA system architecture

In addition to the GPS receiver and the autonomous sensors, the SARHA system contains a microcontroller for the overall data and interface management, and to support data acquisition to an external storage device for post processing purposes. The hybrid navigation software will be divided into two parts and implemented on the low-performance microcontroller and the u-blox GNSS receiver in order to save memory and processor usage, thus, minimising the required power consumption.

To provide magnetometer, gyroscope and accelerometer data, a low cost IMU will be used in the SARHA project. This prototype development represents a first step towards a close integration of the GPS receiver with autonomous sensors and will show the operating principle of the pedestrian navigation system. For mass-market applications, higher integration and cost reduction will still be necessary.

Beside the pedestrian navigation system, the mobile unit provides a MMI (Man Machine Interface) for user interaction and visualization purposes, which can be very useful for navigating in cities and buildings or for route guidance. Additionally, a communication router provides access from the mobile unit to a Service Centre, which supports visualisation and communication capabilities. This is especially important for safety of life operations (e.g. fire fighters) or search and rescue applications, where the overall coordination of all mobile units is of main importance.

4 Hybrid Navigation Software

The hybrid navigation software integrates the data of the u-blox GNSS receiver with the data of the augmentation sensors and the transponder using a Kalman Filter approach (Figure 2). The design of the software is adapted according to the selected types of augmentation sensors. Since the hybrid navigation software is directly implemented on the u-blox GNSS receiver hardware and a low-performance microcontroller, the software must be optimised with respect to memory and processor usage to minimise the required power consumption. The software is developed and implemented in two steps: general adaptation of software to the sensor configuration and interfaces, and porting of software from a windows-based platform onto the target platforms (GNSS receiver and microcontroller).

As already mentioned above, GPS supported by EGNOS represents the main source of positioning information in the SARHA system. Depending on the provided GPS results, 2D or 3D position updates are processed in the Kalman Filter. Using these accurate position updates, the filter is able to estimate drift behaviours of the sensors for online calibration. In case of indoor positioning, if GPS is not available, the position updates of the transponder provide absolute position information and improve the overall position results.

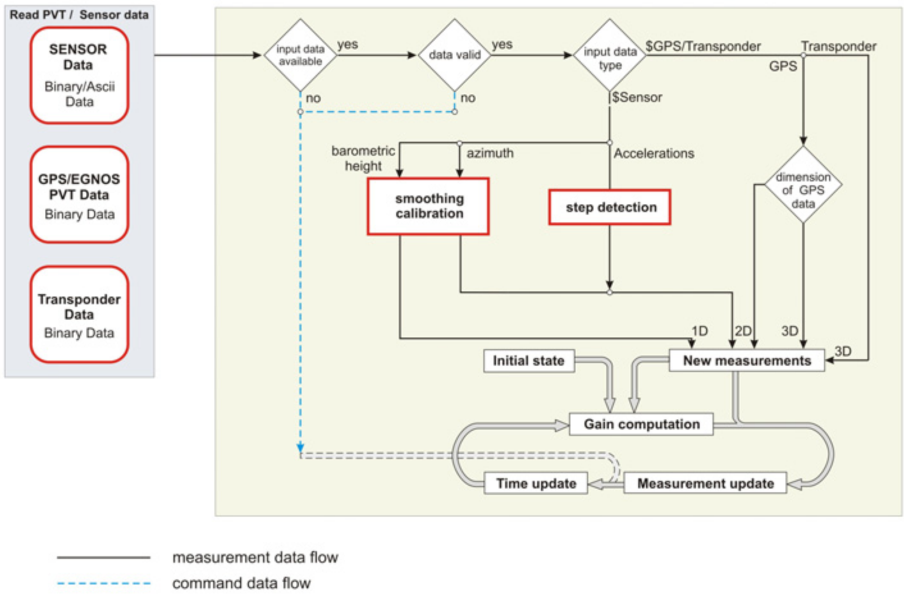

Figure 2: Hybrid navigation software

Beside the GNSS receiver and the transponder transmitters, autonomous sensors provide position information. Especially during GPS outages in difficult environments, the additional sensors can bridge position gaps. Compared to stand-alone GPS receivers, the SARHA system increases availability and reliability, which may be fundamental for the target applications.

Both, magnetometer and gyroscope, provide combined heading information of the pedestrian navigation system, using the magnetometer for the principal direction determination and the gyroscope for tracking very fast movements. Besides heading, distance or velocity information is of main importance for relative horizontal positioning in the absence of satellite signals. Due to movements of a mobile user, accelerometers provide characteristic signals, which can be analysed for step occurrence. Additionally to step detection, the algorithm provides the step frequency which is related to the step length and the pedestrian speed.

