Simulation of GNSS/IMU Measurements

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Abstract

The IESSG has for many years been using simulators of various kinds in its research activities. There are many advantages of using simulators. Simulated data can provide early opportunities for the analysis of a potential measurement process. Simulators can enable a new computational technique to be assessed with controlled error budgets. For some years the IESSG has had a 'GNSS' simulator that enabled measurements to be generated and procedures and capabilities to be assessed. This has provided research opportunities that would not otherwise have been available.

More recently the 'GNSS simulator' has been expanded to include the capability to simulate Inertial Measurement Unit (IMU) components (gyros, accelerometers) in an integrated environment. Detailed models of the performance of the inertial components have been developed, so that synthetic GNSS data and IMU data can be produced from a common platform. A trajectory generator allows synthetic data to be produced from a combined GNSS/IMU platform that is moving in a precisely controlled way. Data from this tool has been validated using an analysis filter from another source, as well as with in-house analysis tools.

To date, these two tools have been used in a number of internal and contract research projects as well as being developed as a teaching tool. Of note is their use to simulate and assess the performance of future low-cost inertial components in an ESA-funded project entitled the 'Low-Cost Navigator'. They have also been used to develop an adaptive Kalman Filter, which integrates measurement data from GPS and inertial navigation sensor data. The aim of the filter is to optimise the blend of these two distinctly different types of measurements and make the best use of the synergy between them, to provide precise and reliable positioning.

Recognising the strengths of the filter design, including its ability to work in a centralised or de-centralised mode, its ability to process carrier phase data, and its adaptive capabilities, the IESSG has recently begun a programme of development to produce a commercial version of the filter, suitable for embedding in bespoke hardware designs.

The paper proposes to describe the simulator and filter, and will demonstrate the potential uses and application of these powerful tools.

1. Introduction

The IESSG has for many years been using simulators of various kinds in its research activities. There are many advantages of using simulators. Simulated data can provide early opportunities for the analysis of a potential measurement process. Simulators can enable a new computational technique to be assessed with controlled error budgets. For some years the IESSG has had a 'GNSS' simulator that enabled measurements to be generated and procedures and capabilities to be assessed. This has provided research opportunities that would not otherwise have been available.

The GNSS simulator has evolved as a research tool and developed as demands have been created by various projects. Not only can the simulator simulate the Global Positioning System, but it also has the potential to simulate any satellite constellation, for example Galileo or a combination of constellations. Of more recent note, is the use of the simulator to simulate and assess the performance of future low-cost inertial components in an ESA-funded project entitled the 'Low-Cost Navigator'. This required the 'GNSS simulator' to be expanded to include the capability to simulate Inertial Measurement Unit (IMU) components (gyros, accelerometers) in an integrated environment. Detailed models of the performance of the inertial components have been developed, so that synthetic GNSS data and IMU data can be produced from a common platform. A trajectory generator allows the synthetic data to be produced from a combined GNSS/IMU platform that is moving in a precisely controlled way.

Although this was developed for the assessment of 'low-cost' components the simulator has the potential for assessing components with a wide range of performance capabilities.

To simulate observations/measurements from GNSS and an IMU is only half of the processing cycle. The other half of the cycle is to take the measurements and combine them in a computation to obtain the optimum position and attitude of the platform. In the real world this optimisation of the position and the attitude from GNSS/IMU measurements is a major area of research interest. The IESSG has been developing an adaptive Kalman Filter for performing the blending of these measurements. The simulator has been an invaluable tool in this process. The process has also provided feedback in to the development of the simulator.

Developed as a research tool, the simulator has also provided the IESSG with a powerful teaching tool. The rapid generation of data and the graphical representation of the results enables students to understand the principles and gain experience of results when parameters are changed.

This paper will describe the basic features of the simulator and how it has been used in some recent projects.

2. The GNSS Data Simulator

The GNSS data simulation tool was originally designed to simulate the types of measurements that can be made using a GPS receiver. Specifically the simulator has the capability of producing code, carrier and Doppler measurements on both the L1 and L2 frequencies. The simulation is achieved by using the true locations of both the receiver and the satellites to calculate the true, error-free measurements. Error models are then applied to account for the various inaccuracies seen in real-world measurements. The simulation results are returned to the user in a file in the standard RINEX (Receiver INdependent EXchange) observations format. A flow diagram illustrating the simulation process is shown in Figure 1.

