INS/GNSS Fusion

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EMPHASIS

EMPOWERING HETEROGENEOUS AVIATION THROUGH CELLULAR SIGNALS

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Abstract

The key objective of the project EMPHASIS (EMPowering Heterogenuous Aviation through cellular SIgnalS) is to increase safety, reliability, and interoperability of General Aviation/Rotorcrafts (GA/R) operations. Interoperability is specifically important for commercial aviation and emerging drones' operations. These performance parameters are critical to secure and improve airspace access for GA/R users in future airspace environment and to guarantee safety of operations.

EMPHASIS WP5 aims at the development and implementation of signal processing algorithms for real-time network-based radio aircraft positioning and tracking – specifically, joint network GNSS-based positioning approaches possibly aided by Inertial Navigation Systems (INS). Methods to estimate the positioning performance (including integrity) of the proposed approaches, and an assessment of their benefits with respect to standalone GNSS, are to be provided.

In this report, output of Task 5.3 of WP5, integration of GNSS with INS is discussed, as a candidate approach able to assist GNSS navigation in sub-urban and urban environments, where satellite visibility is obstructed and multipath/NLOS errors are prevalent. Different strategies of INS/GNSS fusion are compared, advantages and drawbacks pointed out, and a preference given. To support the choice, results from a simulation run with an Airbus developed tool are reported, showing the different performance of two INS/GNSS coupling approaches, in scenarios characterized by heavy multipath and GNSS signal spoofing.

The opinions expressed herein reflect the authors' view only. Under no circumstances shall the SESAR Joint Undertaking be responsible for any use that may be made of the information contained herein.

Table of Contents

List of Tables

List of Figures

1 Introduction

The key objective of the project EMPHASIS (EMPowering Heterogenuous Aviation through cellular SIgnalS) is to increase safety, reliability, and interoperability of General Aviation/Rotorcrafts (GA/R) operations. Interoperability is specifically important for commercial aviation and emerging drones' operations. These performance parameters are critical to secure and improve airspace access for GA/R users in future airspace environment and to guarantee safety of operations.

General aviation (GA) is defined by International Civil Aviation Organization (ICAO) as all civil aviation operations other than scheduled air services and non-scheduled air transport operations for remuneration or hire.

EMPHASIS WP5´s objective is to explore the potential of an integrated positioning platform that combines GNSS, INS and 5G technology, with the hope of expanding the range of applicability of the GNSS technology to safety-of-life operations in challenging sub-urban or even dense-urban environments. To this scope, it is necessary to develop methods to estimate the positioning performance (including integrity) of the proposed approaches, and assess their benefits with respect to standalone GNSS.

The purpose of this document is to describe different strategies of INS/GNSS fusion, able to aid GNSS navigation in sub-urban and urban environments, where satellite visibility is obstructed and multipath/NLOS errors are prevalent. An overview of the INS system and of the different INS/GNSS coupling strategies is provided. The different strategies are compared, advantages and drawbacks pointed out, and an advice for a possible solution given. Results from a simulation run with a Airbus developed tool are reported, showing the different performance of two INS/GNSS coupling approaches, in scenarios characterized by heavy multipath and GNSS signal spoofing.

The results shown suggest that INS/GNSS fusion can guarantee significant improvement in navigation performance with respect to GNSS only, with a contained cost. INS/GNSS fusion is particularly helpful in enhancing the integrity of the navigation solution, as it provides redundancy of measurements in all navigation scenarios, it cannot be spoofed and complements GNSS (bridging outages). Among the different INS/GNSS fusion implementation strategies, the Tight Integration scheme was deemed the most suitable for a reasonably low-cost solution – the simulation results showcased its effectiveness in containing multipath effects and isolating a spoofing attack. However, INS limitation lies in the fact that it can bridge GNSS outages (due to lack of sky visibility for instance) for a limited amount of time, as INS-only positioning accuracy diverges rapidly with time. Use of INS/GNSS integrated systems may therefore not be sufficient to guarantee the required levels of accuracy and integrity in GNSS-challenging environments, and external aiding (for instance from the cellular network) will be necessary, at least in specific areas.

This report is structured as follows:

- Chapter 2 provides a background on GNSS positioning and its limitation in urban and sub-urban environments
- Chapter 3 introduces the INS, its components, structure and operating principles
- Chapter 4 describes the different INS/GNSS coupling strategies, i.e. Loose, Tight and Deep coupling, assessing benefits and drawbacks of each method
- Chapter 5 introduces the principles of extended RAIM for integrated multi-sensor positioning techniques (relying on Kalman Filter)
- Chapter 6 describes the Airbus developed simulation tool PIPE, the simulations set-up and results
- Chapter 7 provides the authors´ conclusions.

1.1 List of Acronyms

AAIM	Aviation Autonomous Integrity Monitoring
ACAS	Airborne Collision Avoidance System
ADS-B	Automatic Dependent Surveillance – Broadcast
AIM	Autonomous Integrity Monitoring
ARAIM	Advanced Receiver Autonomous Integrity Monitoring (RAIM)
ATC	Air Traffic Control
CCF	Cross-Correlation Function
CAT	Commercial Air Transport
DLL	Delay Lock Loop
DOP	Dilution of precision
EASA	European Aviation Safety Agency
ELS	Elementary Surveillance (Mode S)
(E)GPWS	(Enhanced) Ground Proximity Warning System
EHS	Enhanced Surveillance (Mode S)
eRAIM	Extended Receiver Autonomous Integrity Monitoring (RAIM)
FIS-B	Flight Information Service – Broadcast
FL	Flight Level
GA	General Aviation
GA/R	General Aviation/Rotorcraft
GBAS	Ground Based Augmentation System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System

IAS	Indicated Air Speed
ICAO	International Civil Aviation Organization
IFR	Instrumental Flight Rules
INS	Inertial Navigation System
LC	Loose Coupling
MTOM	Maximum Take-Off Mass
PLL	Phase Lock Loop
PPP	Precise Point Positioning
PRS	Positioning Reference Signals
PVT	Position, Velocity, and precise Time
RAIM	Receiver Autonomous Integrity Monitoring
RC	Radio Communications
RSSI	Received Signal Strength Indicator
SBAS	Space-Based Augmentation Systems
SGE	Slowly Growing Error
SSR	Secondary Surveillance Radar
SVFR	Special Visual Flight Rules
TAS	Traffic Advisory System
TC	Tight Coupling
TIS-B	Traffic Information Service – Broadcast
UAV	Unmanned Aerial Vehicle
UE	User equipment
UTM	UAV Traffic Management
VDLL	Vector Delay Lock Loop
VFR	Visual Flight Rules

2 Background: GNSS navigation

GNSS constitutes the backbone of most navigation systems, not only in the aviation domain, but also in others such as road or maritime. As the environment for GA/R is often open sky, accurate localization and tracking in moving aircrafts has traditionally relied on GNSS. However, as technology developments increase the range of potential applications and services, adaptation to different environmental conditions for the navigation systems may be required.

For instance, flying taxi services will likely deal with urban and sub-urban environments, presenting a challenge for GNSS navigation: the availability and reliability of the GNSS-based position estimates may not always be guaranteed due to severe multipath conditions, blockage of satellites' signals, and unintentional as well as intentional interferences such as spoofing and jamming.

In report 5.1, results from a simulation and from a mobile urban environment campaign run by Airbus showed the limitations of GNSS navigation in sub-urban environment. It was shown that the PVT availability in sub-urban and urban environments is not sufficient for critical applications, e.g. safety-of-life services such as General Aviation/Rotorcrafts (GA/R) operations. Rotorcrafts flying bellow 500ft and GA/R aircraft flying in terminal areas are affected. Applications in these scenarios are also facing challenges resulting from potential conflicts with emerging drones' operations (U-space). As a consequence, additional sensors, such as IMU for inertial navigation systems and/or other signals of opportunities (e.g. RF network-based communication schemes), are required to offer a reliable navigation service.

In the frame of an activity of the European Global Navigation Satellite Systems Agency (GSA) supported by Airbus, GNSS data have been collected in an urban environment for a mobile user, i.e. a moving receiver. As shown in report 5.1, the derived and evaluated PVT availability, i.e. the amount of time the receiver had valid position information available, is summarized in Table 1. For this evaluation, different combinations of GNSS constellations are considered, namely the American GPS, the European Galileo and the Russian Glonass satellite navigation system. It may be observed, that even with three different system constellations used in parallel at the receiver side, a reliable positioning continuity cannot be met at all as the overall availability is less than 94%. Consequently, this availability is much too low for safety critical General Aviation/Rotorcrafts (GA/R) operations.

Table 1 - Measured PVT Availability in Urban Mobile Environment

Constellations considered by Receiver	PVT Availability [%]
GPS	91.73
GPS+GAL	93.22
GPS+GAL+GLO	93.84

In this document GNSS/INS fusion and its applicability to GA/R operations will be discussed.

