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GNSSim: An Open Source GNSS/GPS Framework for Unmanned Aerial Vehicular Network Simulation

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Unmanned systems are of great importance in accomplishing tasks where human lives are at risk. These systems are being deployed in tasks that are time-consuming, expensive or inconclusive if accomplished by human intervention. Design, development and testing of such vehicles using actual hardware could be quite costly and dangerous. Another issue is the limited outdoor usage permitted by Federal Aviation Administration regulations, which makes outdoor testing difficult. An optimal solution to this problem is to have a simulation environment where different operational scenarios, newly developed models, etc., can be studied. In this paper, we propose GNSSim, a Global Navigation Satellite System (GNSS) simulation framework. We demonstrate its effectiveness by integrating it with UAVSim. This allows users to experiment easily by adjusting different satellite as well as UAV parameters. Related tests and evidence of the correctness of the implementation are presented.

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1. Introduction

The remarkable growth in mobility and location-aware vehicles, as well as related applications, have led to increased use of such vehicles in almost every domain. Mostly operations in these areas pose a risk to human lives due to the unknown nature of the terrain, weather or other environmental factors. One of the most popular class of vehicles under this category is unmanned aerial vehicles, UAVs. These systems can be sent to distant or inaccessible planetary bodies for research (e.g., Philae aircraft landed on a comet after a 10 year journey [1]) or to detect and monitor real-time catastrophes like earthquake [2] and forest fires [3]. UAVs have found their use in applications like agricultural chemical deployment [4], ecological surveys [5], natural event monitoring (Hurricane Hunter [6]), disaster management [7] and humanitarian response (e.g., damage assessment, search and rescue operations, dropping relief supplies in case of emergency [8]), 3-D Mapping and photogrammetry [9], wildlife protection [10], etc.

In early 2015, commercial UAVs were authorized to fly in US National Airspace (NAS) by Federal Aviation Administration (FAA). More than 7500 UAVs are expected to be seen in the air by 2020 due to this authorization, compared to the number being negligible in 2014 [6]. Even today, FAA does not require people to obtain license for small and mini-UAVs which are used for recreational purpose while limiting the usage up to a height of 400 ft. and away from airport and air traffic [11]. These new laws and availability of low-cost mini-UAVs and Do-It-Yourself (DIY) drones have promoted individual use as well as research in industries and academia. Constructing a drone is nowadays possible within as less as $300 by purchasing separate parts from online stores [12]. Clearly, incorrect or failure in accurate navigation may lead to dangerous and life-threatening accidents for medium-sized UAVs and thus, necessitates prior testing of a model in a simulation environment.

1.1. Role of Navigation

A navigation module is one of the most critical components of location and mobility-aware vehicles

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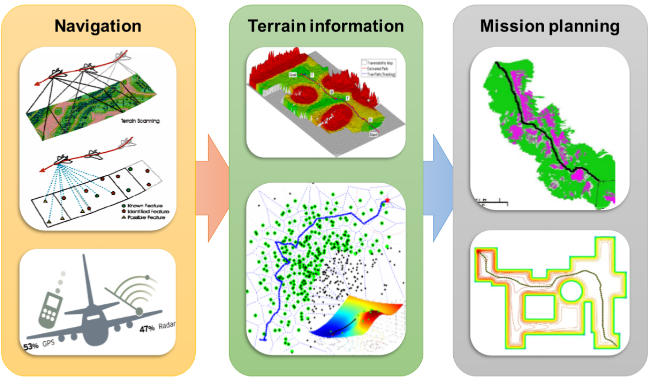


Figure 1. Role of navigation in UAV operations

and has become a necessary part of any vehicular simulation. Navigation serves as the operator's eyes and ears in any unknown terrain. Be it an aircraft, a ship, a car or any other vehicle, navigation allows the vehicle to move around in an area accurately, avoiding any mishaps. In military operations, accurate navigation serves as a necessary intelligence in the mission area and ensures the safety of all involved. Aircraft, Gunship and UAV operators already suffer from stress and performance pressure due to the responsibility of human lives. Accurate and reliable navigation data reduces mission related anxiety, impact on their mental health and optimal operational performance of the team [13]. Figure 1 depicts the role of navigation in such critical UAV operations.

1.2. Problem Statement

This paper focuses on developing a GNSS simulation framework for the location and mobility-aware vehicular networks. Such a framework should allow any navigation system simulation including GPS, GLONASS, Galileo, and BeiDou. Simultaneously, a need was felt for an accurate and inexpensive GNSS simulation framework for unmanned vehicular networks in academia. Previously proposed UAVSim addressed this concern partially as it lacked any navigation related simulation capability [14]. Therefore, an independent GNSS/GPS simulation framework was designed, which can be used in UAVSim as well as with other OMNeT++ based vehicular network simulations. In this paper, we are using GPS to demonstrate the navigation functionality. Therefore, all the discussion from here onwards may refer to GPS and GNSS interchangeably.

The primary component of such a module is its GPS unit that allows it to be location and mobility aware. It also helps the UAV during different preset navigation modes, such as position hold, return-to-home, autonomous flight and object avoidance [15]. Depending on the area in which the UAV is deployed, GPS can be used to link data to its spatial position (geo-referencing). GPS signals are typically very weak, less than 100W and are transmitted over a range of $20 - 25,000$ kilometers. This makes them fall below the noise floor spectrum when they reach the earth's surface [16]. These signals are vulnerable to failure, disruption and interference from unintentional or deliberate sources. The increased dependency of UAVs on GPS signals for localization, navigation and time-synchronization has made it a focus area for adversaries. This shift of adversary focus led to the discovery of its vulnerabilities to attacks like Spoofing and Jamming. Accurate modeling of UAV along with GPS and related navigational aspects is very critical for accurate vehicular network simulations.

To sum up, the following technical contributions have been made in this paper:

- An OMNeT++ framework incorporating real GPS satellite and weather data have been developed. It enables users to capture both the real characteristics of unmanned aerial vehicle mobility and address the complexity of aerial pathways.
- Both the Satellite-end GPS signal transmitter and vehicle-end GPS signal receiver have been implemented using standard trilateration equations. This receiver can be used in OMNeT++ for simulation as a component of any mobile node.
- Extensive simulation studies have been performed to reveal the achievable performance of the simulation framework using a wide range of important parameters. Most importantly, we have investigated the impact of the various mobility models, the angle of motion, and speed. These studies prove the correctness of the proposed framework.

The rest of the paper comprises of five sections. We discuss related work in the area of GNSS simulation framework development in Section 2 while Section 3 gives a brief overview of GPS and presents our implementation of GNSS/GPS. Section 4 presents the design, architecture and operation of the framework when combined with the UAV simulation testbed UAVSim. Section 5 presents the simulation analysis and results, and the paper is finally concluded in Section 6.

2. Related Work

This section discusses the work that has been done in the area of GPS simulation for UAV Networks. Much work is deemed out of scope as they primarily focus on modeling of a single UAV in a closed lab or an open but controlled environment to improve the system performance, flight range, and usability. A lack of close-to-real simulation of a UAV

Table 1. Comparison of software based GPS simulators

Simulator	GNSS Type	Language	Visualization	Vehicular Network Simulation Capability
GSSF	Galileo, GPS	C++	Yes	No
SNACS	Supports All	C++/MATLAB	Yes	No
Open-SESSAME	Supports All	C++	Yes	No

network (UAVNet) including UAVs, Satellites, and Ground Control Stations (GCS) was also noticed. An ideal testbed should allow inter and intra-component communication, and component level behavioral analysis. We present a classification of these existing simulators based on the presence of GPS implementation as well as few independent GPS simulators.

