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GARDSim - "A GPS Receiver Simulation Environment for Integrated Navigation System Development and Analysis"

ABSTRACT: Airservices Australia has recently proposed the use of a Ground-based Regional Augmentation System (GRAS) to improve the safety of using the NAVSTAR Global Positioning System (GPS) in aviation. The GRAS Airborne Receiver Development project (GARD) is being conducted by QUT in conjunction with Airservices Australia and GPSat Systems. The aim of the project is to further enhance the safety and reliability of GPS and GRAS by incorporating smart sensor technology including advanced GPS signal processing and Micro-Electro-Mechanical-Sensor (MEMS) based inertial components.

GARDSim is a GPS and GRAS receiver simulation environment which has been developed for algorithm development and analysis in the GARD project. GARDSim is capable of simulating any flight path using a given aeroplane flight model, simulating various GPS, GRAS and inertial system measurements and performing high integrity navigation solutions for the flight. This paper discusses the architecture and capabilities of GARDSim. Simulation results will be presented to demonstrate the usefulness of GARDSim as a simulation environment for algorithm development and evaluation.

KEYWORDS: Aviation, GNSS, GPS, GRAS, Inertial MEMS, Integrity.

Introduction

The Global Positioning System (GPS) is a navigation system being increasingly used for aviation. One of the major limitations of GPS for aviation user's is that it does not provide adequate integrity monitoring of its navigation solution. Navigation integrity is *"the ability of a system to provide timely warnings to users when the system should not be used for navigation"* [1]. To overcome this limitation, Airservices Australia has proposed the use of an additional system called the Ground-based Regional Augmentation System (GRAS). The GRAS system will comprise of a network of ground-stations that continuously check the integrity of the GPS system and transmit this information to aviation users. To further enhance the safety and reliability of GPS and GRAS, low-cost smart-sensor integration technologies are being developed at QUT to augment the GPS and provide high-integrity navigation for General Aviation (GA) users.

The GRAS Airborne Receiver Development project (GARD) is being conducted in conjunction with Airservices Australia and GPSat Systems, and comprises two PhD students. The aim of the project is to develop new GPS platforms utilising the GRAS technology for GA and incorporating smart sensor technology including advanced GPS signal processing and Micro-Electro-Mechanical-Sensor (MEMS) based inertial components.

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Early in the project, a requirement was identified to develop a sophisticated simulation environment to enable the simulation and analysis of GARD system components in a laboratory environment. This has resulted in the development of GARDSim. GARDSim is a MATLAB-based software simulation package which was developed for the purpose of developing and evaluating new algorithms for improving GPS integrity, through the use of GRAS and MEMS technology.

GARDSim incorporates aircraft flight planning and flight modelling tools, a Receiver Autonomous Integrity Monitoring (RAIM) prediction and analysis tool, generation of inertial system measurements, atmospheric modelling, GPS antenna modelling, and GPS measurement modelling. The development of GARDSim followed a modular approach, which provides a highly configurable simulation environment for new algorithm development.

Brief Theoretical Introduction to GPS and INS

GPS Navigation Solution

The Global Positioning System consists of a constellation of 24 satellites (nominal) which constantly orbit the earth. These satellites continuously broadcast signals to earth which a GPS receiver can use to calculate a navigation solution. With four or more range and range-rate measurements made between the receiver and satellites, three-dimensional position coordinates, three-dimensional velocity coordinates, and the time (receiver clock bias and drift) for the receiver can be calculated.

The receiver measures the range to each satellite by measuring the time of travel of the signal. The range is obtained by multiplying by the velocity, c, the speed of light.

$$Range = c(Ttx - Trx) \tag{1}$$

(1)

Where:

Ttx is the time of transmission of the signal from the satellite; and
Trx is the time of reception of the signal at the receiver.

What is measured is not the true range from the satellite to the receiver but a pseudo-range. This is the true range between the satellite and receiver with errors. Some of these errors are due to the uncertainty in knowing the satellite's true position, delays incorporated onto the signal during its propagation from satellite to user, and errors which are related to the receiver user equipment itself.