3 Inertial Navigation Systems (INS)

An Inertial Navigation System (INS) is a combination of sensors and measurement processors able to determine the navigation states of a moving object, i.e. position, velocity and attitude; the sensors, constituting the Inertial Measurement Unit (IMU), consist of three accelerometers and three gyroscopes mounted on an orthogonal triad (Groves 2013, Chatfield 1997 and El-Sheimy 2004). The accelerometers measure the specific force acting on the object, which nearby the Earth is the resultant of external forces and the gravitational force. The gyros measure the moment acting on the object. To obtain the velocity of the moving object, the measured specific force should be corrected of the gravitational term, integrated once and the result added to the initial velocity. Integrating the obtained velocity and adding the initial position, yields the final position. Figure 1 shows a schematic representation of an INS.

The gyros need also to transform the measured angular acceleration in the navigation frame; the transformation can be mechanic, i.e. by physically aligning the IMU to the navigation frame (Gimbaled configuration), or analytic, i.e. by transforming the acceleration measurements in the navigation frame (strap-down configuration). The strap-down configuration is nowadays the most common implementation. An uncompensated error in the accelerometer measurement (e.g. a bias) is integrated once introducing a linear error in velocity, which when further integrated will introduce a quadratic error in the position solution (Groves 2013, El-Sheimy 2004). The presence of an uncompensated gyro error is more critical, introducing linear error in angles and in turn yielding quadratic error in velocity and cubic error in position. Thus the INS performance strongly depends on the quality of the included gyros.

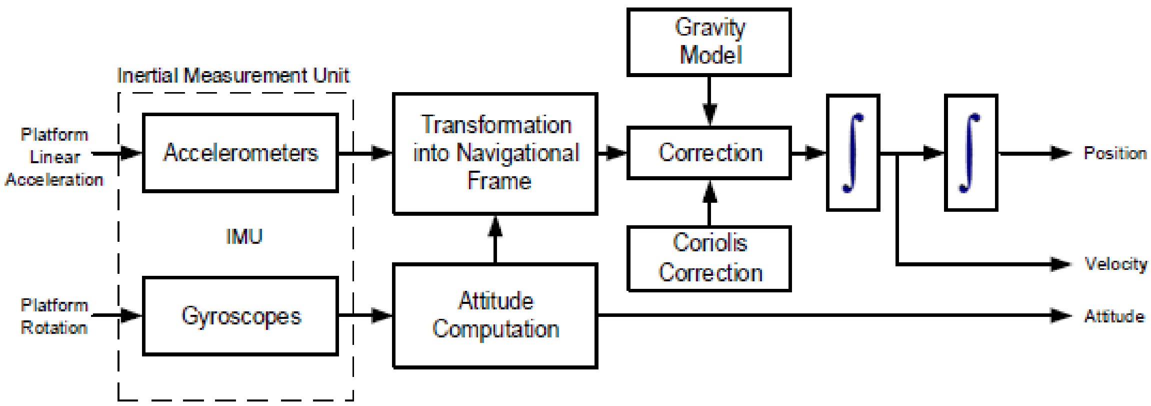

Figure 1 – Scheme of an INS.

3.1 Types of IMU

The main firmware component of the INS is the IMU, and the most important components in the IMU, critical to determine the INS performance, are the gyros. Gyro and IMU accuracy can be roughly divided into performance grades according to bias stability specifications, with the lowest grade being used for consumer products, and the highest performing grades being used for mission critical strategic applications. A bias stability measurement tells you how stable the bias of a gyro is over a certain specified period of time.

Lower performance gyros such as quartz and silicon Micro-Electro-Mechanic Systems (MEMS) gyros are typically used in consumer, industrial and tactical grade applications such as smartphones, smart munitions, and tactical mid-course guidance. More precision-oriented applications such as torpedoes, air/land/sea navigation, geo-referencing mapping and surveying, and autonomous surface or subsurface navigation require performance grades found in high performance Fiber Optic Gyros (FOGs), Ring Laser Gyros (RLGs), and mechanical gyros.

3.2 INS principles

In a strap-down INS, an inertial measurement unit consisting of 3 orthogonally mounted accelerometers and gyroscopes, respectively, is fixed to the vehicle. The gyroscopes provide measurements of the angular rate of the vehicle with respect to the inertial frame, denoted with $\dot{\omega}$. The accelerometers provide measurements of the specific force f, which contains the net effect of vehicle acceleration (a) and gravity (g): $f = a - g$. After initialisation of position, velocity and attitude, the strap-down algorithm integrates the inertial sensor measurements to propagate the navigation solution in time. Often, a navigation frame mechanisation will be used, where position and velocity are expressed in the coordinate axis East, North and Up (ENU frame). The mechanisation (differential) equations can be written in the form:

$$\begin{pmatrix} \dot{r} \\ \dot{v} \\ \dot{R} \end{pmatrix} = \begin{pmatrix} Dv \\ Rf - (2\Omega_{ie} + \Omega_{el})v + g \\ R(\Omega_{ib} - \Omega_{ie} - \Omega_{el}) \end{pmatrix} \tag{1}$$

where r is the position expressed in geographic coordinates latitude, longitude and altitude; v is the velocity in ENU frame; D is a matrix to transform velocity components into derivative of geographic coordinates; $R = R(\theta)$ is the direction cosine matrix (DCM) function of the attitude θ (orientation) of the rover; Ω_{ie} , Ω_{en} , and Ω_{ib} are the skew-symmetric matrices corresponding to the angular velocity vectors ω_{ie} , ω_{el} and ω_{ib}, respectively for the Earth rotation, the transport rate and the angular rate of the body frame (measured by the gyros).

The above differential equations can be solved by integration, with the more common approach using the quaternion method (Chatfield 1997). To be used in a Kalman filter, the equations (1) are linearized, by writing the corresponding perturbation equations.

4 GNSS/INS Integration

The combination of GNSS with Inertial Navigation Systems (INS), to improve accuracy availability and reliability, is known as INS/GNSS fusion. The INS has the advantage to be a continuous navigation system impossible to jam or to spoof.

In the last two decades, research related to the integration of GNSS receivers with Inertial Navigation Systems (INS) has received a large attention. With the GPS, and as well the upcoming GALILEO constellation, the GNSS sensors will continue to provide stable long-term high-accuracy position, velocity and in case of multi-antenna systems being used, also attitude estimates. However, the system may easily experience short-term losses of signals due to the signal blockage, interference or jamming. The self-contained INS is not subject to these geometric line-of-sight constraints that a GNSS system can suffer from, and therefore it can provide short-term high-accuracy position, velocity and attitude information. The accuracy of the INS will degrade over time due to the uncompensated gyro and accelerometer errors, initialization errors, and the noise corrupting the inertial sensor measurements – for low-cost MEMS sensors, this degradation is unfortunately quite fast.

Due to the complementary error characteristics of GNSS and INS, GNSS/INS fusion has already become a standard configuration and a core positioning component for geospatial data collection and mapping tasks, and of course, is widely used in airborne applications, e.g. to provide inputs to the flight control algorithms. Compared to the stand-alone operation of GNSS and INS, the GNSS/INS fusion can improve accuracy, availability, continuity and integrity.

In this section the main aspects of the GNSS/INS integration are reviewed. First the complementary nature of the systems is pointed out, and then an overview on the different integration strategies and configurations is given, with a discussion of advantages and drawbacks of each implementation.

4.1 Complementary Nature of GNSS and INS

GNSS and INS systems are complementary in many aspects. INS short-term errors are relatively small, but they degrade rapidly and are unbounded and so external aiding is necessary (Farrel 2008). On the other hand GNSS systems are more stable in long-term, meaning their errors are effectively time invariant with homogeneous accuracy. Hence GNSS systems can be used as external aiding to bound INS errors. INS can provide accurate short-term data with very high rate and can be used to interpolate GNSS trajectory. In addition INS sensors supply data with continuity, while GNSS are subject to outages, caused by signal blocking or interference. For this reasons high-precision inertial sensors (as tactical or superior grade) can be used to bridge GNSS outages; this may be possible up to a certain level using MEMS sensors, as their error drift is much larger (Abdel-Hamid 2005). Finally INS systems provide the complete navigation state, including position, velocity and attitude, while a single GNSS receiver cannot supply angular information.