For 3D positioning, a barometric altimeter is integrated into the system. While barometric heights are characterised by very good detection of relative height changes, the barometric altimeter provides poor absolute height information. On the contrary, the GPS constellation provides poor relative altitude accuracy due to the satellite geometry and random outliers caused by sky obstructions. Taking advantage of both systems, GPS will be used for absolute height calibration during good GPS solutions, while the barometric altimeter provides the relative height changes.

5 Step detection

Steps may be detected by analysing the characteristic acceleration signals generated due to movements of the mobile user. Depending on the placement of the sensor unit on the user's body, the accelerations show different characteristics. The SARHA sensor assembly, which is mounted on the hip, uses three accelerations: one in the vertical direction, one in anterior-posterior direction and the third orthogonal to the previous ones (Figure 3). In contrast to many other developments, the SARHA system uses the total acceleration magnitude for step detection analysis (i.e. [10] and [11]).

$$a_{total,k} = \sqrt{a_{x,k}^2 + a_{y,k}^2 + a_{z,k}^2}$$

For reduction of additional influences onto the total acceleration, like the earth gravity field and sensor biases, the average of two to three seconds of total acceleration data is subtracted from the actual value.

$$a_{total\,red,k} = a_{total,k} - \sum_{i=k}^{k-n} a_{total,i}$$

$$a_{total\ red,k} = \sqrt{a_{x,k}^2 + a_{y,k}^2 + a_{z,k}^2} - \sum_{i=k}^{k-n} \sqrt{a_{x,i}^2 + a_{y,i}^2 + a_{z,i}^2}$$

with n being the number of samples during the average period of two to three seconds.

Taking the total acceleration has the advantage of being insensitive to the orientation of the sensor unit. Especially in future developments, this aspect could be useful for handheld applications when integrating the accelerometers into e.g. a PDA (Personal Digital Assistant). Nevertheless, heading determination may still be a problem in this case, due to the fact that the PDA direction can be totally different to the walking path direction.

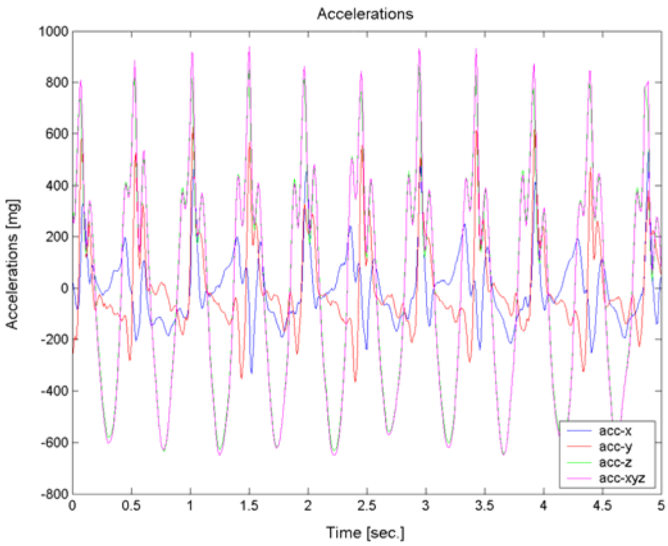

Figure 3: Accelerations in x, y, z direction and the total acceleration magnitude during walking

For step detection and step frequency determination, three different algorithms have been developed and compared to each other:

- Autocorrelation
- Peak detection
- Zero crossing

The algorithms and their related advantages and disadvantages are described in the following subsections.

5.1 Autocorrelation

Step frequency determination is accomplished via computing the autocorrelation of the acceleration function. The autocorrelation is determined via time-shifting a certain interval of the acceleration data against itself and multiplying the shifted data with the non-shifted original data (i.e. [12]). Detecting the two local maxima of the autocorrelation function in Figure 4 allows deriving the step frequency out of time differences.

Depending on the sampling frequency, interpolation techniques may be necessary to improve the autocorrelation results, especially when using lower sampling frequency (e.g. 40 Hz). Therefore, a second-order polynomial function using the two neighbouring points for coefficients calculation can be used to improve the results of the local maxima.