The user is required to define a simulation scenario by supplying the satellite ephemeris data and the true location of the receiver as well as the parameters for the various error models and the time period for which data should be simulated. Kinematic as well as static receivers can be simulated by supplying time-tagged position and velocity information for the receiver in an appropriately formatted file. A separate trajectory building tool has been developed to aid in creating such files for simple dynamic scenarios. The satellite ephemeris data can be supplied using either a data file in the SP3 format developed by the NGS or a file in the RINEX navigation format. It is therefore possible to simulate data using the true locations of the satellites for any day in the past. Alternatively, the user can supply the orbital parameters for each satellite in the constellation and use the Keplerian orbit propagator to determine the locations of the satellites at any time in the future. The scenario definition is completed by selecting the number and type of measurements to be simulated along with the data interval for the measurements and the elevation masking angle of the receiver.

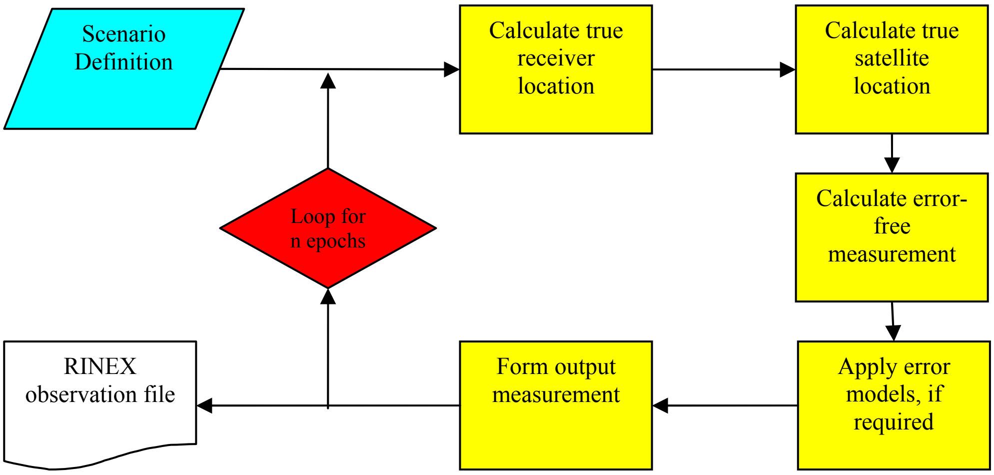

Figure 1: Schematic of the GNSS data simulation process.

The simulator contains a number of models for generating the errors resulting from atmospheric and environmental effects. Propagation delays due to the ionosphere are simulated using either the well-established Klobuchar model or through the application of a TEC (Total Electron Content) map. Default TEC maps are available representing high, medium and low levels of ionospheric activity, however the user can supply their own TEC map using a data file in the IONEX format. The errors associated with the tropospheric path delay may be modelled using one of several models including the EGNOS tropospheric correction model or the Saastamoinen delay model used with appropriate meteorological data. Alternatively the user can supply time-tagged values of the total zenith delay for the troposphere in a separate input-file which are then interpolated and mapped to the appropriate zenith angle. Both the ionospheric and tropospheric delay models can be augmented by a spatial variation model which enhances the spatial resolution of the error models. The model uses Gaussian random fields to overlay a small variation onto the measurement errors returned by the atmospheric models. This ensures that two simulated receivers located in close proximity do not experience precisely the same delay and therefore gives a more accurate simulation for use with differential processing techniques.

Measurement errors due to multipath may also be simulated with a model based on Gaussian coloured noise. The correlation period of the resulting errors is dependent on the motion of the receiver and the amplitude of the errors may be set to be dependent on the elevation and/or azimuth of the satellite. Other sources of error accounted for in the simulations include the satellite and receiver clocks, relativistic effects and receiver noise. The parameters for all the error models within the simulations are user-configurable and any combination of models can be selected.

Although the data simulator was originally designed for the simulation of GPS measurements, the software has recently been upgraded to allow for the simulation of both the proposed European satellite navigation system Galileo and modernised GPS. Using similar techniques to those outlined above it is now possible to simulate measurements on the Galileo Open Service and the Commercial Service as well as on the new GPS L5 carrier. The proposed new GPS public access code on L2 is also accounted for. Data may be simulated for each individual constellation or the user can select both constellations to effectively simulate a joint GPS/Galileo receiver. Since Galileo will not be fully operational until 2008 and the modifications to GPS will not be completed until a similar time, the only way of researching positioning techniques using these future systems is through simulated data. The GNSS data simulator therefore offers an important research capability.