4.2 GNSS/INS Integration Strategies

Several approaches can be used to integrate GNSS and INS systems, differing by the "depth" of the interaction and for the shared information between the systems. The more common strategies are listed below (Groves 2013):

- Uncoupled Integration
- Loosely Coupled (LC) Integration
- Tightly Coupled (TC) Integration
- Deep or Ultra-Tight Integration

In the Uncoupled approach, the systems work independently providing two distinct navigation solutions; usually the GNSS one is considered more accurate and is adopted when available as system solution. Moreover, the GNSS solution is used to correct (or reset) the INS solution, but without estimating the sensor drift (as it happens in the other integration approaches). In absence of GNSS data the system solution is entirely supplied by the inertial sensor, and tends to drift rapidly. Due to these limitations, the Uncoupled strategy is not commonly used. The Loosely and Tightly Coupled strategies are the most common integration techniques, and are discussed in more detail in the next sections. In the Loosely Coupled approach the GNSS solution is merged with the inertial based information to obtain the final output of the integrated system, while in the Tightly approach the integration is "deeper", because the GNSS raw measurements are directly combined with the INS information in a suitable filter. In the Ultra-Tight and Deep integrations the GNSS and INS devices no longer work as independent systems, GNSS measurements are used to estimate INS errors and INS measurements to aid GNSS receiver tracking loops; this integration is at deep level and requires access to the receiver´s firmware, therefore it is usually implemented by receiver manufacturers or with software receivers (Petovello 2003, Gautier and Parkinson 2003). In summary, integration occurs at the PVT *solution* level in the Loose approach; at the range (measurements) level in the Tight approach; and at the tracking level in the Ultra-Tight/Deep approach.

Loosely Coupled Integration

The Loosely Coupled (LC) strategy, also referred to as "decentralized", is realized including a KF to combine INS and GNSS navigation parameters and another block (a further KF or a LS estimator) is used to estimate the GNSS navigation solution using the raw measurements. The LC scheme is showed in Figure 2.

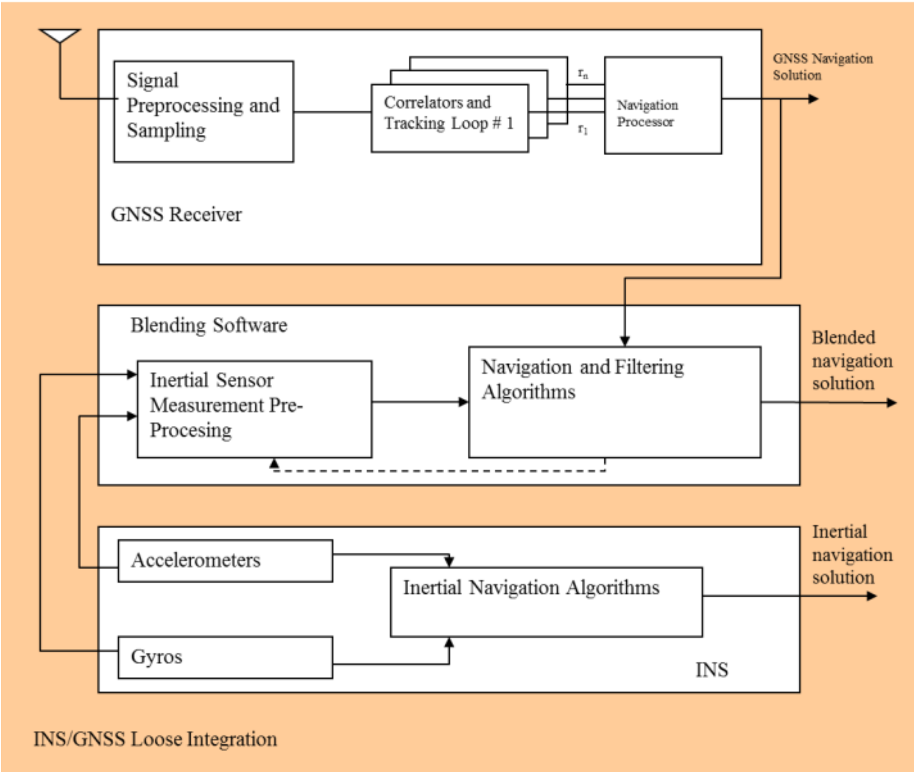

Figure 2 – INS/GNSS Loose Integration

As from the figure, the raw GNSS measurements from the receiver are independently processed in a dedicated block. Similarly, the INS works independently to generate its own navigation solution. GNSS solution and INS solution are then blended together through Least Squares/Kalman Filter – the blending occurs in the *position* (or solution) domain.

Loose Integration can be implemented in closed loop mode or in open loop mode. The closed loop mode consists of sending back the estimated INS errors from the KF to the mechanization and IMU blocks; in detail the estimated navigation errors are sent back to correct the INS state and the sensor estimated errors are used to compensate raw IMU measurements. The alternative mode is the open loop mode, where the INS operates independently from the KF estimator and the estimated errors are not sent back to mechanization and IMU blocks; in this way the inertial sensor errors remain uncorrected and inertial navigation state errors grow rapidly introducing large errors in the integrated systems. The open-loop mode can be used only for high-end inertial sensors, characterized by small errors; usually for low-cost or MEMS based inertial systems the closed-loop is necessary (Godha 2006).

Tightly Coupled Integration

The Tightly Coupled (TC) strategy, also referred to as "centralized", is realized processing INS navigation parameters and GNSS raw measurements in a central KF. The TC scheme is showed in Figure 3.

It can be noticed that the GNSS raw measurements are not processed in a separate filter as in the LC case, but are directly combined in a unique filter. The difference between PR and Doppler measurements and INS-predicted measurements is used as input of the KF; the associated measurements covariance matrix is defined taking into account the inherent accuracies of the GNSS observables and elevation-dependent accuracy of the single measurements as in the LC case. The INS-predicted measurements (range and range-rate) are computed using the GNSS satellite position and velocity from the ephemerides and user position and velocity from the INS. The closed and open-loop concepts are valid also in the TC case.

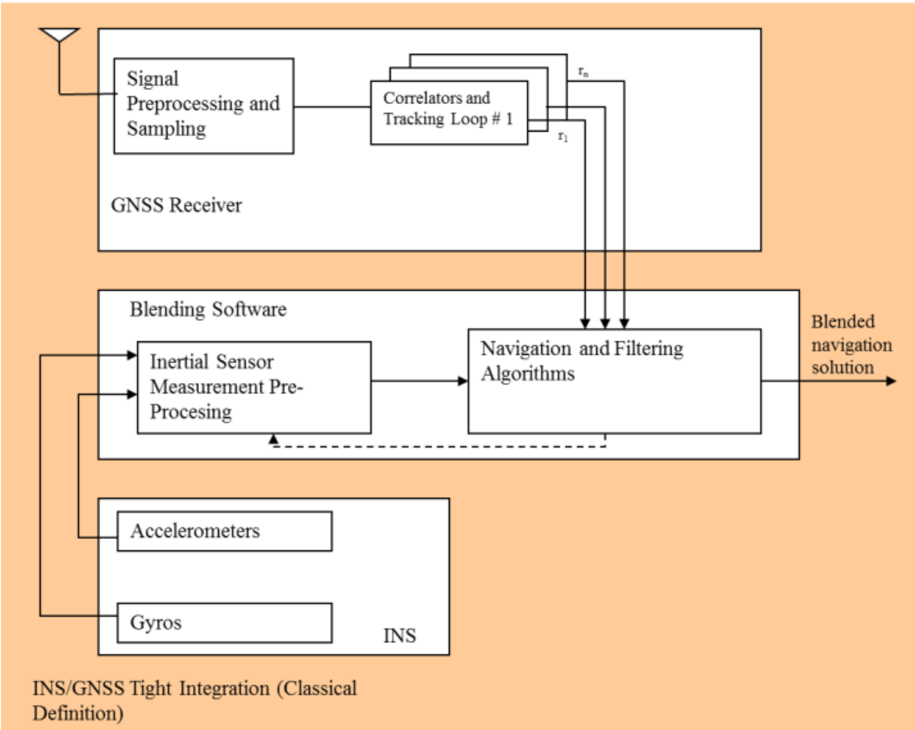

Figure 3 – INS/GNSS Tight Integration (Classical definition)

Filtering models

Below are the main equations employed in a Kalman Filter, the most popular filtering method employed to combine information from multiple measurement systems and dynamic models.

The Process (Dynamic) model can be expressed as:

$$x_{k+1} = \Phi_{k,k+1} x_k + \eta_k \tag{2}$$

where x_{k+1} is the state vector at epoch $k+1$, $\Phi_{k,k+1}$ is the transition matrix between epochs k and $k+1$, η_k is the process noise at epoch k, assumed to have a standard normal distribution, with variance matrix Q_{η_k}, $\eta_k \sim N(0, Q_{\eta_k})$.

The Observation model can be expressed as:

$$z_{k+1} = H_{k+1} x_{k+1} + \varepsilon_{k+1} \tag{3}$$

where z_{k+1} is the observation vector at epoch $k+1$, H_{k+1} is the observation design (or geometry) matrix at epoch $k+1$ and ε_{k+1} is the observation noise at epoch $k+1$, assumed to have a standard normal distribution, with variance matrix $Q_{\varepsilon_{k+1}}$, $\varepsilon_{k+1} \sim N(0, Q_{\varepsilon_{k+1}})$. On the basis of Process and Observation models, the state estimation is performed in two steps:

1. Time update (prediction step):

$$\begin{gathered} \hat{x}_{k,k+1} = \Phi_{k,k+1} \hat{x}_k \\ P_{k,k+1} = \Phi_{k,k+1} P_k \Phi_{k,k+1}^T + Q_{\eta_k} \end{gathered} \tag{4}$$

   where $\hat{x}_{k,k+1}$ is the predictor of the state vector x for epoch $k+1$, $\hat{x}_k$ is the estimator of the state vector at epoch k, P_k and $P_{k,k+1}$ are the variance matrices of estimator and predictor of x at epochs k and $k+1$ respectively.