2.1. UAV Simulators with GPS

A visual 3*D* flight simulation software based on MATLAB and Simulink was an early attempt towards simulating a UAV, which used the navigation module of FlightGear [17]. FlightGear provides a generic GPS support where GPS receivers are yet to be implemented [18]. Another Java-based project called UAV Playground used FlightGear to receive GPS data and implemented GPS tracking in Google Earth [19]. In industry, the aeronautical division of IDS Corporation has implemented an unmanned aerial vehicle simulator Hero UAVSim [20] composed of ground control stations (GCS) [21], a UAV Simulator and a sensor payload simulator [22]. The UAV Simulator has GPS-based auto tracking capability and GPS outage mitigation measures while GCS has an integrated GPS receiver to determine its actual position.

2.2. Independent Hardware based GPS Simulators

Several hardware based GNSS simulators are available for purchase through various manufacturers. In academia, researchers tend to incline towards open source solutions rather than expensive hardware based solutions. Nonetheless, a few popular ones have been discussed here. The LabSat simulator is a low-cost hardware based simulator and provides selection options such as GPS, GLONASS, Beidou, and Galileo [23]. It generates genuine navigation signals that can be stored, replayed and used in different applications. Spirent implements several similar hardware, e.g., GSS9000 multi-frequency, multi-GNSS RF constellation simulator for professional, controllable and repeatable testing in the lab [24]. A GPS simulator by National Instruments (NI) can produce GPS signals of up to 12 satellites and is aimed at testing GPS receivers [25]. Many other simulators such as IFEN Inc. NavX-NCS Professional/Essential, CAST Navigation SGX GPS Satellite Simulator, AeroFlex Portable GPS/Galileo/SBAS Positional Simulator GPSG-1000, etc., also simulate GPS and GNSS but differ with respect to the range of signals produced and constellation implemented. All these devices are quite expensive and could not be considered as low-cost for a UAV simulation testbed developed in an academic setup.

2.3. Independent Software based GPS Simulators

Very few researchers have developed pure software-based GNSS simulators. There are few simulators available for purchase too, but we our focus lies in open source solutions. GSSF, SNACS, and Open-SESSAME were the top-three in this category. Table 1 gives a brief comparative analysis of these three software based simulators. Galileo System Simulation Facility (GSSF) is focused on the Galileo navigation system [26]. Implemented in C++, it provides a simulation for longer time periods and large geographical area coverage. It provides raw Galileo and GPS signal generation, express mode simulation, and good functionality to analyze and visualize data. Another work, Satellite Navigation Radio Channel Signal Simulator (SNACS), is a single GNSS satellite signal generator [27]. It is open source and implemented in C++ with parallel processing. Its radio channel input and simulation results can be analyzed in MATLAB. Open-SESSAME (Open-Source, Extensible Spacecraft Simulation and Modeling Environment framework) is another popular simulator that provides dynamics simulation for spacecrafts for developing hardware as well as testing flight algorithms [28]. Based on C++, it provides attitude and orbit modeling along with features of orbit simulation, space environment assessment or control algorithm validation. One of the biggest limitations of all these simulators is the unavailability of any interfacing with any network simulation software to enable vehicular network simulation.

2.4. OS3

As mentioned earlier, most hardware based simulators were found to be quite expensive while software based simulators were not compatible with any vehicular network simulation platform. A candidate solution to this problem was found as OMNET++ based OS3 (Open Source Satellite Simulator) [29, 30]. OS3 provides a

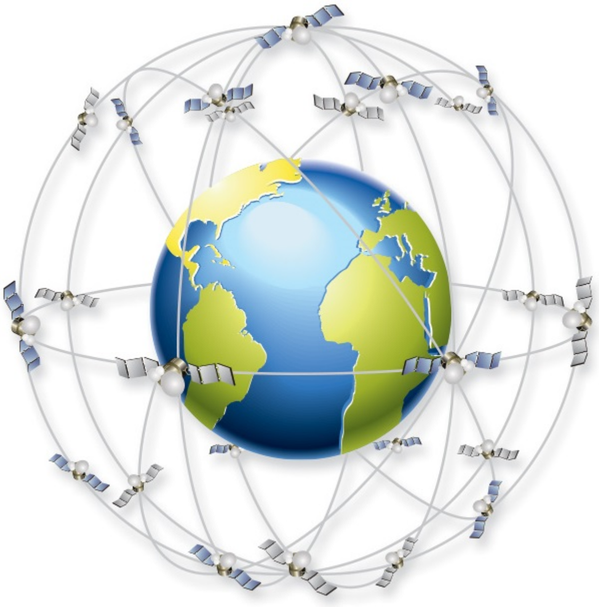


Figure 2. Global Positioning System (GPS) requires a minimum of 24 satellites [31]

generic satellite constellation that seamlessly integrates real satellite tracks and weather data to simulate different conditions along with good visualization. The limitation here was the unavailability of any satellite communication for the implementation of a working GNSS. Nonetheless, the implementation of a highly accurate and stable satellite model and movement in OS3 provided a good base for the development of GNSSim. Being platform independent, OS3 can be deployed easily on any system.

3. GNSS/GPS Overview

In this section, we will briefly introduce GNSS and how the positioning works in a GPS receiver.

3.1. GNSS/GPS Basics

A system of satellites that provides autonomous geo-spatial positioning with global coverage is termed as Global Navigation Satellite System (GNSS). Currently, the GPS and the Russian GLONASS are the only GNSS supporting global coverage. Other prospective GNSSs are BeiDou of China and Galileo of Europe [27]. Any GNSS has three operational segments - the space segment, the ground/control segment, and the user segment.

A working global navigation solution is easily possible with 24 satellites located in six orbital planes as shown in Figure 2 [31]. To improve the accuracy of GPS, its space segment was designed to have 31 satellites. These satellites complete two revolutions around the earth in one day. A GPS satellite sends two ranging codes: C/A, used for public usage, and Precision code, used by the military. The signal consists of GPS data and time, ephemeris data and the almanac. The ground/control segment consists of ground stations that track the GPS satellites, monitor their transmissions, analyze their performance, and send commands and control information to the constellation. The ground network consists of one master control station, one alternate master station, 12 command and control antennas, and 16 monitoring sites. The end-user antenna and GPS receiver make the user segment that receives and calculates the position, velocity and time based on the data from the GPS Satellite. The receiver has to acquire and maintain the lock on four satellites to get its accurate position in the 3*D* space [32].