3. Applications of simulated GNSS data

The GNSS data simulator forms part of the IESSG's teaching software package together with the Navigation Performance Tool (NPT) which calculates global Dilution Of Precision (DOP) and Receiver Autonomous Integrity Monitoring (RAIM) statistics for various combinations of constellations. Sample screen shots of the two tools are shown in Figures 2 and 3. The software package is used to help students gain a better understanding of constellation design, data processing and other aspects of satellite navigation systems. However the data simulator also has an important role as a research capability.

Simulated data can be used to aid the development of new processing techniques. The advantage of simulated data is that the precise location of the receiver is known, as well as the constituents of the errors contained in each measurement. An example of where this has been exploited is in a recent project the Institute has been involved with on ground-based GPS meteorology. Here simulations were used to demonstrate the possibility of using a network of GPS receivers to detect weather fronts through calculation of the tropospheric delay experienced by the signals.

Another important application of simulated data is in the analysis of systems which are not currently operational. The IESSG is one of three partners currently involved in the Furlong project funded by the British National Space Centre, where the future of real-time location and navigation based services is being investigated. The aim of the Furlong project is to show through simulations that future navigation and communication systems can be integrated successfully to provide high precision and reliable location based services. The GNSS data simulator is being used in this project to provide measurement data from both Galileo and modernised GPS satellites.

With the advent of Galileo and modernised GPS new multi-frequency processing techniques may be developed to handle the new data. The GNSS data simulator can play an important role in the optimised development and testing of new algorithms for processing the data and allows progress to be made before the satellite systems become fully operational.

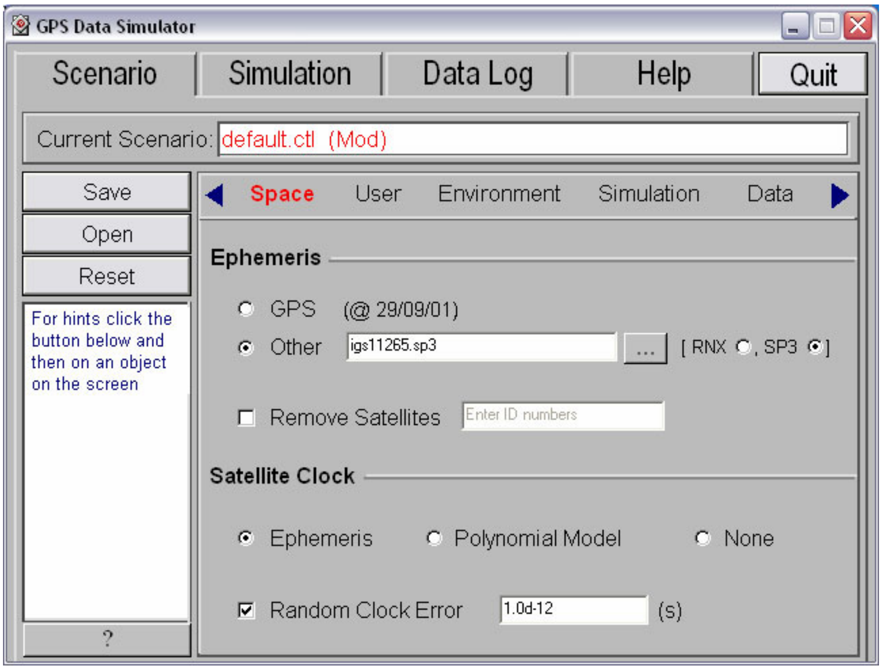

Figure 2: The GNSS Data Simulator.