2. Measurement update (estimation step):

$$\begin{gathered} \hat{x}_{k+1} = \hat{x}_{k,k+1} + K_{k+1} \hat{v}_{k+1} \\ P_{k+1} = (I - K_{k+1} H_{k+1}) P_{k,k+1} \end{gathered} \tag{5}$$

   where K_{k+1} is the gain matrix at epoch $k+1$, $K_{k+1} = \cdots$ and $\hat{v}_{k+1}$ is the vector of predicted residuals, or innovations, at epoch $k+1$.

All INS/GNSS fusion methods employ the Kalman Filter or similar filtering techniques. However, in Uncoupled and Loose integrations separated navigation solution for GNSS and INS are computed, before they are blended together in the filter, whereas in Tight and Deep integration the filter combines INS information directly with GNSS pseudorange measurements. In the loosely coupled case, it is preferable to use a least squares PVT solver to obtain a GNSS PVT, which is then processed in the GNSS/INS filter. The alternative, using a Kalman filter to obtain the GNSS PVT, leads to a cascaded filter architecture, which can be shown to be sub-optimal. Disregarding the Uncoupled implementation, for Loose and Tight integrations we have:

- *Loose integration:* For each of the GNSS and INS systems, a navigation solution is independently obtained. For standalone GNSS, the navigation parameters (constituting vector x) are:

$$x_{\mathrm{GNSS}} = [r, \dot{r}, dt]^T \tag{6}$$

where r is the position vectors (e.g. in East-North-Up components), $\dot{r}$ in the velocity vector, dt is the vector of the receiver clock offsets, of N_c or $N_c + 1$ components, where N_c is the number of GNSS constellations employed, and the eventual additional component is the receiver clock error drift. In case more precise positioning techniques are employed, for instance PPP or RTK, the navigation parameters vector includes a number of other unknowns, which need to be estimated. Among them are for instance the carrier phase integer ambiguities, $a_{s,f}$ (one for each satellite s and each frequency f), the ionospheric delay ι_s, the tropospheric delay τ_s, receiver and satellites hardware delays (d_r,δ_r, d_s,δ_s), etc. The observation vector includes the observations from each satellite, on each frequency used, and both code and phase if precise positioning (carrier phase based) is implemented. Possibly, also Doppler observations can be employed. However, it has to be noted that Doppler measurements are not independent from carrier phase measurements. Depending on receiver specifics, the carrier phase can be the integral of the Doppler, therefore sometimes referred to as Accumulated Delta Range (ADR).

For the INS system, the navigation parameters are:

$$x_{\mathrm{INS}} = [\dot{r}, \theta, b_a, b_\omega]^T \tag{7}$$

where θ is the receiver attitude, b_a and b_ω are the IMU acceleration and angular rate biases. Once the solutions from GNSS and INS systems are separately obtained, they are combined together in a Kalman filter, which parameter vector includes:

$$x = [r, \dot{r}, \theta, b_a, b_\omega]^T = [x_{\mathrm{GNSS}}^T, x_{\mathrm{INS}}^T]^T \tag{8}$$

The observation equations are obtained from linearization of the mechanization equations. A

- *Tight (and Deep) integration:* The navigation solution is obtained by implementation of a single Kalman Filter, in which Measurement update and Time update include the systems of equations from GNSS observation model and parameters dynamic model. The parameter vector includes all navigation parameters from both GNSS and INS systems:

$$x = [r, \dot{r}, \theta, dt, b_a, b_\omega]^T = [x_{\mathrm{GNSS}}^T, x_{\mathrm{INS}}^T]^T \tag{9}$$

With comparison to the LC integration, equation (8), the parameter vector includes the extra parameters dt. The dynamic model accounts for all combined system parameters. In case few GNSS observations are available, in number not sufficient to generate a position solution within the GNSS system only, they can still be used in combination with INS observations, to improve accuracy and reliability of the INS solution.

Loose versus Tight

The loosely-coupled approach is commonly implemented in the GNSS/INS integrated systems due to its simplicity, although it may experience difficulties, especially in urban environments, since it requires at least four available GNSS satellites to compute the navigation solution directly from the GNSS receiver – otherwise the INS remains unaided and the navigation errors grow according to the INS performance. The tightly-coupled integrated system has already proven to be superior to the loosely-coupled system, as with less than four satellites in view, it still allows exploiting the information contained in the available pseudorange and Doppler measurements, which has to be discarded in a loosely coupled system as a GNSS PVT cannot be computed. For this reason, TC strategy is usually preferred in applications with bad visibility conditions as urban canyons. However, only few commercial applications exist due to its complexity and difficulty to implement it.

Ultra-Tight and Deep integration

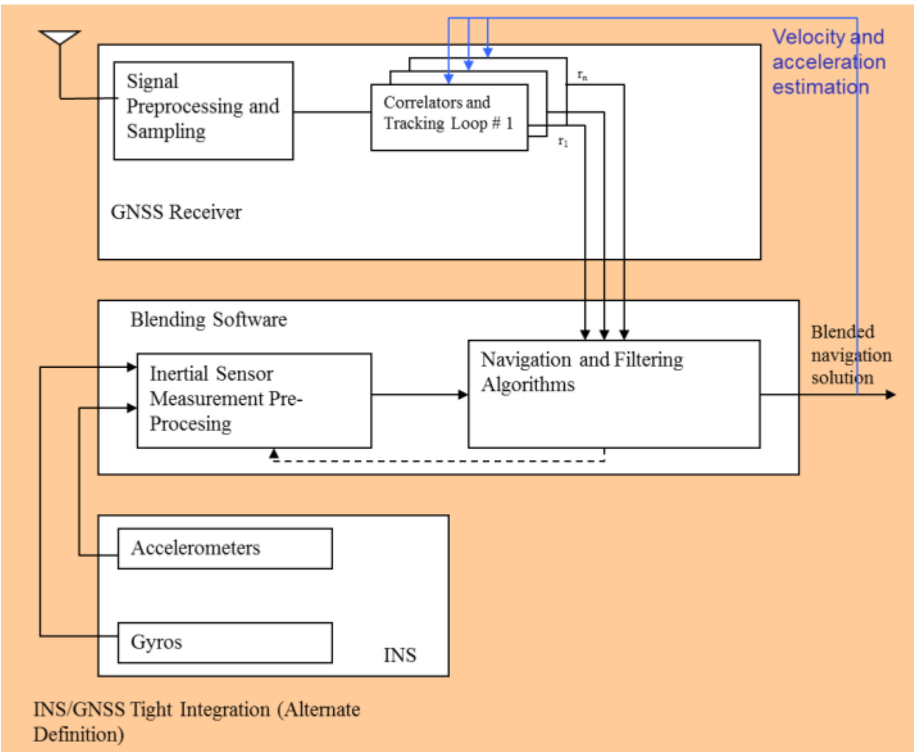

Figure 4 – INS/GNSS Tight Integration (Alternate definition)

Figure 4 shows a schematic representation of an alternate definition of Tight Integration (or Ultra-Tight integration). As from the figure, in this scheme the velocity and acceleration estimates, output of the INS, are input to the correlation and tracking loop. Figure 5 shows a representation of the Deep Integration strategy. In both alternative Tight scheme and Deep integration the GNSS and INS devices no longer work as independent systems, GNSS measurements are used to estimate INS errors and INS measurements to aid GNSS receiver tracking loops; this integration is at deep level and requires access to the receiver´s firmware, therefore it is usually implemented by receiver manufacturers or with software receivers.

In particular, in the Deep integration scheme, a single Vector Delay Lock Loop (VDLL) is used to fulfil the signal tracking function, instead of a batch of independent code and carrier tracking loops employed in conventional receivers (Pany and Eissfeller, 2006). The receiver is no longer an independent navigator since its operation is partly dependent on INS information. The Deep integration represents the optimal fusion of information from INS and GNSS receiver; however, the potential benefits may be achieved at the expense of highly increased hardware complexity, increased computational load and tight time synchronization requirements.