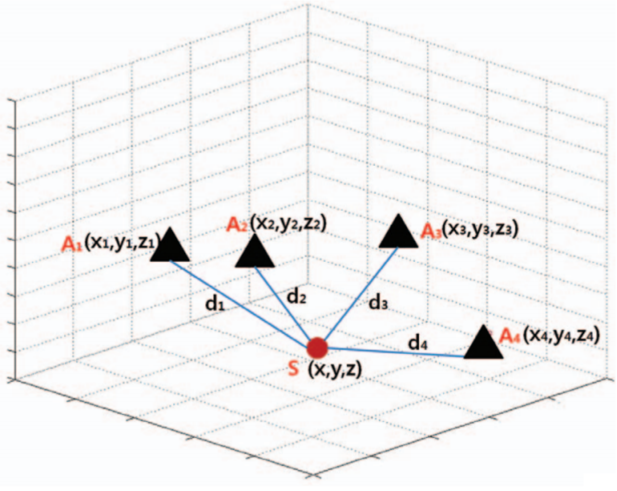


Figure 3. 3D trilatateration [33]

3.2. Position Calculation

A GPS receiver calculates its position by using a method called Trilateration which is shown in Figure 3. Many trilateration algorithms have been proposed to determine location accurately. The most widely accepted mathematical expressions to calculate a position in 2*D* and 3*D* are discussed here [33].

3*D* multi-lateration uses the following standard equations.

$$2\cdot(x_2 - x_1)\cdot x + 2\cdot(y_2 - y_1)\cdot y + 2\cdot(z_2 - z_1)\cdot z = \alpha$$

$$2\cdot(x_3 - x_1)\cdot x + 2\cdot(y_3 - y)\cdot y + 2\cdot(z_3 - z)\cdot z = \beta$$

$$2\cdot(x_4 - x_1)\cdot x + 2\cdot(y_4 - y)\cdot y + 2\cdot(z_3 - z)\cdot z = \gamma$$

where

$$\alpha = (d_1^2 - d_2^2) - (x_1^2 - x_2^2) - (y_1^2 - y_2^2) - (z_1^2 - z_2^2)$$

$$\beta = (d_1^2 - d_3^2) - (x_1^2 - x_3^2) - (y_1^2 - y_3^2) - (z_1^2 - z_3^2)$$

$$\gamma = (d_1^2 - d_3^2) - (x_1^2 - x_3^2) - (y_1^2 - y_3^2) - (z_1^2 - z_3^2)$$

By solving the following matrix based equations, we get the value of (x, y, z) in $3D$ space.

$$x = f(d_1, d_2, d_3, d_4) = \frac{\begin{vmatrix} \alpha & 2Y_1^2 & 2Z_1^2 \\ \beta & 2Y_1^3 & 2Z_1^3 \\ \gamma & 2Y_1^4 & 2Z_1^4 \end{vmatrix}}{\begin{vmatrix} 2X_1^2 & 2Y_1^2 & 2Z_1^2 \\ 2X_1^3 & 2Y_1^3 & 2Z_1^3 \\ 2X_1^4 & 2Y_1^4 & 2Z_1^4 \end{vmatrix}}$$

$$y = g(d_1, d_2, d_3, d_4) = \frac{\begin{vmatrix} 2X_1^2 & \alpha & 2Z_1^2 \\ 2X_1^3 & \beta & 2Z_1^3 \\ 2X_1^4 & \gamma & 2Z_1^4 \end{vmatrix}}{\begin{vmatrix} 2X_1^2 & 2Y_1^2 & 2Z_1^2 \\ 2X_1^3 & 2Y_1^3 & 2Z_1^3 \\ 2X_1^4 & 2Y_1^4 & 2Z_1^4 \end{vmatrix}}$$

$$y = g(d_1, d_2, d_3, d_4) = \frac{\begin{vmatrix} 2X_1^2 & 2Y_1^2 & \alpha \\ 2X_1^3 & 2Y_1^3 & \beta \\ 2X_1^4 & 2Y_1^4 & \gamma \end{vmatrix}}{\begin{vmatrix} 2X_1^2 & 2Y_1^2 & 2Z_1^2 \\ 2X_1^3 & 2Y_1^3 & 2Z_1^3 \\ 2X_1^4 & 2Y_1^4 & 2Z_1^4 \end{vmatrix}}$$

where $X_i{}^j$, $Y_i{}^j$ and $Z_i{}^j$ are referred to as $(x_i - x_j)$, $(y_i - y_j)$ and $(z_i - z_j)$, respectively.

Similarly, in $2D$, which is a trilateration method, the position of an object can be determined by solving the following equations:

$$(x - x_1)^2 + (y - y_1)^2 = (d_1)^2$$
$$(x - x_2)^2 + (y - y_2)^2 = (d_2)^2$$
$$(x - x_3)^2 + (y - y_3)^2 = (d_3)^2$$

The equations are converted to linear equations by subtraction and substitution:

$$2 \cdot (x_2 - x_1) \cdot x + 2 \cdot (y_2 - y_1) \cdot y = \alpha$$

$$2 \cdot (x_3 - x_1) \cdot x + 2 \cdot (y_3 - y_1) \cdot y = \beta$$

where

$$\alpha = (d_1^2 - d_2^2) - (x_1^2 - x_2^2) - (y_1^2 - y_2^2)$$
$$\beta = (d_1^2 - d_3^2) - (x_1^2 - x_3^2) - (y_1^2 - y_3^2)$$

Finally, the position (x, y) is obtained by solving the following matrix operations:

$$x = f(d_1, d_2, d_3) = \frac{\begin{vmatrix} \alpha & 2Y_1^2 \\ \beta & 2Y_1^3 \end{vmatrix}}{\begin{vmatrix} 2X_1^2 & 2Y_1^2 \\ 2X_1^3 & 2Y_1^3 \end{vmatrix}}$$

$$y = g(d_1, d_2, d_3) = \frac{\begin{vmatrix} 2X_1^2 & \alpha \\ 2X_1^3 & \beta \end{vmatrix}}{\begin{vmatrix} 2X_1^2 & 2Y_1^2 \\ 2X_1^3 & 2Y_1^3 \end{vmatrix}}$$

where $X_i{}^j$ and $Y_i{}^j$ are referred to as $(x_i - x_j)$ and $(y_i - y_j)$, respectively.

4. GNSS Framework Design

A very common and major limitation of most satellite simulation software, except OS3, is the difficulty in their integration with other network simulators like OMNET++, NS-2, etc. To fulfill our primary aim of developing a GNSS framework for vehicular network simulation, we chose OS3 due to its base simulation engine of OMNeT++ and the availability of satellite mobility models. OS3 implements a generic satellite constellation and uses a TLE (Two-Line Element) format file for fetching initial positions of various satellites being used for simulation. Depending upon which Navigation System TLE file we use, that specific navigation system can be simulated. As an example, we can use a TLE file containing data of 31 GPS satellites to simulate GPS while we can use a TLE file containing data of 30 Galileo satellites to simulate the Galileo Navigation System. It provides an accurate satellite movement simulation with live weather data, high-resolution altitude data, different visualization options, etc. The comparison of these existing satellite frameworks has been done in [29].