The main sources of error are [2]:

- GPS Satellite
  - Satellite clock – the atomic clocks on the GPS satellites have a bias and drift.
  - Ephemeris – the error in the receiver's estimation of the satellite orbit and clock estimates.

- Signal Propagation Effects - Atmosphere effects play a large role in these types of errors.
  - Ionospheric – caused by the region in the atmosphere where ionised particles and 'free electrons' degrade the signal.
  - Tropospheric – caused by refraction of the signal due to 'dry atmosphere' and water vapour in the tropospheric region of the Earth's atmosphere.

- Local Receiver Effects
  - Receiver clock – the GPS receiver's clock is typically a cheap crystal oscillator which has a certain clock bias and drift.
  - Multipath – caused by reflections off objects near to the receiver antenna.
  - Receiver Noise – Introduced noise due to the receiver hardware and software processes. This includes the precision to which a receiver can make measurements and other effects caused by hardware.

As shown in the figure below, a receiver makes at least four range measurements to each satellite. The true range or geometric range between satellite and receiver is indicated by ρ in figure 1.

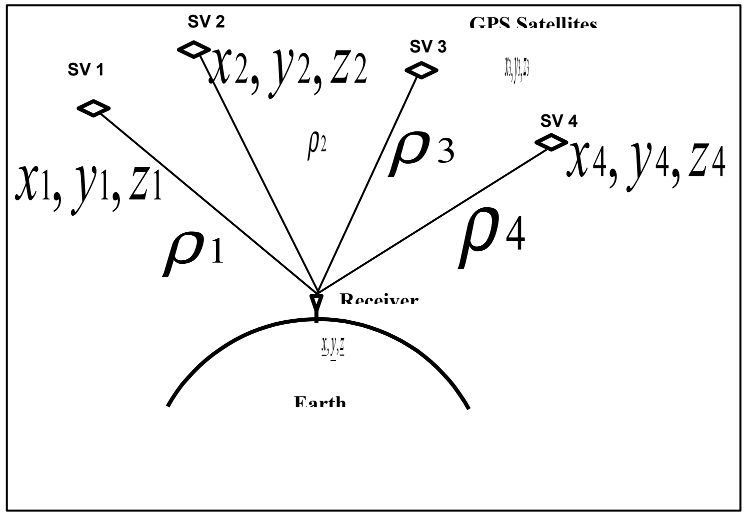

FIG. 1: GPS Positioning

For each satellite the geometric range between satellite and receiver is given by:

$$\rho = \sqrt{(x_s - \underline{x})^2 + (y_s - \underline{y})^2 + (z_s - \underline{z})^2} \quad (2)$$

Where,

x_s, y_s, z_s are the coordinates of the GPS satellite,

$\underline{x}, \underline{y}, \underline{z}$ are the coordinates of the GPS receiver.

The pseudo-range for receiver 'r' and satellite 's' is given by:

$$PR_r^S(t) = \rho_r^S(t) + c(dt_r(t) - dT^S(t)) + \varepsilon mp_r^s(t) + \varepsilon bias_r^s(t) + dion_r^s(t) + dtrop_r^s(t) \quad (3)$$

Where,

ρ is the geometric range between satellite and receiver [m].
c is the speed of light [m/s].
dt is the receiver clock error [s].
dT is the satellite clock error [s].
ε_{mp} is multipath error [m].
ε_{bias} is other error sources including receiver noise [m].

d_{ion} is ionospheric delay [m].
d_{trop} is tropospheric delay [m].

Inertial Measurements

One of the traditional methods of providing integrity to a GPS receiver is to integrate the GPS navigation solution with an inertial navigation solution. Inertial navigation is the process of determining a vehicle's position and velocity by measuring its acceleration with respect to an inertial reference frame. The basic inertial measurements available are specific force (the forces experienced by the vehicle), and rotation rate of the vehicle with respect to the inertial frame [3, 4].