Table 1 presents the advantages, but also the disadvantages of the autocorrelation function. The CPU requirements of the algorithm were estimated from profiling which determines the number of instructions per second to be carried out for the programme execution, using always the same test file with a sampling rate of 40 Hz. The software on source code level is optimised, but no compiler optimisation has been activated. Profiling is a quite stochastic process. Therefore, the results are a rough indication for the required CPU performance. MIPS is short for Millions of Instructions Per Second.

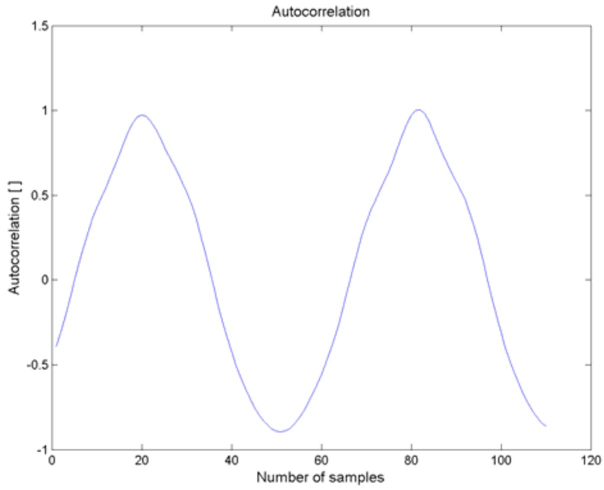

Figure 4: Autocorrelation function

Advantages	Disadvantages
very stable	very time and processor consuming; therefore, high processing power is necessary
also stable in difficult environments like forest areas where unconventional or unrhythmic walking is typical	CPU requirements: 1.21 MIPS
good results	reaction time low - uses old data for correlation
smoothed and filtered results	

Table 1: Advantages and disadvantages of autocorrelation

5.2 Peak detection

In comparison to the autocorrelation method, the peak detection algorithm is based on the measured acceleration signal, searching for two local maxima (Figure 5) (i.e. [6]). Finding two local maxima in the acceleration signal derives step frequency out of time differences. Similar to the autocorrelation function, peak detection can be improved in case of lower sampling frequency by applying a second-order polynomial function. Table 2 compares the advantages and disadvantages of peak detection.

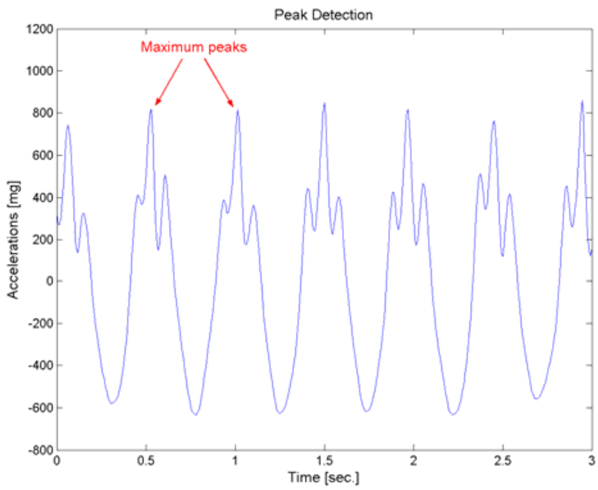

Figure 5: Peak detection

Advantages	Disadvantages
time and processor consumption much lower than for the autocorrelation function, but higher than the zero crossing	not as stable as the autocorrelation method
CPU requirements: 0.75 MIPS	worse results than for the autocorrelation function
reaction time high in case of changes – actual data used	results are not as smooth and filtered as for the autocorrelation function
also stable in difficult environments, like forest areas, where unconventional or unrhythmic walking is typical	

Table 2: Advantages and disadvantages of peak detection

5.3 Zero crossing

Step frequency determination is based on the detection of zero crossings in the measured acceleration signal (i.e. [13]). Figure 6 presents the acceleration signal while walking, showing the zero crossings of the signal. Having time stamps of each crossing allows calculating the step frequency. Similar to the autocorrelation function, zero crossing results can be improved in case of lower sampling frequency. Compared to the autocorrelation function, zero crossing uses a linear interpolation technique to improve the results. Table 3 compares advantages and disadvantages of the method.