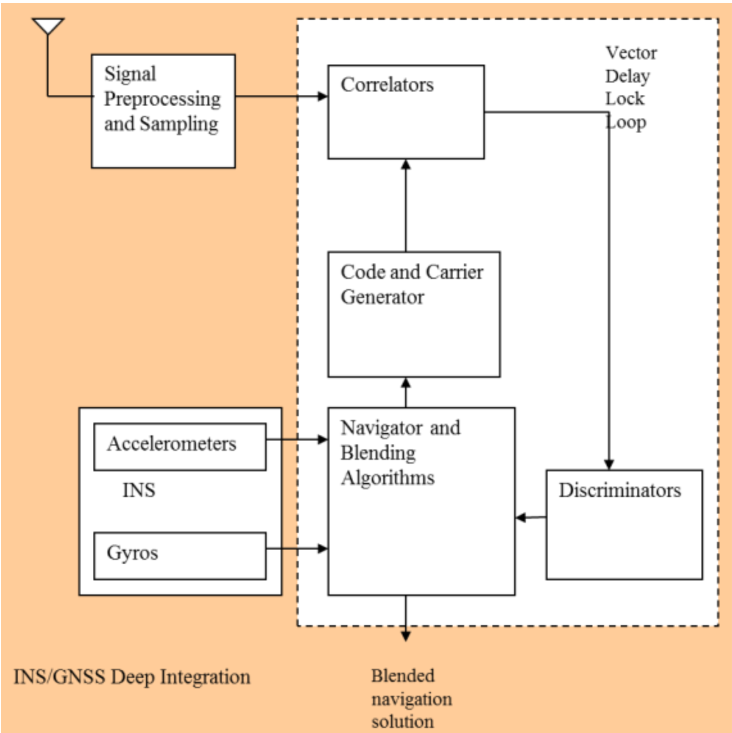

Figure 5 – INS/GNSS Deep Integration

The advantages of aiding the GNSS receiver tracking loop with INS information on the receiver velocity and acceleration, either in the Ultra-Tight or in the Deep implementation, have been reported by several works in literature. Langer and Gert (2013) proposed a comparison of Tight and Deep coupled integration, with kinematic tests in urban and rural areas (a vehicle driving in a city centre and on a highway), showing that the deeply coupled mode outperformed the Tight mode regarding continuity of the navigation – with fewer losses of lock and shorter reacquisition times. Results suggested that bridging of GNSS signal outages of 30s is possible without the need of performing reacquisition, even with a low-cost MEMS IMU. Du (2012) and Yang (2019) discussed promising INS-aided cycle-slip detection and exclusion techniques that rely on Ultra-Tight INS/GNSS coupling. Cycle-slips, after losses of lock, represent the most significant disturbances affecting the observations in carrier-phase based positioning, therefore effective cycle-slip detection techniques are fundamental for integrity monitoring in this context.

External information on the velocity of the receiver is particularly useful during periods of weak GNSS signal, as in such cases it is more difficult for the receiver tracking loop to obtain a correct estimate of the Doppler shift on the received signals. The Phase-Lock Loop (PLL) tracking error can in facts be divided into two parts: the thermal noise and the dynamic stress error (Raquet 2006). The follow basic rule-of-thumb (Kaplan 1996) provides a decomposition of the standard deviation of the PLL phase error, σ_{PLL}:

$$\sigma_{\mathrm{PLL}} = \sqrt{\sigma_t^2 + \theta_A^2} + \frac{\theta_e}{3} \tag{10}$$

where σ_t is the thermal noise, θ_e is the steady state dynamics stress error and θ_A is the Allan deviation oscillator phase noise. The thermal noise can be described with:

$$\sigma_t = \frac{360}{2\pi}\sqrt{\frac{B_n}{c/n_0}\left(1 + \frac{1}{2T_{\mathrm{COH}} \cdot c/n_0}\right)} \tag{11}$$

where B_n is the loop noise bandwidth, c/n_0 is the signal carrier to noise ratio and T_{COH} is the coherent acquisition interval. For a 2nd order loop, θ_e is equal to:

$$\theta_e = \frac{0.2809 \cdot \ddot{\gamma}}{B_n^2} \tag{12}$$

where $\ddot{\gamma}$ is the maximum LOS acceleration in $\deg/s^2$. The equations above show how tracking becomes more difficult in situation of high dynamics and low carrier to noise ratio.

4.3 Performance and Costs

Integrated INS/GNSS navigation systems performance and cost depends on the quality of each of the two constituting sub-systems (INS and GNSS) and of the integrating technology. Table 2 provides an indication of the performance and costs of different categories of IMUs (the main constituents of INS systems).

Table 2 – IMU categories, indicative performance and costs

IMU Type	Navigation Grade	Tactical Grade	Industrial Grade	Consumer Grade
Cost (€)	> 50k	10-20k	0.5-3k	< 500
Weight	> 2.5 kg	about 0.5kg	< 150 g	
Gyro Bias Stability	< 0.1 deg/h	0.1-10 deg/h	< 1 deg/s	> 1 deg/s
Gyro Random Walk Error	< 0.005 deg/$\sqrt{h}$	0.2-0.5 deg/$\sqrt{h}$		
Acceleration Bias	5-10 μg	0.02-0.04 mg		
Example	HW HG9848	HW HG1900	Microstrain GX2	ArduIMU

GNSS receivers and antennas cost and performance are not addressed here, however it is noted that low-cost equipment (e.g. smartphones) is able nowadays to perform differential carrier phase based positioning, with accuracy reaching dm level and higher (when network corrections are available).

The INS/GNSS coupling method has also to be considered when evaluating performance and cost. Tighter coupling techniques are more complex and costly to implement, but deliver better performance. Specifically Deep Coupling is usually implemented on higher quality firmware and is relatively costly.

The quality of positioning of an INS/GNSS integrated system in standard operations is usually dominated by the GNSS performance. The INS has the function of providing positioning continuity, providing redundancy and bridging possibly outages of GNSS signals, as well as allowing to determine the vehicle attitude. Table 3 provides an indication of the time deterioration of the positioning accuracy, when navigation is left to INS only (in absence of GNSS observations), starting from a position known at cm level.

Table 3 – Indicative time for divergence of position accuracy in absence of GNSS measurements

IMU category	$\sigma_e > 0.3\text{m}$	$\sigma_e > 1\text{m}$
Consumer grade	$<$ 5s	$<$ 10s
Industrial grade	$<$ 10s	$<$ 20s

Table 4 provides an assessment of advantages and disadvantages of the different INS/GNSS integration techniques discussed in previous chapter.

Table 4 – Advantages and drawbacks of the different INS/GNSS coupling architectures

Coupling Level	Benefits	Disadvantages
Loosely coupled	• Easy implementation • In-flight calibration and alignment increases inertial navigation performance	• GNSS receiver is not aided: • No improvement in jamming resistance • No increase in GNSS receiver acquisition and tracking

Coupling Level	Benefits	Disadvantages
	• Separate subsystems keep maintenance and simple integration • Wide range of usable equipment • Significant improvement in accuracy, data rate, availability, continuity and integrity compared to standalone GNSS	performance • Non optimal case since no aiding of the INS is possible with less than 4 satellites in view.
Tightly coupled	• Significant performance improvement in accuracy, data rate, availability, continuity and integrity compared to standalone GNSS • Optimum use of reduced set of visible satellites, i.e. INS aiding with less than 4 satellites in view • Possibility to exclude individual satellite observations from the filter	• Higher integration and implementation complexity • Two additional error states in the navigation filter for receiver clock error and receiver clock error drift • Still no receiver aiding to overcome jamming and interference problems or improve acquisition and tracking performance
Ultra-tightly coupled	• Reliable tracking under high dynamics • Reduced tracking loop bandwidth improves jamming resistance • Improved DLL and PLL tracking performance • Improved acquisition performance due to search space reduction • Improvement in accuracy, availability, and continuity of integrated system compared to tightly coupled	• Subsystems are not independent anymore • Subsystem failures influence other subsystems • High implementation and integration efforts • Reduced number of available GNSS receivers (Tracking loop access)
Deeply coupled	• Highest possible jamming resistance • Individual channels are aiding each other (e.g. vector tracking) • Excellent re-acquisition performance after loss of signal • Highest possible integration of both sensors • Improvement in accuracy, availability, and continuity of integrated system compared to ultra-tightly coupled	• High correlation between the subsystems • Highest integration and implementation efforts • Reduced number of available GNSS receivers (Tracking loop access)

Test drive results (Loose and Tight coupling)

In the following, some illustrative examples shall be given which allow comparing qualitatively the performance of the different GNSS/INS coupling approaches described in the previous sections. For this purpose, raw GPS pseudoranges and delta-ranges, as well as velocity and angle increments from a low-cost MEMS IMU have been recorded during a test drive. Then, this data was post-processed using different GPS/INS integration architectures.

Figure 6 shows the GPS positions that were calculated from the raw pseudoranges with a weighted least squares snapshot algorithm without any type of filtering or integrity check. On the right, a large gap is visible, which is caused by the fact that during the drive through the respective street, buildings intersected the line-of sight to some satellites, so that less than four satellites were available which prohibited the calculation of a PVT. On the left, two position fixes can be seen, where the position error is really huge. Investigations showed that this error was not caused by the pseudorange measurement quality or multipath. Instead, while driving by, buildings had shadowed satellites which led to a visible constellation of four satellites still allowing for a PVT calculation, but the resulting visible constellation had and extremely high GDOP of several hundred. Such high GDOP values are actually not too rare in urban environments.