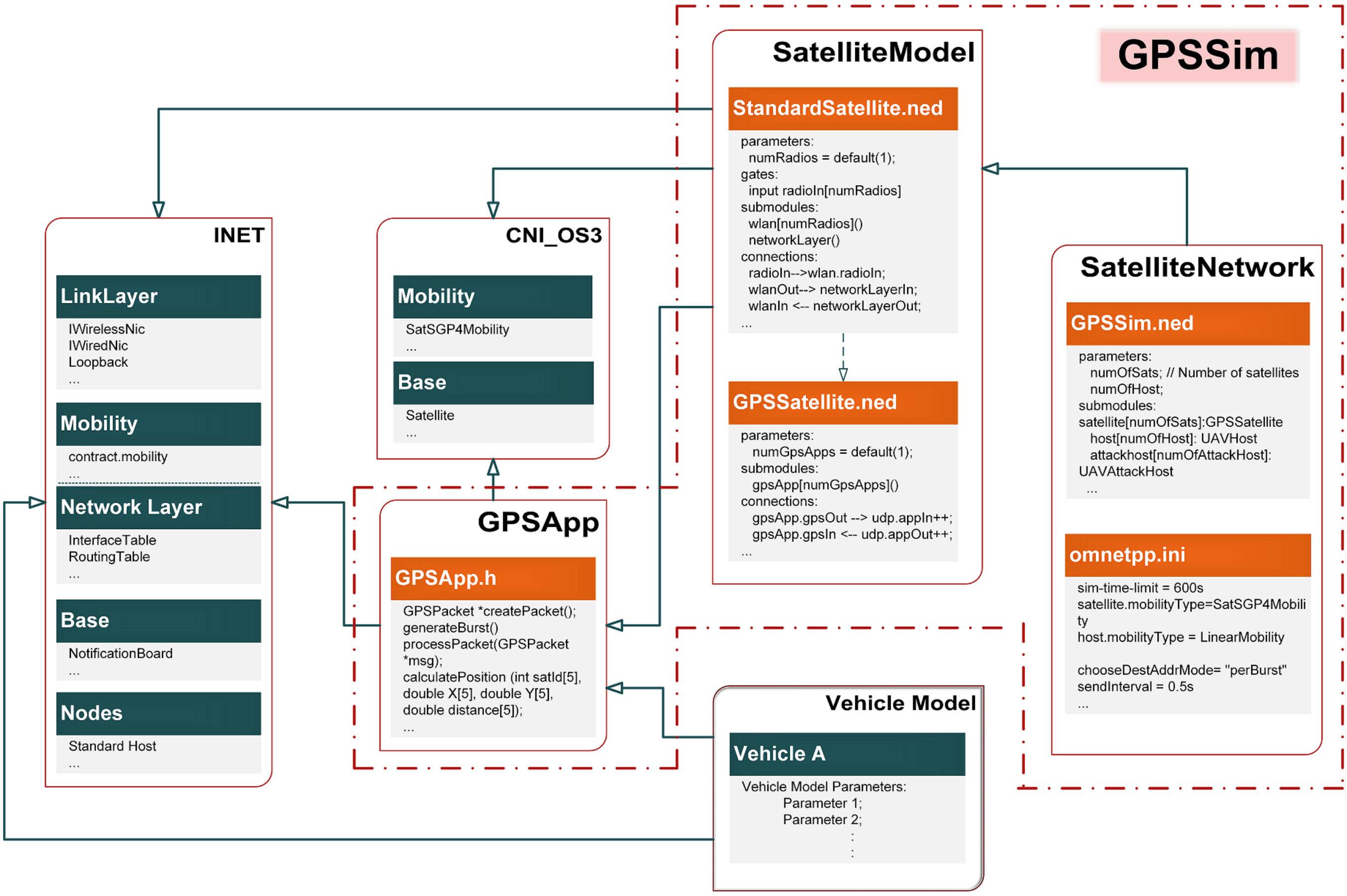
Some major limitations of OS3, and how they were addressed during the implementation phase, have been discussed in the next subsection.

4.1. OS3 Limitations and Solutions

- *No Satellite Communication*: We designed various satellite communication modules in our framework to make satellites capable of transmitting signals and establish communication links.

- *No GNSS*: GPS or any other navigation technique was not implemented in OS3. We implemented the GNSS using basic trilateration equations mentioned in the section 3.2.

- *No Vehicular Simulation*: OMNeT++ allows any discrete event simulation within its framework and thus allows vehicular simulation as long as proper models are designed. Therefore, we used our previously developed UAV simulation testbed UAVSim [14] to demonstrate the proposed GNSS framework's capability in vehicular network simulation.



```
parameters:
  numRadios = default(1);
gates:
  input radioIn[numRadios]
submodules:
  wlan[numRadios]()
  networkLayer()
connections:
  radioIn-->wlan.radioIn;
  wlanOut--> networkLayerIn;
  wlanIn <-- networkLayerOut;
...
```

```
parameters:
   numGpsApps = default(1);
submodules:
   gpsApp[numGpsApps]()
connections:
   gpsApp.gpsOut --> udp.appIn++;
   gpsApp.gpsIn <-- udp.appOut++;
...
```

```
parameters:
   numOfSats; // Number of satellites
   numOfHost;
submodules:
satellite[numOfSats]:GPSSatellite
   host[numOfHost]: UAVHost
   attackhost[numOfAttackHost]:
UAVAttackHost
  ...
```

```
sim-time-limit = 600s
satellite.mobilityType=SatSGP4Mobili
ty
host.mobilityType = LinearMobility

chooseDestAddrMode= "perBurst"
sendInterval = 0.5s
...
```

```
IWirelessNic
IWiredNic
Loopback
...
```

```
contract.mobility
...
```

```
InterfaceTable
RoutingTable
...
```

```
NotificationBoard
...
```

```
Standard Host
...
```

```
SatSGP4Mobility
...
```

```
Satellite
...
```

```
GPSPacket *createPacket();
generateBurst()
processPacket(GPSPacket
*msg);
calculatePosition (int satId[5],
double X[5], double Y[5],
double distance[5]);
...
```

```
Vehicle Model Parameters:
        Parameter 1;
        Parameter 2;
              :
              :
```

Figure 4. Architectural design of the GNSSim framework

4.2. GNSS Framework Modules

GNSSim framework comprises of several modules, as depicted in Figure 4. The GNSSim modules are shown in red in this figure. UAVSim modules are not shown in this figure and more about these modules could be found in [14]. UAVSim allows us to create the UAV Network along with enabling option of choosing from several UAV models. The GNSSim modules are discussed here.

Satellite Model Library. Satellite model library has the standard satellite model that inherits its basic features from the satellite model defined in CNI_OS3. The GPS functionality has been added to the satellite model through the development of a broadcasting application that sends position information to the receivers through radio signals of the $L1$ frequency range as per the standard GPS implementation. The GPS/SATNAV implementation has been described in detail in section 3.

Satellite Network Module. Similar to the UAV network module of UAVSim, this module defines the network stack of satellites. It defines the communication protocol, transmission power, access points, etc. This module imports several basic packages from INET for satellite communication while the satellite mobility packages are imported from OS3.