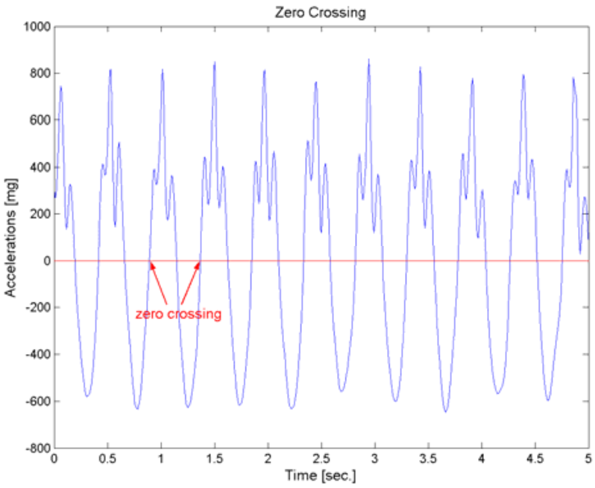

Figure 6: Zero crossing

Advantages	Disadvantages
fastest algorithm - reduced time and processor consumption	not as stable as autocorrelation and peak detection methods
CPU requirements: 0.30 MIPS	not stable in difficult environments, like forest areas, where unconventional or unrhythmic walking is typical
reaction time high in case of changes – actual data used	worse results than for the autocorrelation function
	results are not as smooth and filtered as for the autocorrelation function

Table 3: Advantages and disadvantages of zero crossing

5.4 Conclusions

The comparison of the three step detection algorithm shows that all of them have their advantages and disadvantages. While zero crossing represents the fastest algorithm with the lowest CPU requirements, the autocorrelation function provides the most stable and smooth filtered results. Therefore, a recommendation for choosing one of those is very difficult, and mainly depends on the available CPU resources and the main field of application. Other step detection algorithms are based on FFT or Kalman Filtering, which have not been analysed during this research, but may have the disadvantage of high CPU requirements.

6 Galileo Study

The Galileo satellite based navigation system is not yet available to be incorporated into the SARHA system. Nevertheless, a study is being conducted in the framework of the project with the objective of assessing the impact of Galileo in handheld applications and proposing an Assisted Galileo (A-Galileo) concept.
These objectives are being addressed from two distinct perspectives, namely on the side of system performance and system design:

- System performance: the SARHA system aims at meeting the requirements for handheld applications targeting a specific niche of professional users. The conditions under which these professionals usually operate are not favourable for satellite based positioning. Is Galileo able to bring some added value for such handheld applications in terms of performance (accuracy, availability, reliability, etc.)?
- System design: the aim here is to address such questions as how can Galileo be incorporated into the SARHA design in combination with existing GNSS technology and techniques? What changes in system design are needed for this? What impacts are foreseen in design complexity, computing power, power consumption, etc…?

6.1 System Performance

Regarding the first point, system performance, the study has focused on analysing the improvements of the Galileo Signal In Space (SIS) (i.e. [14]) compared to the GPS signals.

Signal Ground Power
Galileo signals will be transmitted with significantly more power than current GPS signals, thus improving signal reception and robustness in challenging environments.

Signal Modulation
The Galileo signals using BOC modulation will be broadcast over wider frequency bandwidths, improving their robustness against jamming and multipath. Their accuracy is also higher thanks to the lower correlation losses of BOC modulation and to the possibility of transmitting many side-lobes. Longer code sequences, furthermore, result in increased cross-correlation separation. The primary code of the Galileo signal E1B (4092 chips), e.g., is longer than its counterpart the GPS C/A code (1023 chips). The pilot signal E1C is additionally modulated by a 25 chips long secondary code resulting into a code sequence of 102300 chips. This results into a cross-correlation separation of about 40 dB (i.e. [15]). An improved correlation separation helps to mitigate the problems related to false acquisitions by the receiver in the presence of both, weak and strong satellite signals, which is quite common for urban canyon scenarios. On the other hand, longer codes imply a larger search space for the acquisition of the incoming signals, with an increased Time To First Fix (TTFF) as penalty. Also, coherent integration time is constrained to less than 4 ms (= 4092 chips of primary code) until the secondary code is first synchronised and demodulated, after which unlimited integration becomes possible as no navigation message modulation is present in the E1C signal.

Furthermore, as Galileo is not intended to replace GPS, but rather to be combined with it, further improvements in availability and reliability can be expected due to the quasi-doubled number of satellites available for acquisition and tracking. This is a clear advantage for the less favourable scenarios targeted by the SARHA system.

6.2 System Design

Concerning the system design, the study is analysing the impact of incorporating the future Galileo into the SARHA system. The analysis is being carried out at the hardware level, with the main conclusions being:

- Increased equipment complexity which results from the need to acquire and track signals with different characteristics. The higher chip rate of Galileo signals implies a larger bandwidth and higher sampling rates. This added complexity is also due to the effort of decoding the Galileo navigation message (Viterbi decoding), which most likely requires a dedicated chip or fixed point processor.