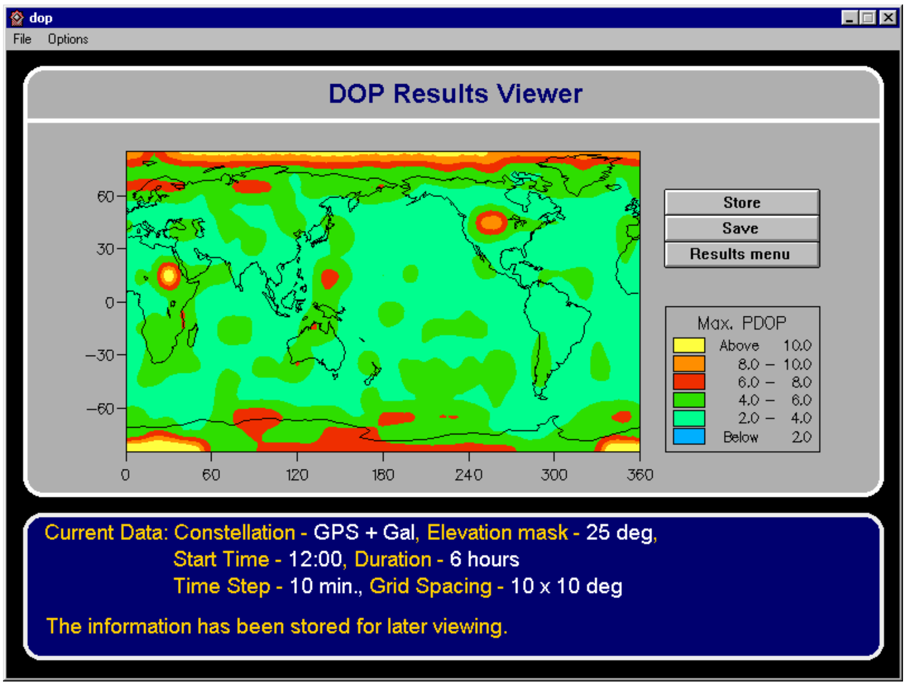

Figure 3: The Navigation Performance Tool.

4. Inertial Measurement Simulation

The GNSS simulator was extended to simulate inertial sensor measurements as part of the 'Low Cost Navigator Project'. The inertial sensor simulation is typically used to simulate measurements for an inertial measurement unit (IMU) consisting of three orthogonally mounted gyros and accelerometers. However, the simulator also allows definition of the nominal axes of the inertial sensors allowing for various configurations of inertial sensor assemblies. Figure 4 shows the algorithm used to simulate the inertial measurements.

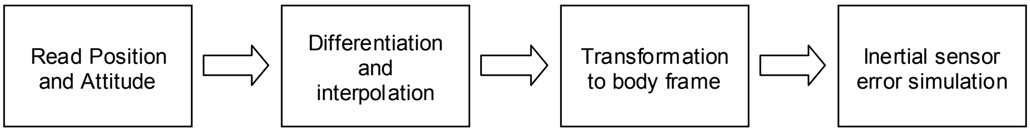

Figure 4 : Inertial measurement simulation algorithm.

The inertial sensor simulation routine is embedded into the main GNSS algorithm. This allows the inertial measurements to be simulated using the same trajectory as the GNSS observations. Therefore, in addition to the vehicle position and velocity in the input trajectory file, attitude is required in the form of roll, pitch and yaw for the simulation of the gyro measurements.

A key component in the simulation of inertial measurements is the algorithm used to interpolate and differentiate the position and attitude from the trajectory file. The data rate required for simulation of the inertial measurements is typically greater than 100Hz which means that interpolation is required to provide a smooth trajectory between the points provided in the trajectory file. The interpolation is achieved by fitting equations to the discrete position and attitude observations from the trajectory file, with the condition that the slope and curve at the adjoining equations is equal. This ensures that the interpolated curve is continuous. The single differentiation of the attitude and the double differentiation of the position required for simulation of the inertial measurements is achieved by differentiating the equations obtained from the interpolation stage. This ensures that no error is introduced by differentiating the trajectory input which would otherwise occur using numerical differentiation techniques.

The third stage in the inertial measurement simulation is the transformation of the interpolated acceleration and rotation rates into the body frame coordinate system of the inertial sensor. This is achieved using the direction cosine matrix formed using the interpolated attitude measurements. At this stage, the rotation rate of the Earth is added to the body frame angular rate measurements, and the Coriolis and gravity accelerations are added to the body frame acceleration. The effect due to the lever arm separation between the phase centre of the GNSS antenna and the origin of the IMU axes is also modelled.

The final stage of the simulation of the inertial measurements is the introduction of the inertial sensor measurement errors in the body frame. The models used for simulation of the gyro and accelerometer measurements are described by Figures 5 and 6. The figures show that the nominal axes can be defined for various inertial sensor assemblies. Misalignments in the sensor axes can also be modelled. Typical error sources that occur in inertial sensors are bias, scale factor and random noise. Other sensor error sources such as cross-axis sensitivity can also be modelled depending on the error characteristics of the sensor. Figures 5 and 6 describe one possible configuration for the simulation of an orthogonal triad of gyros and accelerometers. The figures also show that saturation (the maximum range of the sensor) and quantisation (the minimum resolution of a measurement, typically caused by the resolution of the sampling electronics) are also modelled. The output of the inertial measurement simulation is a tab-delimited file containing the measurement time and body frame gyro and accelerometer measurements.