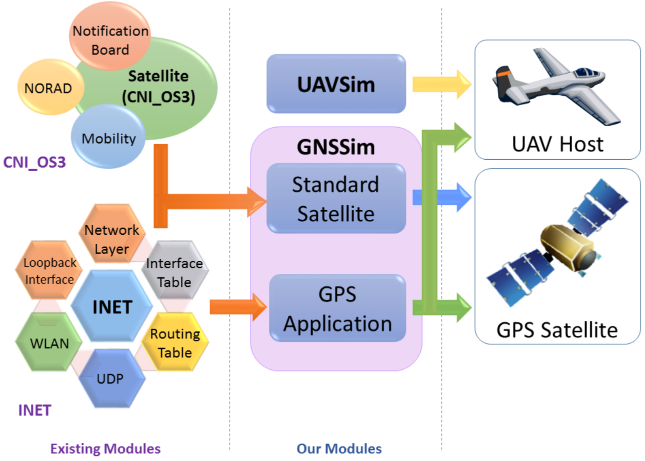


Figure 5. GNSS/GPS implementation

Navigation Module. The navigation module has the receiver end GPS application that enables the hosts to receive satellite navigation signals carrying position

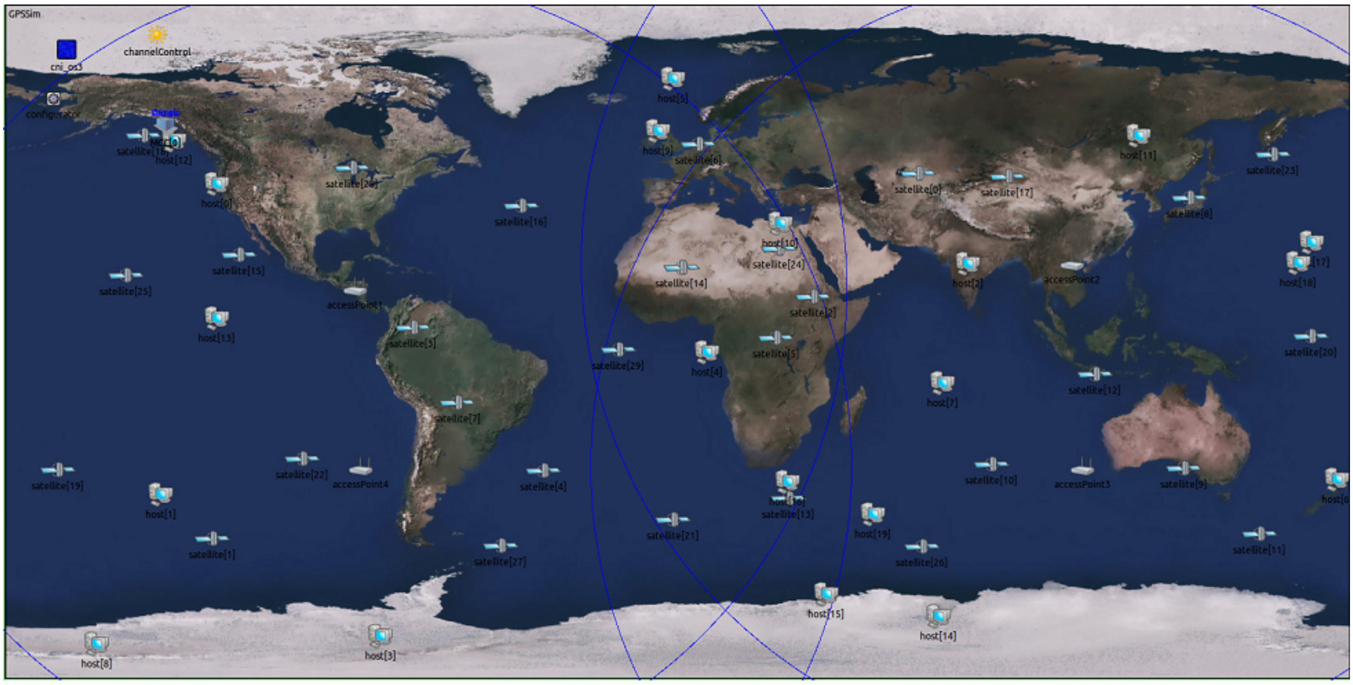


Figure 6. World map used for GPS simulations

information. The information from four or more satellites is required to calculate the position of the UAV using multi-lateration in the $3D$ space. In our implementation, we have used trilateration for localization. Therefore, a minimum of three satellites are required.

4.3. Implementation

Figure 5 explains the implementation of the GPS system. The space segment constitutes of GPS satellites while the user segment in this scenario would be UAV hosts. The base satellite model with the NORAD (North American Aerospace Defense Command) module, mobility model, and notification board has been defined in CNI_OS3. The base satellite model has been enhanced to the standard satellite model that now includes the communication protocol stack.

The GPS Application has been designed from scratch over a connectionless broadcasting protocol. This application is required in the satellites to create and broadcast packets. On the UAV host, this application acts as a GPS receiver in the navigation module. It receives the packets from the satellites and process received data for localization.

The communication between UAVs and satellites or any GPS receiver is unidirectional. Satellites broadcast signals without waiting for any acknowledgment. That is why a connectionless broadcasting protocol was used to implement GPS. The packets contain the satellite index, X coordinates and Y coordinates of the satellite sending the packet, in map meters, and the distance with each host. For the first time when a UAV receives the packet, it locks on that particular satellite. After obtaining a lock on three different satellites, the UAV calculates its position. Further, it calculates its position whenever it receives three more packets from these satellites using the $2D$ trilateration equations as defined in section 3.2. If the UAV does not receive any packets for $10s$, the lock is released, and a new satellite to lock on to is searched. Such a situation is termed as Locate-the-sky.

The implementation of GPS is very basic and an approximation of the real GPS. We have implemented the localization using trilateration, considering the map meters as the position of the satellites and hosts. The scaling of the earth to the map has been done as follows. Considering that the radius of the earth as 6371 km, the circumference of the earth will be

$$2\pi r = 2 \times 3.14 \times 6371$$

If we imagine opening the globe vertically, the circumference will give the length of the map while the width of the map will be half the circumference. The map dimensions are defined as

$$1080 \times 2160$$

The Figure 6 shows the world map in the simulation environment. So horizontally, each pixel on the map corresponds to

$$\frac{2 \times 3.14 \times 6371 \times 10^3}{2160} = 18.5km$$

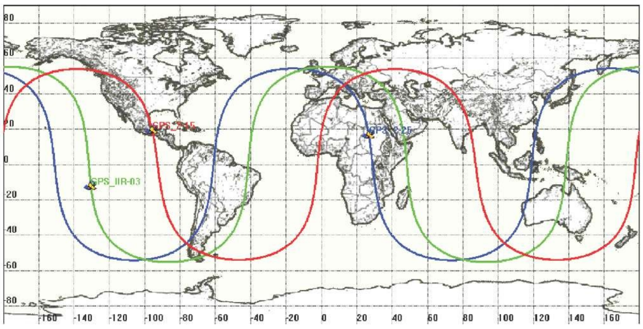


Figure 7. Satellite ground track [34]

or vertically,

$$\frac{3.14 \times 6371 \times 10^3}{1080} = 18.5km$$

Therefore,

$$1m = \frac{1}{(18.5 \times 10^3)} m(onmap)$$

Different UAV models available today have different speeds depending upon its design and usage. The Arcangel-1 has a speed of 150 km/h while USAF mission UAVs like Patroller can fly at a speed of 241 km/h. Taking an approximate speed of 250 km/h of a UAV or 69.5 m/s, the speed of the satellite on the simulation map will be

$$69.5/(18.5 \times 10^3) = 0.0037m/s(onmap).$$

This speed value is set in the simulation configuration file *omnetpp.ini*.