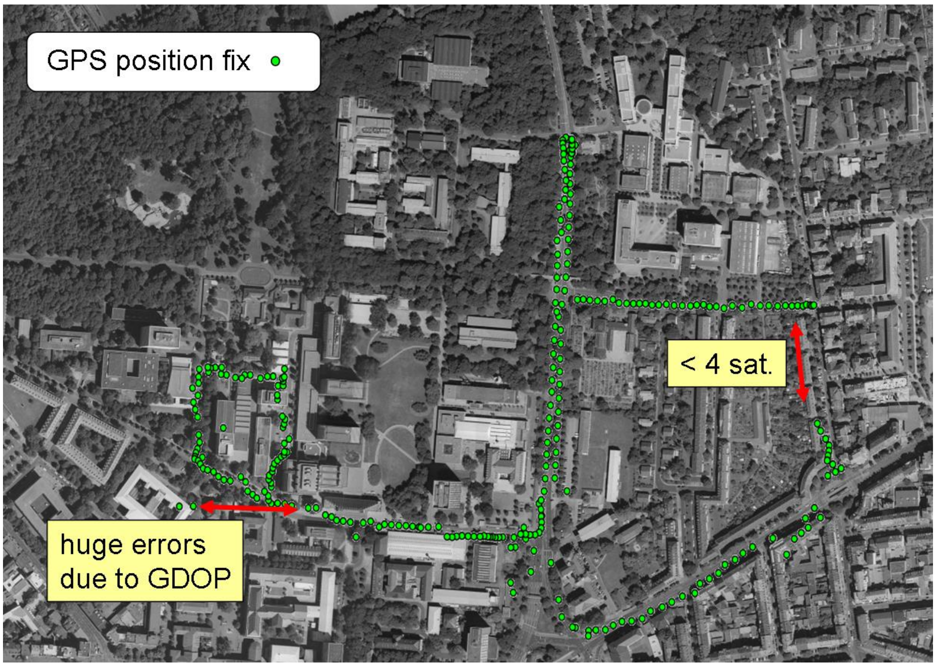

Figure 6 - GPS positions from pseudoranges (standalone)

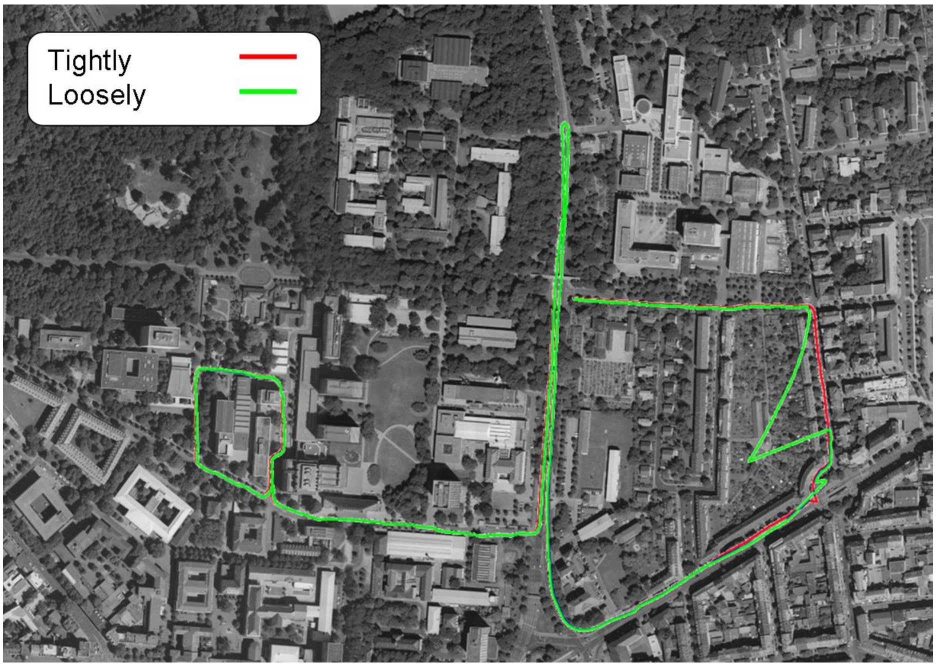

Figure 7 - Trajectories obtained from loosely and tightly coupled GPS/INS integration approaches

Figure 7 shows the position solutions that were obtained by a fusion of the recorded GPS and INS data using loosely and tightly coupled navigation filters developed by Airbus. The improvement from GPS/INS coupling w.r.t. stand-alone GPS is clearly visible in the most critical areas (on the far left and right stretches of the track, and also during the wide turn at the bottom), as well as the difference between loose and tight integration: in the part of the test drive on the right where less than four satellites were available, the loosely coupled solution starts to drift according to the inertial navigation performance achievable with the low-cost MEMS IMU, while the tightly coupled solution maintains a very good position accuracy by aiding the INS with the raw GPS measurements to the remaining satellites.

Simulations results (Tight and Deep coupling)

A comparison of tight and deep integration performances in presence of high platform dynamics can be seen in Figure 8. This plot was obtained from a software simulation developed by Airbus, which is capable to simulate loose, tight, ultra-tight and deep GNSS/INS systems. Due to the high dynamics at the end of the simulation run, a very high tracking loop bandwidth had to be chosen for tight integration in order to maintain lock, because for that architecture no INS aiding of the GNSS receiver is performed. This explains the larger errors compared to the results for deep integration in the beginning of the simulation run, where the platform dynamics are low. Later into the run, the huge platform dynamics cause massive errors for the tight integration, while the deep integration results are not affected. Significant performance differences between tight and deep integration can be observed at low c/n_0 ratios, too.

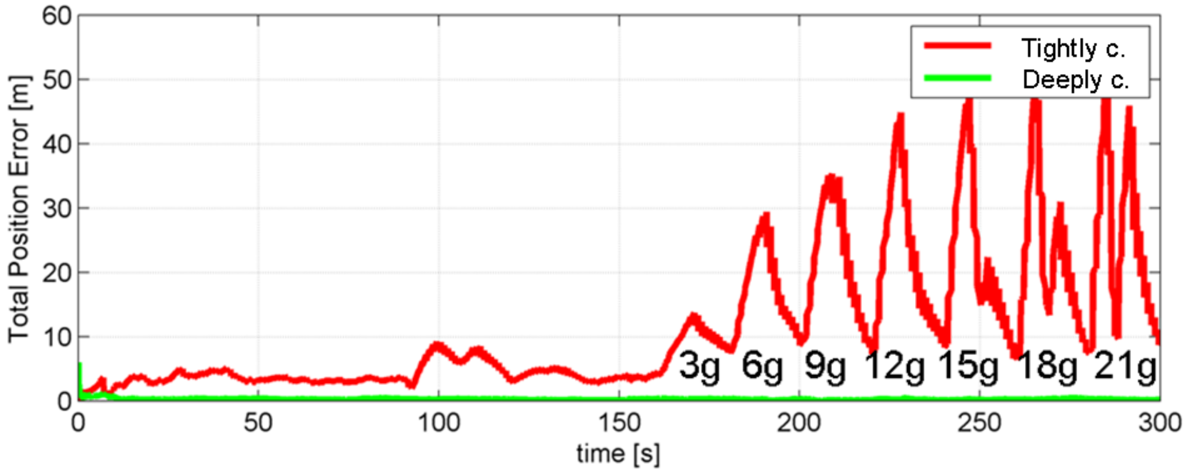

Figure 8 - Position errors for tight and deep architectures in presence of high platform dynamics

The results reported so far showed the advantages of TC over LC approaches – in environments with obstructed satellite visibility – and the advantages of DC over TC – in high dynamics scenarios. As mentioned before, the more deep is the integration, the more costly is the implementation. In particular, Ultra-Tight and Deep integrations are not available at consumer or industrial grade quality.

5 RAIM for GNSS/INS integration

5.1 eRAIM

This section describes the so called extended RAIM (eRAIM), which is commonly used in many receivers to identify and reject malicious GNSS observations, when additional sensors basically increase redundancy of observations. In aviation application, it is also called AAIM (for Aviation-AIM). It consists in comparing the difference between the actual measured and the predicted observations (this difference is called innovation), and allows a statement of the quality of the observation respectively. If this innovation exceeds a certain threshold, for example triple standard deviation, then the observation can be identified as malicious and therefore rejected from the position solution. The mathematical background is briefly explained in the following (more details can be found in Hewitson (2010)).