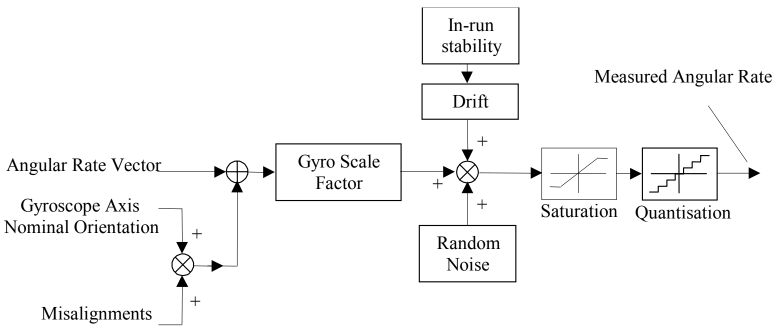

Figure 5 : Typical gyro simulation model.

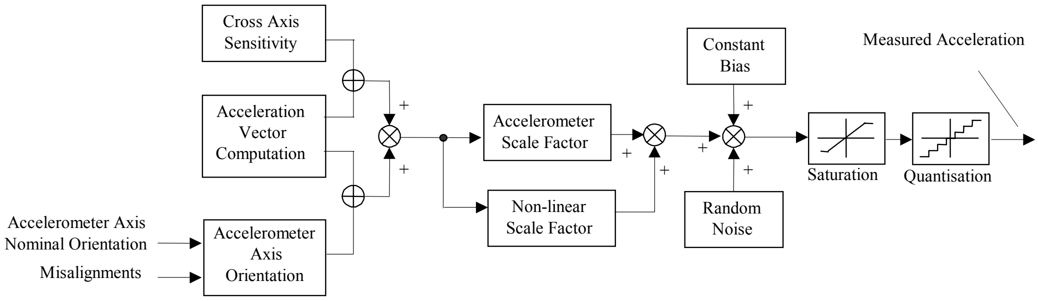

Figure 6 : Typical accelerometer simulation model

5. Integration of GNSS and INS measurements

A further tool under development at the IESSG is the integration software called KinPos^i. KinPos^i is based on the framework of the IESSG's existing GPS processing software called KinPos. KinPos provides differential processing of raw GPS pseudorange, carrier and Doppler observations using one or more reference stations. An important part of KinPos is the ability to resolve the carrier phase integer ambiguities on-the-fly. Resolution of the carrier phase ambiguities is performed using a two stage process. The first stage forms and solves the wide lane combination of double difference carrier phase ambiguities. The second stage uses the fixed wide lane ambiguities to reduce the number of ambiguity candidates for an L1 search. In both stages, the 'Lambda' [1] ambiguity search routine is used, which transforms the ambiguity observations to another search space, resulting in a decorrelation of the ambiguity sets. This gives a fast and efficient ambiguity search that is capable in many cases of resolving the carrier phase ambiguity in a single epoch. KinPos also provides kinematic processing using multiple reference stations for improved ambiguity resolution, error estimation and integrity.

In addition to processing GPS measurements, KinPos has recently been modified to process Galileo measurements and modernised GPS measurements as part of the Furlong project. KinPos provides a modular filter architecture that can be used to process different combinations of GPS, Galileo and combined GPS/Galileo measurements. This includes the ability to process measurements using a Three-carrier Ambiguity Resolution (TCAR) or Cascade Integer Resolution (CIR) algorithm where ambiguity resolution is achieved by forming an extra-widelane, widelane, then single frequency search (for more information see, for example [2]). The KinPos architecture is modular which provides a variety of processing strategies for analysis of the new types of measurements.

The framework of the KinPos software was used as the foundation for the development of the integrated GNSS and INS software package, KinPos^i. This means that KinPos^i inherits all of the kinematic processing capability of the KinPos software including the capability to process Galileo and modernised GPS observations.