The inertial navigation equation is given by Equation 4.

$$\left.\frac{d\overline{V}}{dt}\right|_N = \overline{u} - (\overline{\omega} + \overline{\Omega}) \times \overline{V} + \overline{g} \tag{4}$$

Where

V is the vehicle velocity;
u is the acceleration measurement vector in the locally-level navigation frame;
g is the local gravity vector;
ω is the inertial angular rate vector of the navigation frame;
Ω is the inertial angular rate of the earth;

Accurate knowledge of the vehicle attitude is required to resolve the acceleration measurements in the vehicle body frame to the locally-level navigation frame. Equation 4 is solved by integrating the vehicle acceleration to velocity, and then velocity to position as the vehicle moves around the earth. Due to the integration process, small errors build up over time, and thus the navigation errors in a stand-alone navigation system are unbounded. For this reason, inertial navigation systems are commonly integrated with supplemental navigation systems, such as GPS to provide an overall high performance navigation system.

Due to the high noise of low-cost MEMS inertial sensors, this technique does not yield high enough performance for extended periods of navigation using traditional techniques. One of the aspects the GARD project will examine is whether or not improved integrity can be achieved without using a full inertial navigation system mechanisation, thus taking advantage of the lower cost MEMS components.

Architecture

GARDSim is developed in MATLAB which is a high-level programming language ideal for performing computationally intensive tasks quickly. The architecture of GARDSim consists of three main parts. These are the Planning module, Core Run-time modules and Output modules as shown in Figure 2. There is also the Input Configuration, Support Functions, Simulation Data and Results, and Simulation Output parts. The planning module simulates GPS or INS measurements within the airborne environment, the core run-time module simulates the operation of the GPS or INS system within the airborne environment, and the output modules are for outputting the results. It can be seen there are no direct links between the Planning, Core Run and Output modules. Each module obtains whatever data it needs from a storage area of all the data. This collection is called the Simulation Data in Figure 2. This is to enable logging of all variables used throughout the simulation for later analysis. It also allows easier accessibility and interchange-ability of the various functions.

System errors can be simulated within the planning module as external effects (such as atmospheric errors degrading the signal), or in the core run-time module as GPS or INS anomalies (GPS clock or accelerometer failure for example).

It must be noted that GARDSim does not seek to model GPS and INS systems at the hardware level, but seeks to simulate the sensor outputs. What is most relevant to the research is how errors impact the navigation solution and how integrity monitoring can be improved through the development of new algorithms utilising GPS, GRAS and MEMS-INS technologies.

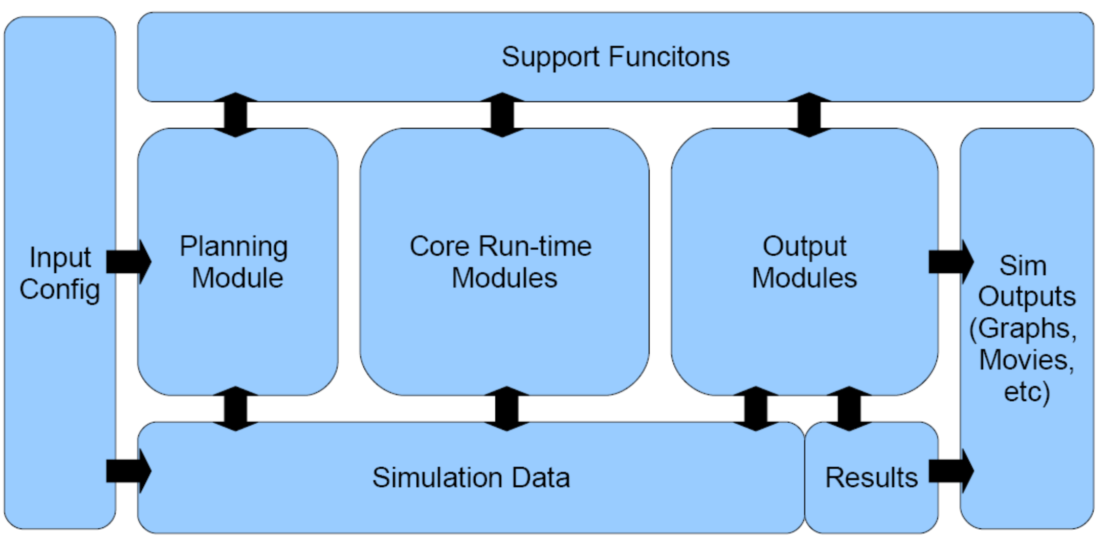

FIG. 2: GARDSim Architecture

GARDSim Capabilities

GARDSim is able to perform a number of functions to simulate an individual GPS or INS or combined GPS-INS platform in an airborne environment. This is most useful to the research in the system and algorithm development and testing processes. The following highlights a number of these capabilities.

