

# THE USE OF SIMULATION TO TEACH AERIAL TRIANGULATION WITH GPS AND IMU MEASUREMENTS

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### ABSTRACT:

The Institute of Engineering Surveying and Space Geodesy (IESSG) at the University of Nottingham, UK has developed a number of simulators which have been used on a number of commercial and research projects. They are also playing an ever greater role as teaching tools at undergraduate and masters level. This paper presents some of the key packages developed and used by the IESSG over the last 10 years as well as a more detailed explanation about our more recent aerial triangulation / in-flight GPS/IMU simulator (including examples and student results).

## 1. INTRODUCTION

For many years the Institute of Engineering Surveying and Space Geodesy (IESSG) at the University of Nottingham has been using simulators of various kinds in its research activities. There are many advantages of using simulators. Simulated data can provide early opportunities for researching new equipment or procedures. The analysis through simulation of a potential measurement process can provide confidence before full commitment is made to invest. Simulators can enable a new computational technique to be assessed with controlled error budgets enabling the testing and optimising of new algorithms.

The IESSG is also aware of the exciting uses and powerful benefits that simulators can bring to teaching. Simulators can develop skills and knowledge of the processes as well as an appreciation of the quality of the process and results that can be achieved.

In October 2001 the IESSG started a new MSc course in Satellite Positioning Technology. As part of this course we have a module on integrated systems. For sometime, we have been researching the use of GPS and IMU measurements integrated with aerial photography and line scanner imagery. This provides us with an excellent example of how sensors can be successfully integrated. We therefore decided that the students learning experience would be considerably enhanced if they could work with a simulator to investigate different photographic scenarios and different qualities of GPS and IMU. In the new academic session the simulator has provided a new and exciting approach to teaching.

In this paper we present case studies exploring two of our current research driven simulators (Section 2.1) and two of our existing teaching-related simulators (Section 2.2). Section 3.1 then introduces our new simulation suite designed to aid in the teaching of aerial triangulation (both traditional and including the input from a range of GPS/IMU sensors) with actual results from undergraduate, Masters and Doctoral students presented in

Section 3.2 Section 4 summarises our findings and conclusions.

## 2. EXISTING SIMULATION FACILITIES

### 2.1 Research-driven Simulation at IESSG

The IESSG already utilises a range of software simulation within its varied research portfolio. Some of these have been developed in-house by successive Masters and Doctoral level students, others have been initiated by contract research from industry or institutions such as the European Space Agency. In this section, case studies are presented of just two of our simulators, the ESA funded GalileoSat simulator facility and the BNSC funded integrated GPS-Galileo-Communications facility (FURLONG)

**The GalileoSat System Simulation Facility (GSSF)** project is a contract funded by the European Space Agency (ESA) to produce an end-to-end software simulation of Europe's planned 'Galileo' satellite navigation system. It will model all of the components of the future system, from the satellites themselves, to the ground segment that will control them and the user receivers that will navigate with their signals.

As part of the VEGA-led team working on the study, the IESSG is acting as a consultant on technical aspects of satellite navigation and specific modelling details. The IESSG's role is to provide definitions of suitable simulation and modelling algorithms, with the necessary algorithm description, sample source code where necessary, and test data. The IESSG is also responsible for the validation of the software, which will provide the necessary proof that GSSF produces the correct results.

One of the future aims of GSSF is to be able to replace software components of the system with real hardware - a so-called hardware-in-the-loop design. For instance, early versions of GSSF will simulate a Galileo user receiver in software, but later versions may wish to replace the software receiver with a

prototype hardware version. This requires that the simulation models are as true to life as can practicably be achieved. The project is currently in Phase 2, in which the main effort is to refine the models incorporated in the Phase 1 release, to ensure high fidelity modelling.

**The FURLONG Simulation Facility:** The British National Space Centre funded Future Real-time Location and Navigation study (FURLONG) was concerned with simulating the signals of future satellite positioning systems (the proposed European Galileo system and the Modernised GPS) in order to assess the precision and reliability of future real time positioning services. It based this work on research and practical modelling efforts undertaken by three United Kingdom based organisations that are at the forefront of this application domain; namely the IESSG, SciSys Ltd, and the UK's Centre for Ecology and Hydrology.

During the study the IESSG Navigation System Simulator (see Section 2.3 below) has been further developed to include Galileo signals and those of the modernised GPS. In addition a detailed environmental model has been developed which simulates both difficult and challenging environments, including such factors as terrain and building signal obscuration and multi-path. There was also a need to advance the development of new processing algorithms and tools to process these new GNSS observables in a dynamic, and often difficult, simulated environment.