Various levels of GNSS/INS integration are implemented in the KinPos^i software, the highest level of which is often termed tightly coupled integration. This means that the full advantage of the synergistic characteristics of the INS and GNSS systems is exploited. The structure of the tightly coupled algorithm is described in Figure 7. The figure shows that the inertial measurements are used to form the double difference range and range-rate observations for a single, centralised Kalman filter. Therefore, the inertial measurements are used to test and correct for cycle slips in the GPS carrier measurements, check the validity of the double difference observations and also reduce the linearity errors in the extended Kalman filter. Furthermore, the inertial measurements are used when resolving the carrier phase integer ambiguities which results in a faster time to fix the ambiguities after GPS outages. The range measurements can also be used to aid the inertial system when fewer than four satellites are available. Other levels of integration are also implemented in KinPos^i, including a decentralised filtering algorithm where the GPS and INS measurements are processed using two separate Kalman filters.

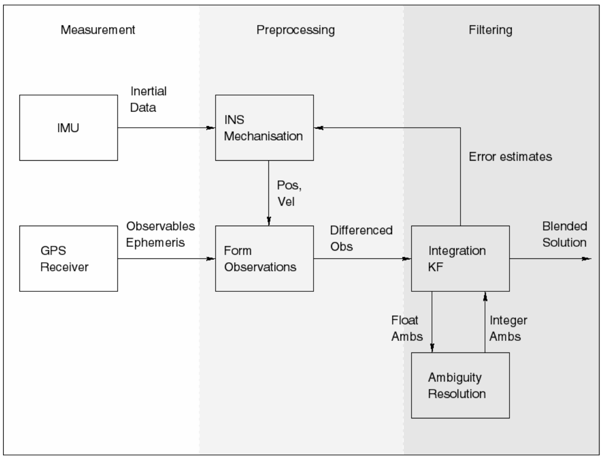

Figure 7 : Tightly coupled KinPosi integration architecture.

6. Testing the performance of an integrated GNSS/INS system using simulation

A key use of the GNSS/IMU data simulation is for testing the performance that can be expected from an integrated system when using different quality sensors, an example of which is shown in Figures 8 and 9. Figure 8 shows the effect of increasing the gyro scale factor errors on the estimation of the roll misalignment. The trajectory file used for the simulation was obtained from a marine vessel which for the first 150 seconds is operating in low dynamics. At 150 seconds, the vessel begins a figure-of-eight alignment type trajectory manoeuvre to aid the estimation of the yaw misalignment state in the integration filter. As a result, the gyro scale factors become observable due to the increased movement of the vessel. The figure shows the magnitude and error characteristic of the scale factor which is invaluable for selecting the correct sensor specification for a given application.

The same trajectory was used to obtain Figure 9 which shows the contribution of the gyro sensor axis misalignment on the roll accuracy. It should be noted that the scale factor and axis misalignment states were not estimated in the integration filter when obtaining these results. The figures do, however, show that simulation can be used to allow thorough investigation of various sensor error sources on the final navigation parameters. The GNSS/IMU simulator provides great flexibility for changing the error characteristics of individual sensors, which allows investigation to take place without the need for constructing different sensor assemblies and carrying out expensive trials. The simulator can also be used to model various dynamic conditions which is important as different dynamic environments require different sensor performance for integrated systems.

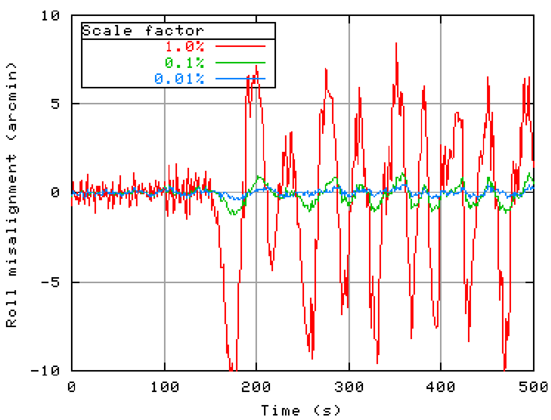

Figure 8 : Roll misalignment due to varying the gyro scale factor errors.