GPS Navigation Solution

GARDSim can calculate a GPS navigation solution for both real measurements and simulated measurements at the same time. Real measurements from a GPS receiver can be imported into GARDSim. This allows for direct comparison between real and simulated data.

Receiver Autonomous Integrity Monitoring (RAIM) prediction and analysis

GARDSim allows the detection of faults of a GPS or GPS/INS navigation solution. This incorporates the exclusion of detected faults to allow navigation to continue, otherwise known as Fault Detection and Exclusion (FDE). A RAIM method has been implemented based upon the pseudodange residual method [5]. A parity method has also been implemented as an alternative [6]. GARDSim can be used to make a prediction of the availability of GPS integrity monitoring during a flight. It can also be used for integrity analysis of post-processed real flight data.

Error generation

GARDSim allows specific errors to be generated at any point in the simulation, to simulate certain events. Such examples are bad clocks on the satellite or receiver, severe atmospheric effects and sudden loss of satellite lock.

Flight Path and Inertial Measurements Simulation

A major part of the planning module is the Flight Simulation component. This component incorporates the AeroSim block-set by Unmanned Dynamics LLC. This is a library which provides components for development of nonlinear 6-Degree-of-freedom aircraft dynamic models. This allows for the simulation of any flight path, and provides simulated INS measurements.

Error Modelling

Errors which affect the GPS receiver are modelled as outlined below. Currently, the clock and atmospheric (ionospheric) models are the two main error models implemented in GARDSim. The modelled errors are primarily used in the generation of simulated pseudo-range measurements. The modelled errors also serve as ‘truth’ data for the errors. Truth data is very useful for evaluating the performance of error prediction models within the simulation environment.

Clock Modelling

A two-state GPS clock error model has been implemented according to [2, 3]. This clock model is used to simulate a GPS receiver clock bias and drift. This model is based upon available clock instability measures for real clocks. A standard crystal oscillator clock error model is currently implemented in GARDSim.

Atmospheric modelling

Currently, the atmospheric modelling component of GARDSim consists of simulating what the true ionospheric delay would be on a given day. To achieve this, ionospheric Total Electron Count (TEC) maps are used. When the user applies the ionospheric correction model provided by GPS ephemeris data, a residual between the modelled ionospheric state and the true ionospheric state will exist.

The TEC maps are obtained from the International GNSS Service (IGS), which is a collection of more than 200 worldwide bodies which collect data and generate precise GNSS products. The specific product used is the Final Ionospheric TEC Grid data, which provides world-wide vertical TEC values (VTEC), and is available with a latency of approximately 11 days.

The range delay is calculated by multiplying the slant TEC value (the TEC experienced by the satellite signal) by a liner delay relationship of 16.2cm per TEC unit. Thus, the simulation must determine the slant TEC value which is applicable to the given satellite measurement. Firstly, the simulator calculates the ionospheric pierce point (IPP) with respect to the user's true position. The VTEC is taken from the TEC Map value for the IPP. Finally, the VTEC value is converted to a slant TEC (STEC) value as a function of the satellite elevation and user position.

Simulated Pseudo-range Generation

GARDSim simulates GPS pseudo-ranges by calculating the geometric range from the satellite positions to the user's true position, and adding various errors from the clock and atmospheric models to simulate the environment. This is done according to Equations (2) and (3) above. The above-mentioned clock and atmospheric models are the two main error models currently implemented in GARDSim. These are also the major contributors to GPS position solution accuracy degradation and have received the most attention so far in GARDSim's development. The simulated pseudo-ranges currently include the following errors:

- GPS Satellite
    - Satellite clock – obtained from available IGS precise ephemeris data.
    - Ephemeris – not included.