Based on the least-squares principles, the optimal estimator, $\hat{x}_k$, for the state parameters x_k can be derived. To do so, the measurements z_k are combined with the predicted values of the state, $\hat{x}_{k-1,k}$. The corresponding measurement model is depicted as follows:

$$l_k = A_k x_k + v_k \tag{5.1}$$

$$l_k = [z_k;\ \hat{x}_{k-1,k}]; \quad v_k = [\eta_k;\ \varepsilon_k]; \quad A_k = [H_k;\ E_k] \tag{5.2}$$

Herein:

- l_k is the combined measurement vector containing z_k and $\hat{x}_{k-1,k}$,
- A_k is the combined design matrix, with E an $m_k \times n_k$ identity matrix.
- v_{z_k} is the combined error vector.

The optimal estimates for the state parameters are $\hat{x}_k$ and the error covariance matrix $Q_{\hat{x}_k}$ are:

$$\hat{x}_k = \left(A_k^T C_{l_k}^{-1} A_k\right)^{-1} A_k^T C_{l_k}^{-1} l_k \tag{5.3}$$

$$Q_{\hat{x}_k} = \left(A_k^T C_{l_k}^{-1} A_k\right)^{-1} \tag{5.4}$$

With C_{l_k} being the covariance of the stochastic variable l_k. The filtering least-squares residuals $\hat{e}_k$, consisting of v_{z_k} and $v_{x_k^-}$ can then be calculated from:

$$\hat{e}_k = l_k - A_k \hat{x}_k \tag{5.5}$$

The cofactor matrix of the filtering residuals $Q_{\hat{v}_k}$ is as follows

$$Q_{\hat{e}_k} = C_{l_k} - A Q_{\hat{x}_k} A_k^T \tag{5.6}$$

Once a fault has been detected with a global detection algorithm such as the variance factor test, the w-test can then be used to identify the corresponding measurement, where the test statistic is

$$w_i = \left| \frac{u_i^T C_{l_k} \hat{e}}{\sqrt{u_i^T C_{l_k} Q_{\hat{e}_k} C_{l_k} u_i}} \right| \quad 5.7$$

where u_i is a unit vector in which the ith component has a value equal to one and dictates the measurement to be tested.

Under the null hypothesis (H_0), w_i has a standard normal distribution (zero mean). For an outlier ∇S_i (H_1 case), w_i has a shifted distribution with mean δ_i:

$$\delta_i = \nabla S_i \sqrt{u_i^T C_{l_k} Q_{\hat{e}_k} C_{l_k} u_i} \quad 5.8$$

Based on the distribution for w_i under H_0 and H_1, fault detection, exclusion and PL computation can be performed following the same principles of standard RAIM (detailed in report 5.1, or Blanch (2012)).

GNSS/INS integrated systems are able to detect and identify instantaneous biases under the condition that there are two or more satellites (and/or RF network base stations) visible. The detected instantaneous biases may not be isolated when there is only a single satellite visible. Introducing a second GNSS such as Galileo, and/or an RF based network positioning system, in addition to GPS increases redundancy and hence FD performance significantly, as already accounted into the ARAIM concept. Slow Growth Errors (SGE) or slowly increasing ramp errors are less common than instantaneous biases but far more difficult to detect. SGE cannot be distinguished from the normal system dynamics and is therefore an undetectable error for an integrated GNSS/INS system when less than four satellites are available, with a standard snap-shot RAIM algorithm. Possible RAIM algorithms able to cope with SGEs are Filterbank approaches, discussed in next section.

5.2 FilterBank approach

Based on early work in Brenner (1995), a full GNSS/INS integrity monitoring using a bank of navigation filters is developed in Vanderwerf (2001), which is based on the solution separation method. In this approach, a primary hybrid navigation solution is maintained by means of a navigation Kalman Filter which processes pseudorange and Doppler measurements from all N satellites in view. In addition, N sub-filters are running in parallel, each of which excludes the measurements from a different satellite. Given that the measurements from one satellite are faulty, one or more navigation solutions will deviate from the solution provided by the primary filter. In that case, the separation between the primary filter and least one of the sub-filters exceeds a threshold which is calculated from the separation statistics and the desired false alarm rate, a fault is detected. In order to identify the faulty satellite, each of the N sub-filters runs a set of N-1 sub-sub-filters in parallel, each of which excludes a different satellite in addition to the satellite already excluded from the parent sub-filter. Now for each sub-filter, the separation between the sub-filter and each of its sub-sub filters is assessed; if for one sub-filter the all separations are lower than a threshold, the satellite excluded by the sub-filter is the faulty one. The hierarchy of filters used in this approach is illustrated in Figure 9.

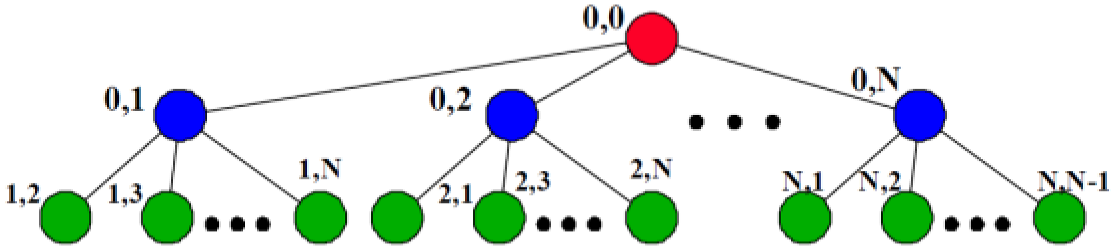

Figure 9 - Filter Hierarchy (Vanderwerf 2001)

For this filter bank approach, all relevant integrity parameters including horizontal protection levels can be calculated. A detailed performance analysis of this approach, including availability assessments for different scenarios, is given in Vanderwerf (2006). The drawback of this approach however, is the huge number of filters that has to be used, which is computationally extremely demanding.

Other approaches make use of interacting multiple model (IMM) filter banks, see White (1998). In the IMM formalism, a bank of elemental filters is used, for each of which also the probability that the models employed by the respective elemental filter are correct is maintained. This approach was originally developed for target tracking purposes, and the filters used employed e.g. models for straight and level flight, coordinated turns or other manoeuvres. In order to apply the IMM formalism to provide integrity for a GNSS/INS system, each elemental filter assumes a different satellite to be faulty and estimates the pseudorange measurement error as an additional state. In the presence of a fault, the elemental filter which assumes the respective satellite to be faulty will achieve a high probability, while the probabilities of the other filters processing the faulty measurements as healthy decay towards zero. This approach shows a very good performance, too, but is also computationally very demanding. Interestingly, in Wendel (2008) a modification of this approach is proposed, which replaces the N individual propagation steps of each elemental filter with one single common propagation step without a visible sacrifice in performance. As most of the computational load of a GNSS/INS filter is produced in the propagation steps, this approach overcomes the drawback of an almost prohibitive computational burden usually experienced with the filter bank integrity monitoring techniques.

Finally, it must be noted that if integrity shall be provided for a multi-sensor integrated system, also the integrity issues of individual subsystems must be considered. Therefore, integrity monitoring for the INS might also be required, a can be achieved by redundant inertial sensor configurations.

Within this project, different GNSS/INS integrity monitoring strategies for the different integration architectures will be assessed. The capability of the EMSAU to replay recorded ADC samples together with the corresponding inertial sensor data will allow comparing the performance of the different GNSS/INS architectures and integrity monitoring algorithms in a realistic environment representative for the applications of interest.

6 Spoofing scenario simulation

Airbus, responsible for the activity INLU (*definition missing*), got a unique opportunity to develop an end to end tool "PIPE" capable to simulate a large number of environments. This tool is used to model different environments of application and assess signals and navigation systems performance.

In the frame of this activity, the "PIPE" software and ESA laboratory hardware were employed to assess the integrated INS/GNSS systems performance in a reference environment.

The PIPE software is described in the annex 2 of the technical proposal. It contains already some multipath model like the physical-statistical wideband LMSS model described in Recommendation ITU-R P.681.

The combination of "PIPE" software + Hardware offers a large flexibility for the configuration of the signal transmitted (pulse shape, bandwidth) and environment (e.g. in presence of multipath, spoofing etc.), as well as for the configuration of the receiver (e.g. Rx bandwidth code/carrier discriminator, code/carrier loop bandwidth, loop order, PVT algorithm, INS coupling, ARAIM implementation).

A simulation illustrating the positioning performance – especially the integrity performance – of two different INS/GNSS coupling techniques, LC and TC, and of an in-house developed FilterBank integrity monitoring technique, is discussed in the following. Specifically, the experiment showcases the response of the two coupling methods to a spoofing attack.

In the simulation, a vehicle is travelling at low speed (<50km/h) over a circuit of about 3km length in sub-urban area, completing three loops. During this time stretch, 8 GNSS satellites are visible to the vehicle, 4 GPS and 4 Galileo. After the first 100 seconds, a spoofing attack is simulated by inserting a coherent error in three pseudorange measurements from 3 Galileo satellites, linearly growing with time (from 0 to 700m). The attack, if undetected, would cause the position solution to drift by over 500 meters in North-East direction.