- Increased computational needs due to longer search spaces required for the acquisition of signals with longer codes.
- Increased power consumption as a result of the previous points.

6.3 Assisted Galileo

The study also includes a proposition of an A-Galileo concept, which is largely based on the experience that has been gathered with its counterpart A-GPS. Nevertheless, the proposed concept introduces specific features that are exclusive to the Galileo design as to mitigate its drawbacks. These features concern terminal architecture and type of assistance data conveyed from the assistance server to the mobile terminal.

The main features of the A-Galileo concept (Figure 7) can be summarised as follows:

- Ephemeris and acquisition assistance: instead of tracking all the visible satellites, the dual mode GPS/Galileo receivers use the ephemeris and acquisition assistance provided by the assistance server to determine the best visible Galileo/GPS satellites, in order to reduce the impact on the acquisition processing.
- Precise time assistance: in the absence of accurate timing information, the acquisition of the E1C secondary code at full sensitivity requires the processing of 25 sets of 4 ms correlation results after 100 ms in order to find simultaneously the correct secondary sync and correlation offset. The storage of these sets, each with a length of 4092 chips, represents a significant memory overhead to low-cost receiver design (i.e. [15]). On the other hand, receiver design can be simplified if accurate time synchronisation is possible (up to 4 ms accuracy). When precise timing information is not intrinsically available from the network infrastructure, receiver synchronisation has to be obtained by other means. The approaches already developed for A-GPS also apply for A-Galileo. However, another approach that can be used in A-Galileo is based on the same principle of the A-GPS navigation data alignment technique. It consists of transmitting the known secondary code phase as assistance information through the network and aligning it with the received signal to obtain an accurate time stamp.

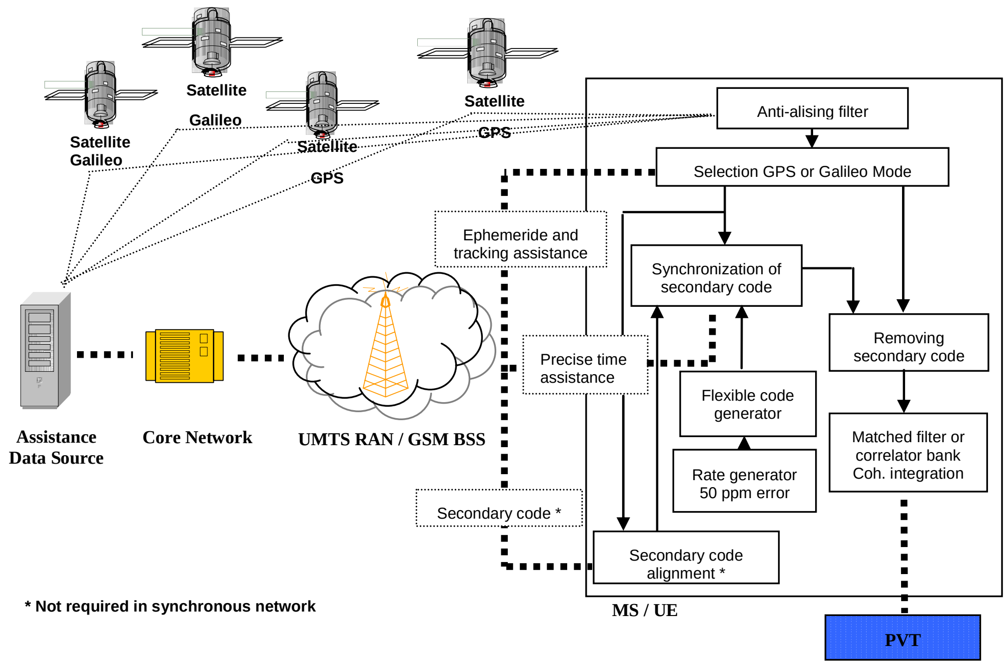

Figure 7: Assisted Galileo concept

7 Conclusions

The SARHA project aims at meeting the requirements of handheld applications acting in difficult environments for satellite navigation, like urban canyons or indoors. A hybrid navigation system is developed during the project combining a low-cost GNSS receiver, autonomous sensors and a transponder receiver with optimised navigation software.