A further key development within FURLONG was the communication emulator which includes GSM networks (2G), GPRS networks (2.5G), and UMTS networks (3G). In the case of the 3G emulation, care was taken to adjust the operational parameters to allow for T-UMTS operation, S-UMTS operation and combined S/T-UMTS operation. In every case the aim was to emulate the performance of the communications system as perceived by an ordinary user with bandwidth (both nominal and degraded due to adverse location), propagation delays, hand-over glitches, dropouts and data congestion all modelled.

## 2.2 Simulation in Teaching

Gaining experience of methods, techniques, and practical applications can play a major role in the learning process. Analysing these experiences often leads to significant understanding of all aspects of a subject from fundamental principles through to advanced applications. To provide significant amounts of such experience in a one-week intensive teaching block, which is the module staff contact time on our Masters level courses, is not practicable. Likewise it is not feasible to provide everyone with equipment, often expensive, and the practical scenarios to enable them to undertake tasks outside of the one-week teaching blocks. For a number of years, therefore, we have been exploring how best to create, develop and utilise a range of simulators and emulators for computer-based learning. The main technologies to be simulated have been GPS and IMUs as described in the following sections.

**The GPS Computer Aided Learning (CAL) Facility:** Our involvement in the development of simulations for teaching is not just a recent event. During the mid-90's the IESSG developed a series of Computer Aided Learning (CAL) Tools related to various aspects of surveying. At the time, the drivers were much as they are today eg an improved student learning environment, greater control of learning, the development of an exciting and interesting environment and alternative methods of learning. Positive feedback from both undergraduate and postgraduate students was received over a period of years with clear messages emphasising how the CAL packages improved teaching, complemented lectures, increased awareness before practicals and allowed a more efficient use of resources.

**IMU Simulation Facility:** The IESSG has internally developed a MathCAD based IMU simulator which is used very successfully within a number of our teaching and research activities. One particularly popular exercise involves the Master's level students designing a navigation solution for use by an autonomous robot on the moon.

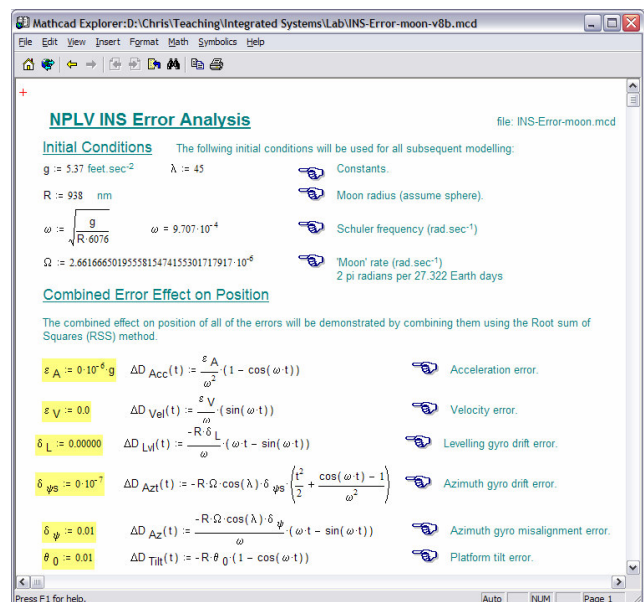


Figure 1 – INS Simulation Teaching Tool Screen Shot

The intuitive mix of education, assistance and calculations within the package (see Figures 1 and 2) enables the students to explore a range of performance characteristics including acceleration error, azimuth gyro drift, levelling gyro drift and velocity error, never forgetting critical issues such as the Schuler Period on the Moon's surface and the impact of the Lunar environment ("Moon rate") on the Azimuth Misalignment and Azimuth Gyro Drift terms!

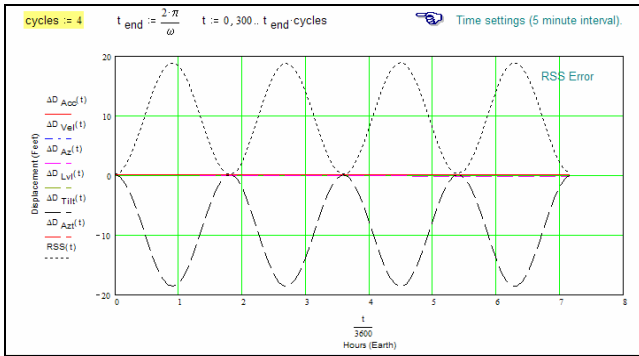


Figure 2 - INS Simulation Teaching Tool Screen Shot

### 2.3 IESSG's GPS/IMU Simulator

Over the last 15 years the IESSG has independently developed a GNSS simulator that enables measurements to be generated and procedures and capabilities to be assessed. This has provided research opportunities that would not otherwise have been available.