The user-defined parameters, such as the number of satellites and UAV hosts, can be defined in the same configuration file. The simulation world map shown in the Figure 6 shows 30 satellites in orbit. The motion of the satellites in their orbits around the planet appears as a sine wave on a planar map, as shown in Figure 7.

For illustration, 20 hosts are shown on the map. The number of hosts can be varied for each simulation. The OS3 module defines the web-service related data, weather control data, and a calculation module that calculates the distance, attenuation, and other channel characteristics. We have also implemented the DGPS stations in the form of access points, which function as a ground-based central transmitter and receiver of satellite radio signals. The blue circles show the range of each access point. If a host is outside the range, it will not receive any packets. The range of access points needs to cover the whole area of the map so that the host is always in the line-of-sight of one or more satellites. A minimum of four access points is sufficient to cover the whole area with the given range.

Table 2. Default satellite parameters

Parameter	Value
Simulation Time Limit	600s
Mobility Type	SatSGP4Mobility
Transmitter Power	500W
Packet Interval	0.5s
Burst Duration	10s
Sleep Duration	0s
Position Update Interval	1s

Table 3. Default host parameters

Parameter	Value
Mobility Type	Linear Mobility
Transmitter Power	10W
Speed	0.0037 m/s
Burst Duration	10s
Sleep Duration	0s
Position Update Interval	1s

Limitations and Assumptions. Some of the assumptions and limitations of GNSSim implementation are listed here:

- Although GNSSim implements both the space segment and user segment; the control segment is not implemented.
- Only the primary functionality of GPS, position calculation of the UAV is implemented at the receiver end.
- Use of ephemeris and almanac data for calculation of the position is implemented approximately. The satellites sends its position information relative to the UAV in the packet as a parameter rather than calculating the distance using the speed of light and the time of transmission.

5. Simulation Analysis and Results

In this section, we demonstrate the simulation results based on the implementation of the navigation module in UAV hosts. The results are analyzed to demonstrate the correctness of the implementation. The various scenarios and variation in parameters have been analyzed with respect to the localization. The below tables show the default values of the satellites and the host during our simulations.

The background image of the map of the earth used is the default one used in OS3. Other background images can easily be used by changing it in the configuration file. Using the testbed, we analyzed how the UAV performed with the navigation module implemented. The following simulation experiments show the accuracy of UAV localization with respect

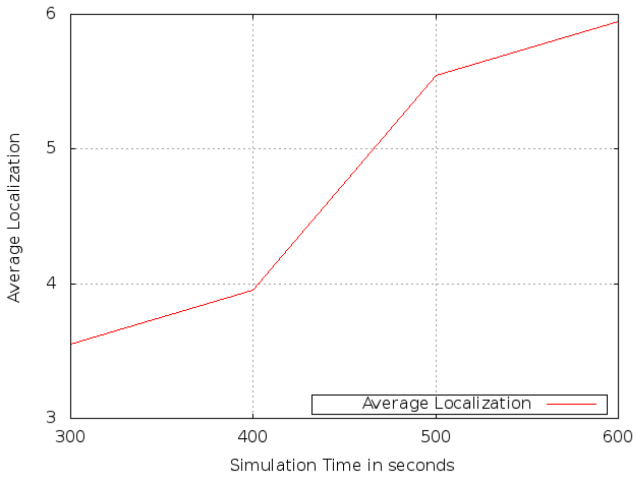


Figure 8. Variation in localization with simulation time

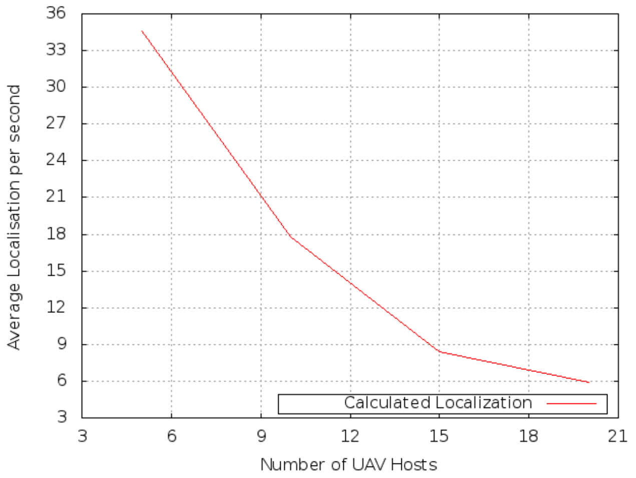


Figure 9. Variation in localization with number of hosts

to variation in different parameters, using the average error as a indication of correctness. The average error is obtained by calculating the distance between actual UAV position and the calculated position, and taking an average over the whole simulation.

5.1. Average Localization versus Simulation Time and Number of Host

Although the localization count is not the same in every run, with the increase in the simulation time, the average localization increases, as shown in Figure 8. It should be noted that the average localization decreases with the increase in the number of hosts, as shown clearly in Figure 9.

5.2. Average Localization versus Satellite Lock

Obtaining a lock is important to get a very accurate position. Satellites broadcast signals all the time.

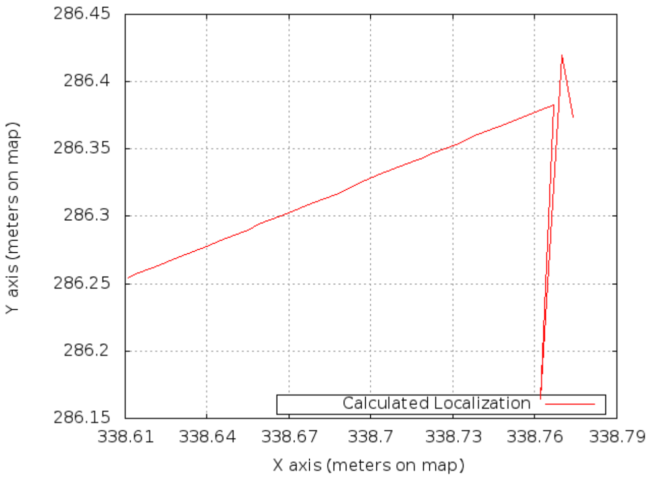


Figure 10. Localization curve without lock implemented on satellites during localization

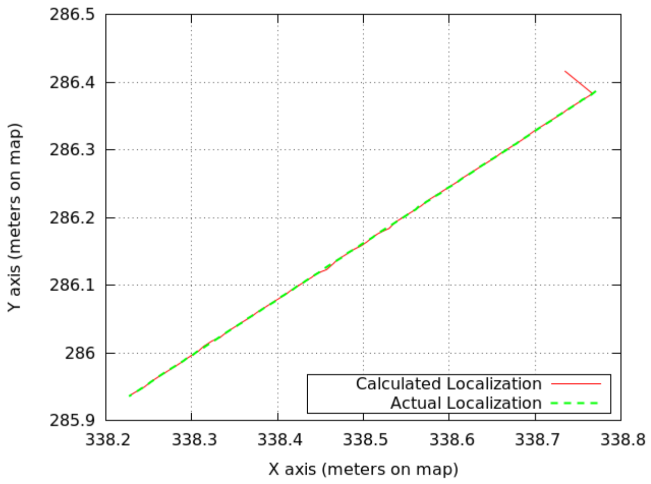


Figure 11. Localization curve with lock implemented on satellites during localization

Also, there can be more than three satellites (2D implementation) in line-of-sight but at different distances from the host. The calculated distance is prone to error, but the effort should be to have a minimal error. If every calculation of the localization uses data from different sets of satellites, it will lead to a larger variation between the calculated position and the original position. Figure 10 shows the variation in localization when no lock on the satellites is in place. The variation between the calculated localization curve and the actual curve was so large that they could not be plotted together.