- Signal Propagation Effects
    - Ionospheric – modelled.
    - Tropospheric – not included.

- Local Receiver Effects
    - Receiver clock – modelled using the GARDSim two-state clock model.

- Multipath – not included.
- Receiver Noise – modelled as a measurement precision value in the simulated pseudo-range calculation.

From this, Equation (3) is modified to give the simulated pseudo-range equation currently used in GARDSim:

$$PR_r^s Simulated(t) = \rho_r^s(t) + c(dt_r(t) - dT^s(t)) + \varepsilon bias_r^s(t) + dion_r^s(t)) \quad (5)$$

Where,

ρ is the geometric range between satellite and receiver [m].
c is the speed of light [m/s].
dt is the receiver clock error [s].
dT is the satellite clock error [s].
ε_{bias} is other error sources including receiver noise [m].
d_{ion} is ionospheric delay [m].

Ongoing and Future Capabilities

As GARDSim is modified and changes according to the needs of the research, it is expected to be extended to include the following capabilities.

GPS Antenna Modelling

The antenna modelling component of GARDSim is intended to model the effects of antenna masking due to variations in the aircraft's attitude.

The antenna gain pattern of a common aviation GPS antenna is shown in figure 3. The general pattern shows peak gain along the antenna bore-sight, decreasing down to almost zero perpendicular to the bore-sight. Gain variation grows large at high off-bore-sight angles and some side lobes are present on the underside of the antenna.

Typically the antenna is mounted on the roof of the cabin area of the aircraft, or on top of the tail cone towards the back of the aircraft. In any case, the orientation of the antenna is dependant on the roll and pitch angles of the aircraft, which can affect satellite signal reception when the aircraft is maneuvering. Under normal conditions, pitch angles can vary between ±10° and roll angles between ±30°.

A receiver mask angle of 7.5° is normally applied to limit the effects of high pseudo-range noise due to the longer signal path length at low elevation angles. When the aircraft banks, the effective receive area of the antenna is reduced by the bank angle, as shown in figure 3.

By modelling the receiver antenna gain pattern, GARDSim can simulate the effects of loss of satellite measurements due to aircraft manoeuvres, and improve the overall integrity of the simulation.

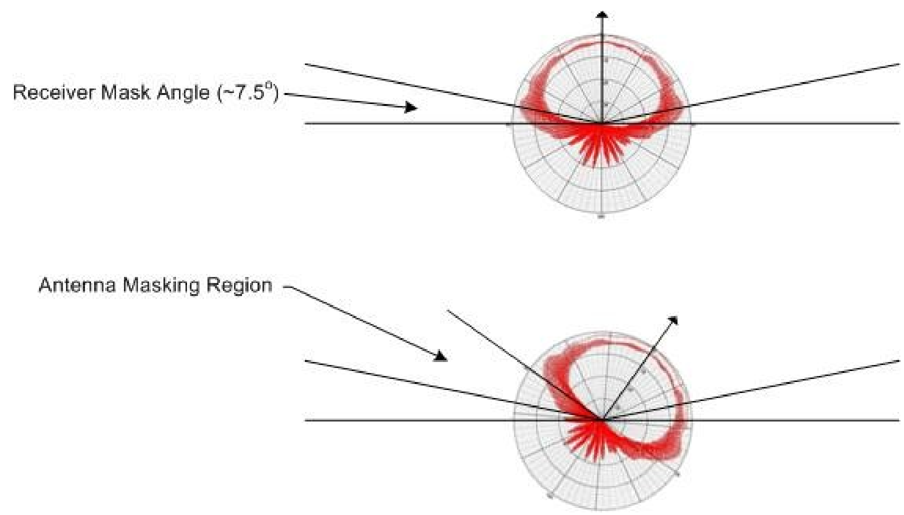

FIG. 3: Antenna Modelling Geometry. The upper plot shows the aircraft in straight-and-level flight. The lower plot shows the aircraft in a bank to the right and its effect on the receiver gain pattern.

MEMS Sensor Modelling

An important aspect of GARDSim is the generation of realistic sensor measurements. Most of the work to date has focused on the development of adequate GPS error models for the generation of realistic GPS measurements for use in the simulation. GARDSim is also required to generate realistic inertial sensor measurements.