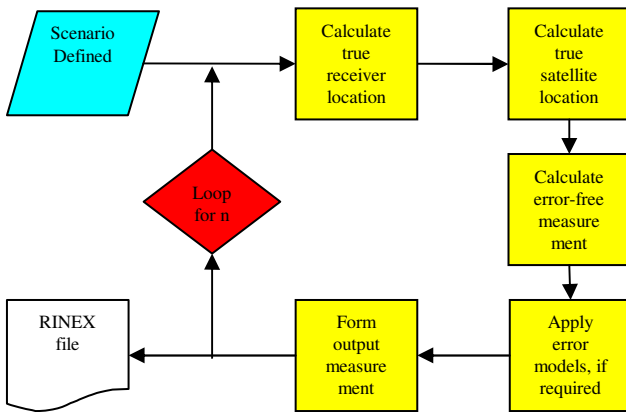


Figure 3 - Schematic of the GNSS data simulation process

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.

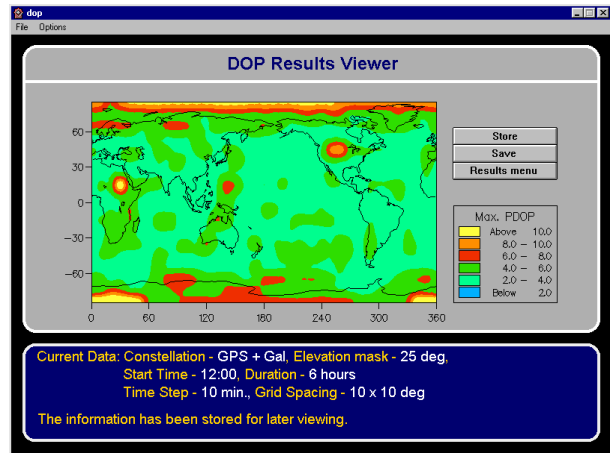


Figure 4 - IESSG's Navigation Performance Tool

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.

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.

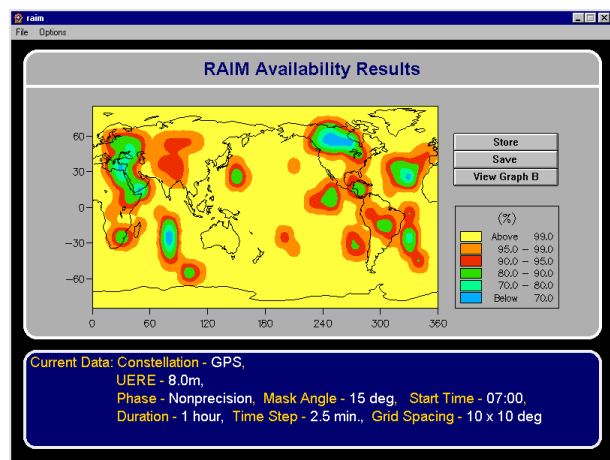


Figure 5 - IESSG's RAIM Analysis Tool

## 2 IESSG's Aerial Triangulation Simulator - SIMAT2

### 2.1 Background

SIMAT2 is a research program that simulates all the data required to complete an aerial triangulation including:

- Ground Control Points
- Photo Points
- In-flight GPS
- In-flight IMU

The user can define all relevant parameters at run time including:

- Number of photos

- Number of strips
- Flying Height / Photo Scale
- Amount of overlap between photos/strips (fore/side)
- Camera focal length
- Accuracy of photo point observations
- Accuracy of ground control point observation
- Accuracy of in-flight GPS
- Accuracy of in-flight IMU
- Weights for the “observations” (ground control points, photo points, in-flight GPS and in-flight IMU) to be used within the bundle adjustment program 3DB.

The SIMAT2 output is a series of files in the format required by the IESSG’s in-house bundle adjustment program 3DB.

## 2.2 So How Does it Work?

SIMAT2 consists of a series of 8 sub-routines (which are invisible to the user at run time); Figure 6 graphically describes the flow within the SIMAT2 program.