When the lock on the satellites is implemented, the variation in error reduces to a minimum of 0.001. The calculated position almost overlaps the original position. Figure 11 shows the localization curve to be

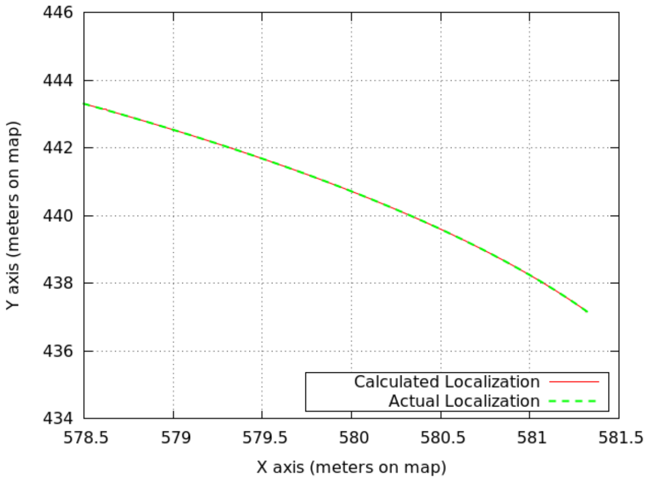


Figure 12. Graph of circular mobility

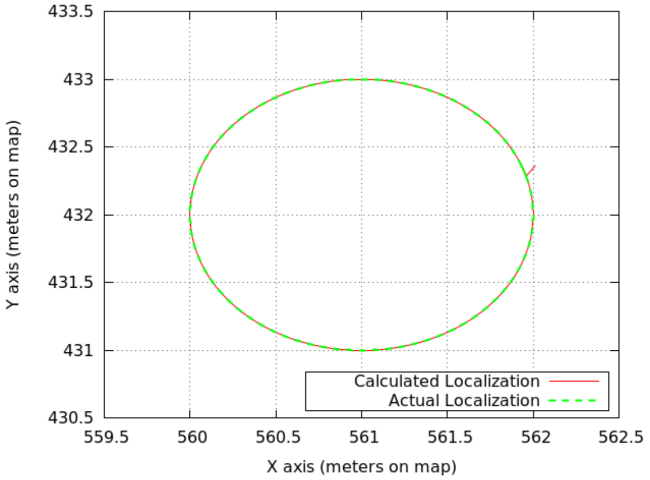


Figure 13. Graph of complete trajectory of circular mobility

in sync with the original path through the lock on the satellites.

5.3. Implementation of Circular Mobility Model

The simulation runs as expected in different mobility models. For Linear Mobility, the UAV travels a linear path as shown in the above figures. Most of our simulation analysis is performed with Linear Mobility. Figure 12 shows the circular path of the UAV host when the mobility model is changed to Circle Mobility. The user needs to define the center of the path and the radius. To get the complete circular trajectory as in Figure 13, the simulation was run for 1000 simulation seconds. For this particular case, the center was taken as (x,y) = (561m, 432m) in map meters and radius as 1 meter which corresponds to 18.5 km in the real world. These mobility models are already defined in the INET module. Other mobility models can also be used for simulation.

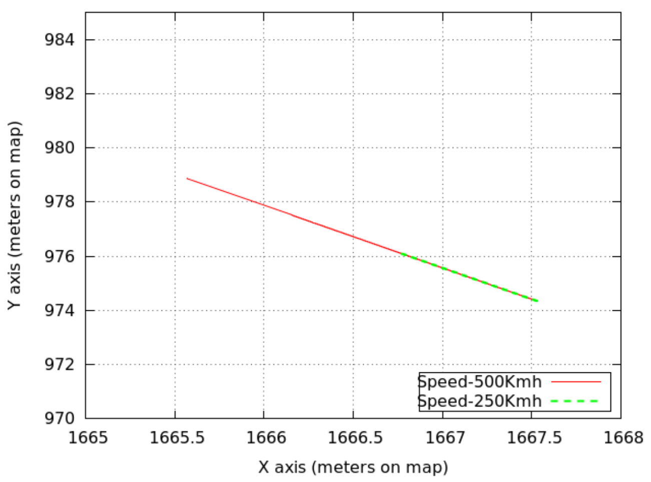


Figure 14. Distance traveled with speed

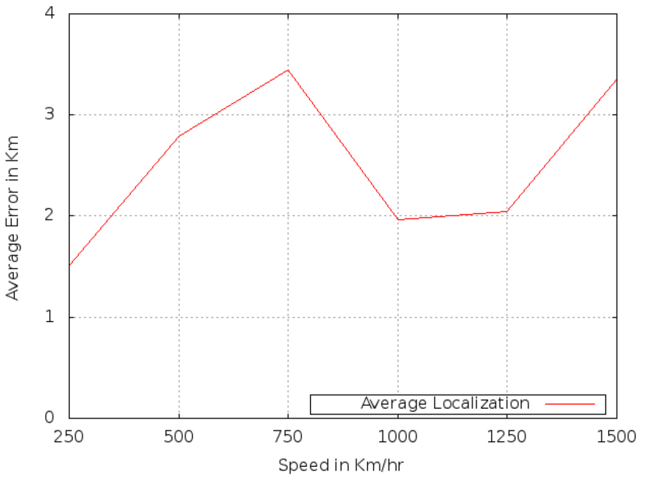


Figure 15. Average error variation with change in speed of host

5.4. Average Localization versus Speed

As the speed of the UAV host increases, as expected, the distance covered by the UAV increases. Figure 14 shows the distance traveled by the UAV with different speeds. The green curve shows the distance traveled when the speed is 250 km/h, and the red curve shows the distance traveled when the speed is 500 km/h keeping the simulation time as 400 seconds. With the increase in speed, the average localization error increases, as shown in Figure 15. The default value of the speed is 0.0037 mps, i.e., 250 km/h. The speed could also be defined in the configuration file as a Gaussian function with a normal distribution truncated to non-negative values and a standard deviation of 0.005.