An inertial sensor is one which measures the motion of a body with respect to inertial space according to Newtonian physics. Inertial sensors include accelerometers and gyroscopes, of which there are a number of different sensor classes. GARDSim focuses on the simulation of low-cost inertial sensor based on micro-machining technology. This class of sensor is usually termed Micro-Electro-Mechanical Sensors (MEMS).

MEMS inertial sensors typically have very high levels of bias and noise compared to their more expensive mechanical counterparts. However, MEMS sensors are much cheaper to produce, use less power, are lighter and in some cases more durable than other sensors.

Atmospheric Modelling

GARDSim's currently implemented atmospheric modelling will be further enhanced with the inclusion of a tropospheric model and an improved ionospheric model.

Aircraft Flight Data Integration

It is intended to incorporate real aircraft flight data into GARDSim. This will further enhance the capability of GARDSim to be able to use real flight data.

GRAS Integration

It is intended to incorporate GRAS and other augmentation system's data into GARDSim. The inclusion of such things as ground station locations and signal propagation models are future GARDSim capabilities which are being considered.

Results

Closed Loop GPS Simulation

This section presents the results from a closed loop GPS Simulation. This simulation utilises the flight model and pseudo-range simulation components of GARDSim.

Firstly, an arbitrary flight path is generated using the GARDSim Flight Model component. The flight path is stored as the 'true' state of the aircraft throughout the simulation time.

The next component reads in the aircraft true flight path, plus information regarding the true state of the GPS constellation and other environmental parameters such as the state of the ionosphere. This information is used to generate simulated pseudo-range measurements that are analogous to those collected by GPS receiver hardware. The simulated pseudo-range measurements are constructed according to Equation (5) above.

The final component of the simulation takes in the simulated pseudo-range measurements, plus GPS information that is available to a normal GPS receiver and performs a least-squares GPS position solution.