At the end of the project, the SARHA system will demonstrate availability, reliability, and the position performance in unfavourable environments, such as urban canyons and indoors. This prototype development represents a first hardware step to integrate a GNSS receiver with autonomous sensors and will show the operating principle of the pedestrian navigation system. For mass-market applications, higher integration and cost reduction will still be necessary.

8 Acknowledgements

The SARHA project is carried out by TeleConsult Austria GmbH and its partners OECON GmbH, u-blox AG, Dynatronics AG, and EPFL Lausanne and is managed by the Galileo Joint Undertaking through EU 6FP funds. We would like to thank Dr. Vincent Gabaglio from GJU and Dr. Ismael Colomina, the Director of the Institute of Geomatics, Castelldefels, Spain, for the GJU support.

9 Acronyms and Abbreviations

AltBOC	Alternative BOC
A-Galileo	Assisted Galileo
A-GPS	Assisted GPS
BOC	Binary Offset Carrier
C/A	Coarse Acquisition
COM	Communication
CPU	Central Processing Unit
DR	Dead Reckoning
E1C	E1 code pilot signal
EGNOS	European Geostationary Navigation Overlay Service
GJU	Galileo Joint Undertaking
GNSS	Global Navigation System
GPS	Global Positioning System
MIPS	Millions of Instructions Per Second
MMI	Man Machine Interface
INS	Inertial Navigation System
IMU	Inertial Measurement Unit
PDA	Personal Digital Assistant
PVT	Position, Velocity, Time
RF	Radio Frequency
SARHA	Sensor-Augmented EGNOS/Galileo Receiver for Handheld Applications in Urban and Indoor Environments
SIS	Signal In Space
TTFF	Time To First Fix

References

[1] European Commission, 2000. Cost benefit analysis results for Galileo. Commission staff working paper, November 22, SEC(2000).
[2] Galileo Joint Undertaking, European Commission, European Space Agency, 2003. Business in satellite navigation. An overview of market developments and emerging applications. March 2003.
[3] Styles J., Jenkins B., Sage A., 2005. An update on the market context for Galileo. Proceedings of the ION GNSS 18th International Technical Meeting of the Satellite Division, pp: 400-406, Long Beach, CA, September 2005.
[4] Wasle E., Ott B., Abwerzger G., Branco P., Nicolè R., 2004. SHADE – system architecture. ENC-GNSS 2004, Rotterdam, The Netherlands, May 2004.
[5] Legat K., Lechner W., 2000. Navigation systems for pedestrians – a basis for various value-added services. ION GPS 2000, Salt Lake City, UT, September 2000.
[6] Levi R.W., Judd T., 1996. Dead reckoning navigational system using accelerometer to measure foot impacts. United States Patent No. 5,583,776.
[7] Ladetto Q., Gabaglio V., van Seeters J., 2002. Pedestrian navigation method and apparatus operative in a dead reckoning mode, Patent No. EP 1 253 404 A2.
[8] Hofmann-Wellenhof B., Legat K., Wieser M., 2003. Navigation – principles of positioning and guidance, Springer, Wien New York.

[9] Ladetto Q., 2000. On foot navigation: continuous step calibration using both complementary recursive prediction and adaptive Kalman filtering. ION GPS 2000, Salt Lake City, Utah, September 2000.
[10] Lachapelle G., Godha S., Cannon M. E., 2006. Performance of Integrated HSGPS-IMU Technology for Pedestrian Navigation under Signal Masking. ENC-GNSS 2006, Manchester, Great Britain, May 2006.
[11] Kubrak D., Macabiau C., Monnerat M., 2005. Performance Analysis of MEMS based Pedestrian Navigation Systems. ION GNSS, Long Beach, CA, September 2005.
[12] Legat K., Lechner W., 2001. Integrated Navigation for Pedestrians. GNSS 2001, Seville, Spain, May 2001.
[13] Käppi J., Syrjärinne J., Saarinen J., 2001. MEMS-IMU Based Pedestrian Navigator for Handheld Devices. ION GPS 2001, Salt Lake City, UT, September 2001.
[14] European Space Agency, Galileo Joint Undertaking, 2006. Galileo Open Service, Signal in Space Interface Control Document (OS SIS ICD). Draft 0, May 23, Reference: GAL OS SIS ICD/D.0.
[15] Mattos P., 2006. Galileo L1c – Acquisition Complexity: Cross Correlation Benefits, Sensitivity Discussions on the choice of Pure Pilot, Secondary Code, or Something Different. IEEE, 2006.