The PIPE tools are used to:

- Generate a trajectory from selected waypoints
- Generate observation data for the trajectory and the navigation data from a RINEX file.
- Generate IMU sensor data for the trajectory
- Insert realistic GNSS observation errors and spoof 3 Galileo channels.

The recorded samples are then fed to the PIPE receiver, for the signal to be tracked and the localization to be performed. The performance can be checked using tools implemented in PIPE, but also by comparing the true trajectory with the detected one.

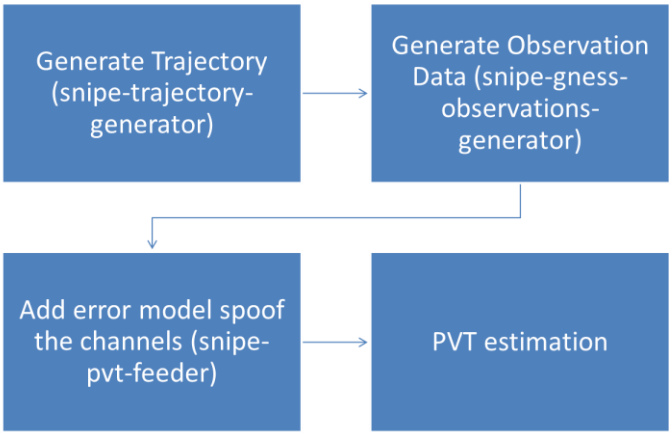

Figure 10 – Using PIPE tools to generate channel model and spoofing data and to make it Spirent compatible.

Figure 10 shows the steps of the simulation, and an overall scheme of the procedure is given in Figure 11. The PVT results are also saved in *.kml files, which can be read by Google Earth.

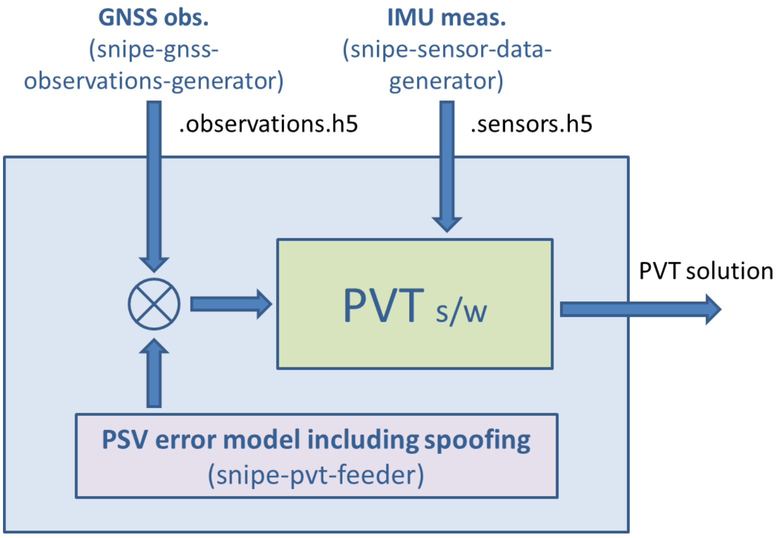

Figure 11 – General scheme of the PIPE-based integrated INS/GNSS simulator

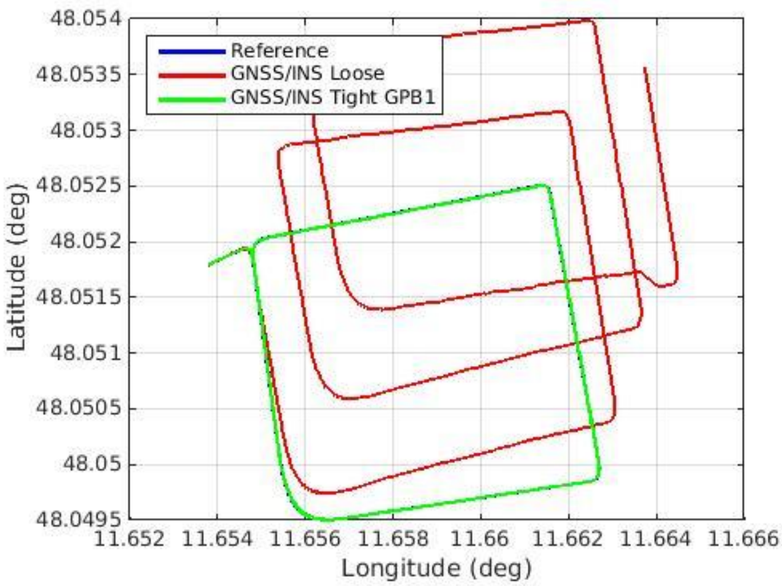

Figure 12 – Positioning results of Loosely coupled and FilterBank aided Tightly coupled systems

In Figure 12 the positioning results are shown. In green is the TC solution, whereas in red is the LC solution. It can be observed that TC INS/GNSS receiver with Filterbank integrity is able to successfully exclude the spoofed signals. Instead the LC INS/GNSS is unable to detect the spoofing attack and the generated position solution rapidly deviates from the actual path, with a final rover position estimate hundreds of meters away from the actual position. These results showcase how higher integrity – specifically resilience to spoofing attacks – can be obtained adopting TC integration rather than LC integration.

7 Recommendations

Following the analysis of the INS-GNSS fusion state-of-the-art presented so far, in this chapter the authors´ recommendations for implementation within the EMPHASIS project are given.

It is recommended to implement a Tightly Coupled (TC) INS/GNSS integration scheme, as it provides the best trade-off between cost and performance. At the time of writing more deeply integrated schemes are not easily available to the general public and present high implementation costs, and upsides that are mostly relevant only in high dynamic scenarios. Instead the advantages of using a TC approach over a LC one are sensible in terms of availability (in GNSS-challenging environments) and integrity.

It is recommended to implement an integrity monitoring technique tailored to recursive processing (Kalman Filter), as the suggested FilterBank technique. The simulation results reported in previous chapter showed how the application of the FilterBank technique (which requires TC INS/GNSS integration) guaranteed a high resistance to spoofing attacks or SGEs in general.

As INS can bridge GNSS outages only for short periods of time, it is further recommended to provide the integrated INS/GNSS positioning system of additional assistance from different external means (e.g. cellular network) in user environments characterized by poor satellite visibility.

8 Conclusions

Following the initial assessment of INS/GNSS fusion techniques for use in GA/R operations, the following conclusions were made:

- INS/GNSS fusion can guarantee significant improvement in navigation performance with respect to GNSS only, with a contained cost. In particular, low-cost (consumer grade) INS can guarantee an improvement of performance of GNSS network-based precise positioning techniques (e.g. PPP), specifically in environments with degraded satellite visibility (e.g. urban and sub-urban).

- INS/GNSS fusion is particularly helpful in enhancing the integrity of the navigation solution, as the INS provides redundancy of measurements in all navigation scenarios, it cannot be spoofed (differently from GNSS), complementing GNSS in most aspects (especially in bridging outages). In carrier phase based navigation, INS can be used to aid cycle-slip detection methods.

- Among the different INS/GNSS fusion implementation strategies, the Tight (Figure 3) scheme was deemed the most suitable for a reasonably low-cost solution for commercial drones. The reasons are:

    - It allows to use GNSS observations to aid positioning also when less than 4 satellites are visible, which is not possible with Loose integration (Figure 2)

    - It guarantees higher integrity with respect to Loose Integration strategies (Figure 2), as anomalies affecting specific GNSS measurements can be detected with RAIM (or eRAIM techniques)

    - It allows the implementation of Filterbank integrity monitoring techniques, showcased in this report, which guarantee integrity in case of SGEs (e.g. spoofing attacks)

    - It is a solution commercially available, at reasonably low costs, differently from the more complex Ultra-Tight and Deep integrations (Figure 4, Figure 5).

  Ultra-Tight and Deep integrations (Figure 4, Figure 5Figure 3) can guarantee higher continuity with respect to simpler Tight integration strategies, as the velocity and acceleration information obtained from the INS facilitate the GNSS receiver acquisition and tracking, reducing the number of losses of lock and the re-acquisition times in sub-urban or urban environments. However these solutions are complex, high-cost and not easily accessible on the market. If such solutions were to become more easily accessible in the near future, they would constitute the authors´ preferred choice.

- INS limitation lies in the fact that it can bridge GNSS outages (due to lack of sky visibility for instance) for a limited amount of time. INS only positioning accuracy in fact diverges rapidly with time, and when using low-cost IMU the positioning error in absence of GNSS observations, or in presence of only few of them, can grow over 1m in few tens of seconds. As a results use of INS/GNSS integrated systems may not be enough to guarantee the required levels of accuracy and integrity in GNSS-challenging environments, and external aiding (for instance from the cellular network) will be necessary, at least in specific areas.

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