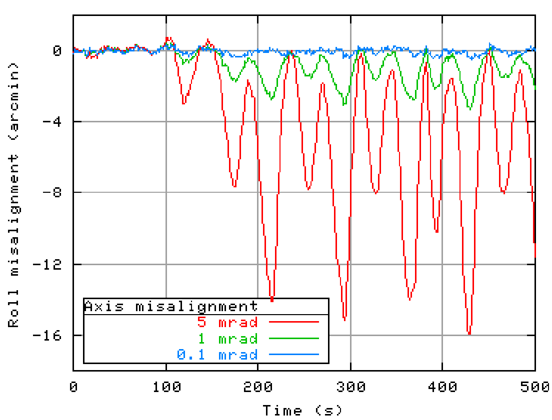

Figure 9 : Roll misalignment due to varying the gyro axis misalignment errors.

7. Development of an adaptive Kalman filtering algorithm using simulation

An important use of the combined GNSS/IMU measurement simulation is in developing and testing new integration algorithms. An example of this is the development at the IESSG of an adaptive Kalman filtering algorithm for GPS and a low cost INS integration.

The recent development of Micro-machined Electromechanical Sensors (MEMS) for mass fabrication of inertial instruments has resulted in the production of low cost inertial sensor assemblies. MEMS sensors were originally developed for automotive applications but the last decade has seen the increasing use of such technology in navigation applications due to the synergistic error characteristics of GPS and INS systems. For low cost sensors, the inertial sensor errors are significant and can vary significantly over time. Research into improving the estimation of inertial sensor errors at the IESSG resulted in the development of so called 'adaptive' Kalman filtering algorithms. The term 'adaptive' is used to describe the adjustment of the stochastic information used in the Kalman filtering algorithm using information contained in the Kalman filter innovation and residual sequences. The use of the measurement simulator software was a key stage in the development of such algorithms due to the ability to strictly control the inertial error characteristics and provide truth information, not only for navigation errors, but also for inertial sensor errors.

Figure 10 shows a typical use of data simulation to examine the ability of the integration filter to correctly resolve the sensor bias errors. The figure shows the Z-axis gyro bias state estimation for the conventional Kalman filter compared to the state estimation obtained from a bank of multiple Kalman filters running in parallel (this is termed Multiple Model Adaptive Estimation or MMAE). The figure shows that the adaptive filter is able to adjust the stochastic information used in the filter to identify the correct sensor bias estimate. Simulation is an invaluable tool for examining the ability to resolve sensor error sources. Further results using GNSS/IMU measurement simulation are provided in [3].

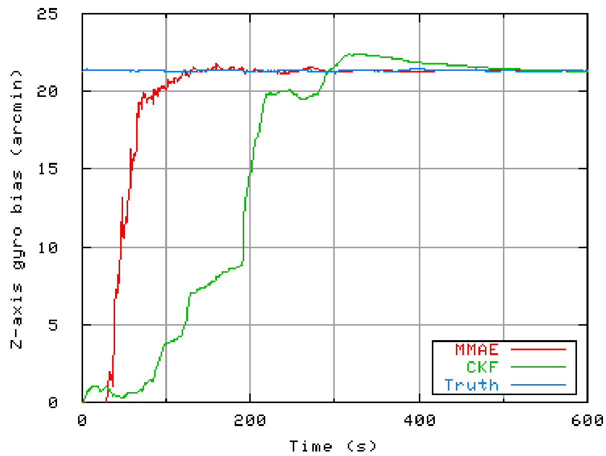

Figure 10 : Z-axis gyro bias error estimation using conventional Kalman filtering and mutiple model adaptive estimation.

8. The 'Low-cost Navigator' project

The measurement simulator has an important role in researching new navigation systems and has already been used in a number of internal and contract research projects, most notably the ESA-funded 'Low-Cost Navigator' project. The aim of this project was develop a low-cost, high performance product through the combination of a GPS receiver and an IMU consisting of three accelerometers and three gyroscopes. To achieve this requires a good selection of the components, integration scheme and processing methods. Simulation of the sensors aids the refinement and optimisation of the baseline design and demonstrates the viability of the project objectives, giving confidence in their achievement. Several test scenarios have been simulated, showing the performance levels achievable using different grades of sensors under different dynamic conditions. Sensitivity tests were also conducted, where the effects on the overall navigation solution of improvements/degradations to specific aspects of the sensors were investigated. The drifts, biases, scale factors, noise and sampling rates of the accelerometers and gyroscopes were analysed in turn. These tests resulted in the identification of specific areas where improvements could be made to optimise the navigation performance.

9. Conclusions

The simulator has been developed and applied to a number of projects for a variety of uses. Its potential application in research has not been fully exploited. The use of the simulator as a teaching tool is also being pursued and it is already being used on Masters level modules in the Institute.

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