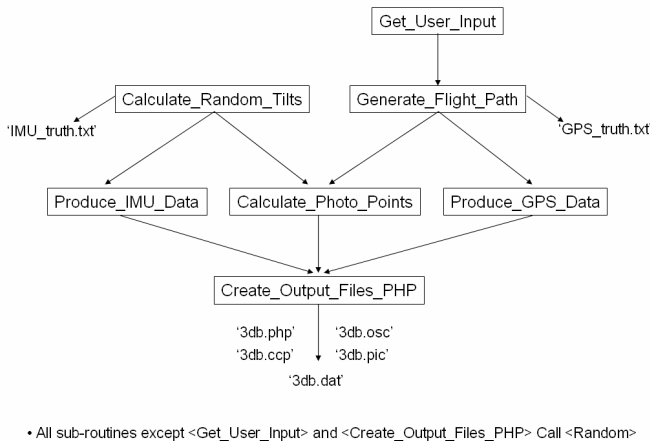


Figure 6 – SIMAT2 Program Flow

**Subroutine Get\_User\_Input:** (see Figure 7) read file ‘user\_input.txt’; store user defined parameters for use in later subroutines including:

- X coordinate of the centre of the first photo (any real number)
- Y coordinate of the centre of the first photo (any real number)
- Direction of the first flight line (0 – 360 degrees)
- Number of photos per strip (integer)
- Number of strips (integer)
- Amount of Forward Overlap (as a percentage)
- Amount of Sidelap (as a percentage)
- Flying Height (in metres)
- Camera principal distance

**Subroutine Generate\_Flight\_Path:** Generates a ‘perfect’ flight path based upon user inputs. Points created for each photo include:

- Photo’s Footprint on the ground (4 corners)
- The location of 4 Fiducial Marks (diagonally in from Corners) on the ground
- 3 Ground Control Points (down the centre of the photo)

All ground points are aligned with user defined flight direction (if number of strips > 1 it is assumed that consecutive strips are parallel to, and flown in the opposite direction to the previous strip). The centre of Photo 1 is at user defined X, Y coordinates. Terrain is assumed flat and at 100m, although user has an option to add random terrain variation to all points (user inputs value in metres which is sent as input to sub-routine <Random> with mean = 100).

**Subroutine Calculate\_Random\_Tilts:** Gives user the option to have either no tilt on photos (‘vertical truth’) or create a file of random levels of tilt that will be applied to all photos in later sub-routines. If tilt is not zero, user may define the 1 standard deviation figure in degrees (eg 3 degrees). This is sent as input to sub-routine <Random> with mean = 0.

**Subroutine Produce\_IMU\_Data:** Random tilts from <Calculate\_Random\_Tilts> are taken as the ‘true’ IMU reading at each photo centre. User then has the option to blur this truth by the addition of random, user-defined errors (to recreate the effect of different quality inertial measurement systems) to produce the  $\omega$ ,  $\phi$ ,  $\kappa$  data that is used in the bundle adjustment. User is also asked to provide the value of standard error to be used in the relevant bundle adjustment input file.

**Subroutine Produce\_GPS\_Data:** The ground coordinates of the centre GCP in each photo (principal point) are taken as the ‘true’  $X_0$ ,  $Y_0$  GPS values. The ‘true’  $Z_0$  GPS value is calculated as the user defined flying height + 100m. User then has the option to blur this truth by the addition of random, user-defined errors (to recreate the effect of different quality GPS measurement systems) to produce the  $X_0$ ,  $Y_0$ ,  $Z_0$  data that is used in the bundle adjustment. The user is also asked to provide the value of standard error to be used in the relevant bundle adjustment input file.

**Subroutine Calculate\_Photo\_Points:** Uses collinearity equations to calculate complete array of photo points given that details of all ground control points,  $X_0$ ,  $Y_0$ ,  $Z_0$ ,  $\omega$ ,  $\phi$ ,  $\kappa$  are known (generated /calculated in previous sub-routines). Clearly, the values used to create the photo points are the ‘true’ (ie no artificial errors added) values from <Generate\_Flight\_Path> and <Calculate\_Random\_Tilts>. The subroutine then compares the location within the image of each ground control point and the four corners of the photo and determines (given the specific tilts of each photo) which ground control points would actually be visible in the image. This subroutine also allows the user to define an observation error ( $\sigma$ , between 1 and 20  $\mu$ m) on all photo point observations.