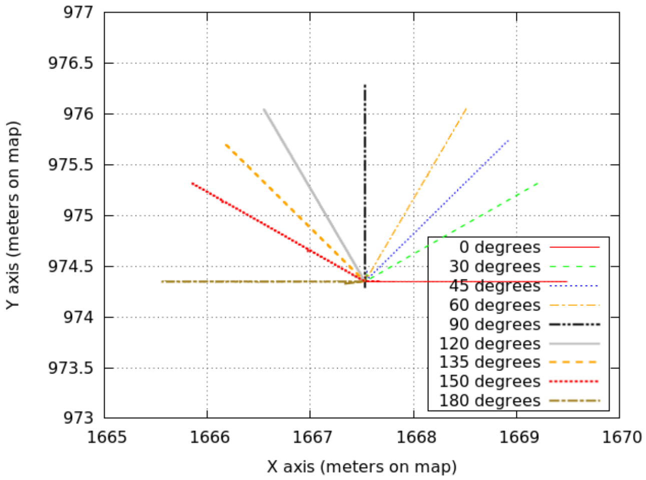


Figure 16. Path of host at different start angles

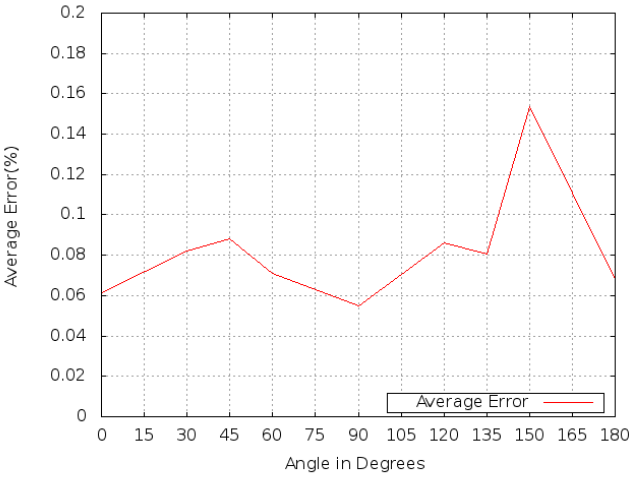


Figure 17. Average error variation with change in start angle

5.5. Variation in Angle of Linear Motion

The default value of the angle of linear motion is random and uniformly distributed between 0 to 360 degrees. Figure 16 shows the calculated path of the host at different angles. As we can see from the figure, the host follows a correct path using its calculated localization data. Figure 17 shows the average error at different angles. The average error increases as we move from its linear axis and becomes minimum again at 90 degrees. Figure 18 shows the variation in the localization error with the simulation time for three different angles. The maximum localization error is less than 1% for all evaluated cases. As we can see from the figure 18, the number of errors in localization varied with change in the starting angle of the UAV host.

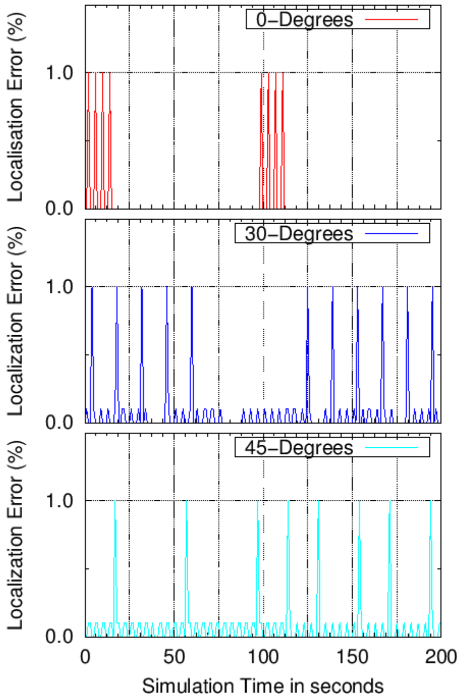


Figure 18. Localization error variation with simulation time

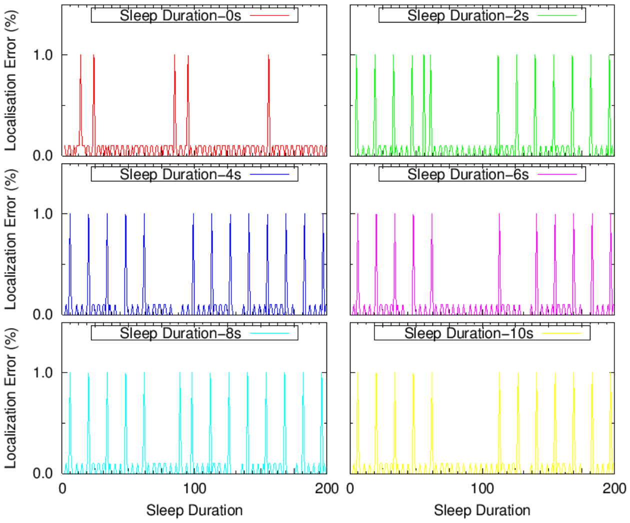


Figure 19. Localization error variation with change in sleep duration

5.6. Sleep Duration versus Localization

GPS based navigation can offer relatively consistent accuracy if sufficient GPS signals can be tracked during the entire UAV mission [35]. Due to its low power range, intentional or unintentional interference can cause UAVs to lose the signals. The GPS signal outage can cause a significant deviation in the navigation solutions.

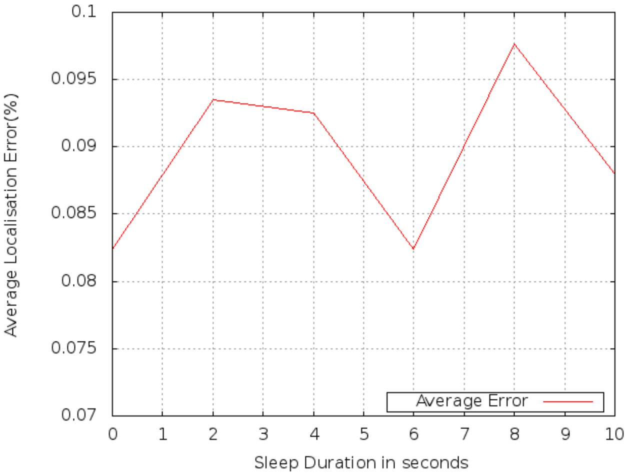


Figure 20. Average localization error variation with change in sleep duration

To represent such a scenario where UAVs lose the signal because of interference from television signals, mobile signals, ultra wideband communications or when traveling around high buildings and trees, our testbed has a parameter called ’sleep duration’, which corresponds to such a GPS signal outage. The parameter can be assigned to both the satellites and the host. In case of satellites, during the specified sleep duration, they would be inactive and would not broadcast any packets while the hosts would reject packets even if a satellite is sending them. The default sleep duration has been kept at 0s for the satellites as well as the host assuming that there is no outage, and the UAV receives signals during entire simulation.

The Figures 19 and 20 show the effect of a change of sleep duration on the localization error. The simulation has been mapped from 0s - 10s of sleep duration with an interval of 2s for 200 localization values. These figures clearly show that the maximum error reaches about a maximum of 1% for all evaluated cases. The average localization error is almost negligible which shows the accuracy of the localization algorithm.

6. Conclusion and Future Work

In this work, we proposed a generic GNSS simulation framework called GNSSim. We also utilized this framework to simulate UAV networks using an existing UAV simulation testbed called UAVSim, which was incomplete without a navigation module. To fully implement the GPS navigation, we needed the GPS satellite constellation and a GPS signal receiver in UAV. Various simulation experiments were performed by varying different parameters in GNSSim, and the results were analyzed and discussed to prove the correctness of the implementation. Incorporation in another OMNeT++ based simulation testbed was aimed at proving its utility as a generic GNSS framework for any vehicular simulation in OMNeT++. Future work may include improvement upon a few limitations of UAVSim and GPS/SATNAV implementation. Another important future work might include the implementation of different GPS related attacks and their mitigation techniques, such as GPS spoofing and GPS Jamming.

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