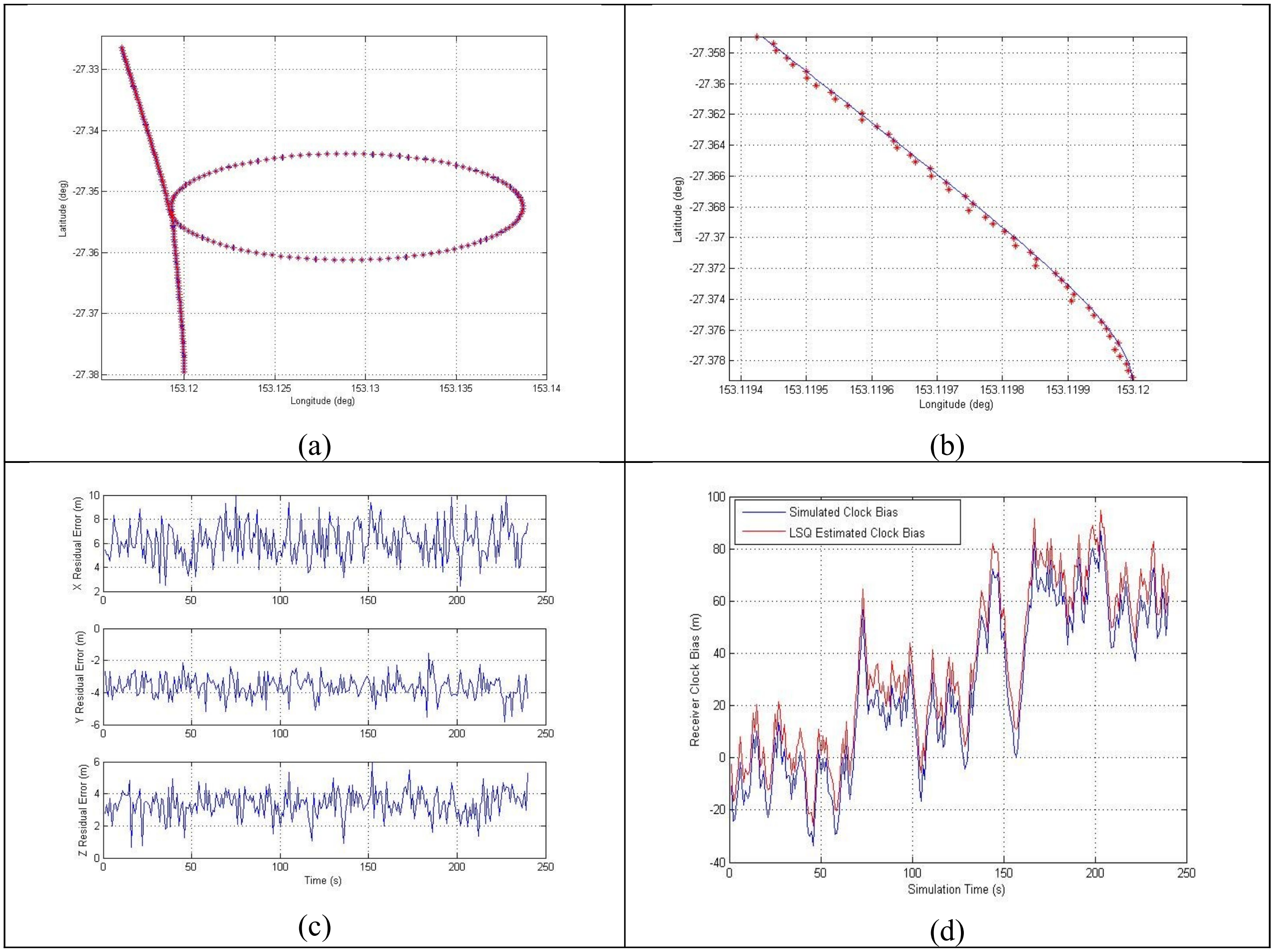

FIG. 4: (a) The simulated flight path (blue) overlayed with the simulated GPS position solutions (red). (b) A close-up view of a portion of the flight path showing the variation between the simulated (blue) and calculated (red) positions. (c) The residual errors in ECEF Cartesian coordinates of the GPS position solution. (d) Simulated (blue) and estimated (red) receiver clock bias from the GPS position solution.

The results show that the process outlined above works very well for the simulation of GPS pseudo-range measurements, and subsequent position solution for an arbitrary simulated flight path.

The residual error from the receiver clock bias estimate contains errors including residual ionospheric delay and receiver measurement precision and residual noise. No other error sources, such as multipath delay, are being simulated. The error statistics of the position solution are shown in Table 1.

TABLE 1: Statistics of Simulated Position Solution

Mean	Standard Deviation

E<x>	6.074 m	σ_x	1.388 m
E<y>	-3.635 m	σ_y	0.605 m
E<z>	4.405 m	σ_z	0.872 m

The behaviour of the position solution from the Least-Squares algorithm is quite realistic. For a basic comparison with published commercial GPS receiver performance specifications, the Circular Error Probability (CEP) for the data in Table 1 is calculated as 1.17 metres. This is the radius of a circle that encompasses 50% of the navigation errors [2]. The CEP for a standard single frequency commercially available receiver (the Novatel Superstar II) is given as less than 5 metres typical [7]. A more prestigious Novatel OEM-4 receiver's CEP is 1.8 m [7]. This shows that the simulation environment gives values which are comparative and perhaps somewhat improved to existing commercial GPS receiver performance specifications. It is not expected that the results be identical because not all GPS errors are modelled in the simulation, nor is GARDSim configured to model any particular GPS receiver type. In addition, only 250 seconds of data is considered in this comparison. These would account for the simulation environment CEP being the lowest. Following future enhancements to GARDSim, it is intended that the simulated position solution accuracy will follow more closely the expected performance of a real GPS receiver in the airborne environment. Furthermore, GARDSim's error models can always be adjusted to simulate different GPS receiver's to suit the intending application.

Conclusion

GARDSim has been presented as a useful platform for future algorithm development for this type of research. The modular structure of GARDSim allows for the further integration of other technological aspects should they be required. It is intended that GARDSim will be further refined and developed as research in the GARD project at QUT progresses. GARDSim itself will become a useful tool for future research in these areas.

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