**Subroutine Create\_Output\_Files\_PHP:** This final subroutine creates all the output files ready for use by the in-house bundle adjustment program 3DB4 (based on previous subroutines) including:

- GPS data and IMU data (including random ‘observation’ errors) plus user defined weights.
- Observations of Ground Control Points.
- Observations of photo points.
- Information on the number of cameras, photos, ground control points, and photo points.
- The camera focal length (no other camera parameters are modelled currently in SIMAT2 although this would be easy to implement if required)

The screenshot shows the SIMAT2 software window with the title 'SIMAT2' and menu options 'Edit View Help'. The main heading is 'Create Simulated Data + Bundle Adjustment' with a sub-note: 'Either leave default settings or enter new values'. The interface is divided into two columns: 'Photo Parameters' and 'Control and Observations'. Each parameter is represented by a text input field with a numerical value and a range in parentheses. At the bottom, there are four buttons: 'Confirm Data', 'Simulate Mission', 'Filter GCPs?', and 'Complete Solution'.

Photo Parameters		Control and Observations	
Number of Photos	10 (2 - 20)	Photo Point Observation Error	5 (microns)
Number of Strips	3 (1 - 3)	GCP Observation Error	0.05 (metres)
Forward Overlap	60 (20 - 60)	X co-ordinate of First Photo	1000 (metres)
Side Overlap	20 (10 - 60)	Y co-ordinate of First Photo	2000 (metres)
Focal Length	0.1524 (metres)	Direction of First Flight Line	90 (degrees)
Flying Height	1520 (metres)	In-flight GPS - 1st Position Error	0.05 (metres)
Photo Scale	10000 (250 - 50000)	In-flight GPS 'Weight'	0.1 (metres)
Photo Tilt	3 (0 - 3 degrees)	In-flight IMU - 1st Angular Error	0.001 (degrees)
Terrain Variation	25 (metres)	In-flight IMU 'Weight'	0.005 (degrees)

Figure 7 – SIMAT2 Screen Shot – User Data Input

**Subroutine Random:** At the start of the simulation process, this sub-routines generates an array of 100,000 pseudo-random numbers (x) with user-defined mean (m) and standard deviation (s) using a “sum of uniform deviates tactic”. This data is heavily used by the other sub-routines in the generation of random errors.

### 2.3 Postgraduate Results

Image orientation is a key element in any photogrammetric project, and this task has been exclusively and very successfully solved using traditional aerial triangulation for many years. More recently a great deal of theoretical and practical research and development has allowed a combination of in-flight GPS and IMU observations to directly determine exterior orientation parameters and/or provide additional observations in the aerial triangulation bundle adjustment.

During 2002-3, one of the students studying for an MSc in Geodetic Surveying at the IESSG carried out a project to investigate the quality and accuracy available from traditional Aerial triangulation, GPS/IMU observations assisted aerial triangulation and GPS/IMU direct exterior orientation. As the main indicator/metric, residuals for each ground point were derived from the discrepancy between the final estimated ground coordinates calculated in the triangulation and the initial coordinates calculated from the simulation.

In each series of tests, four simulated sets of observation data were used: image point observations, ground control point observations, GPS antenna phase centre position observations and IMU observations. The importance of ground control points and the quality and (potential) impact of directly measured exterior orientation parameters were examined for a series of different “flights” including a short, single strip of between 5 and 20 photos, and blocks varying in size from 2 photos by 5, to 3 photos by 20. Within each “flight”, further experiments explored the effect of additional observations from GPS/IMU on the aerial triangulation solution via three configurations of ground control: three ground control points in each photo, 4 ground control points (in the corners of the block of photos) and no ground control points.

The resulting solutions were internally statistically assessed, and also compared to real boresight data (including GPS/IMU output from an Applanix POS-AV system, ground control data, and aerial triangulation solutions) provided courtesy of Simmonds Aerofilms, UK. Very pleasingly, the simulation was found to accurately model the real world with the simulated Simmonds mission producing statistically identical results to the actual results.

The simulation suite is now being further utilised and developed by a PhD student as part of their work in the area of “The Future of Aerial Triangulation”.

### 3 CONCLUSIONS

The IESSG has developed a number of simulators which have not only been used on a number of commercial and research projects but are playing an ever greater role as teaching tools at undergraduate and masters level.

In this paper we have presented a brief summary of some of the key packages developed and used over the last 10 years as well as a more detailed explanation about our more recent aerial triangulation / in-flight GPS/IMU simulator (including examples and student results).

Feedback about the use of simulation in teaching has remained very positive over the last 10 years, although it is perhaps not surprising to note that students consistently prefer access to a (full time?!) real person to guide and assist over a computer-based simulation. However, the simulation(s) are almost always preferred to a textbook-based approach to teaching and learning.

Further details on all of the simulators, facilities and projects described in this paper may be obtained by contacting the IESSG.

### 4 ACKNOWLEDGEMENTS

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