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Design of complete software GPS signal simulator with low complexity and precise multipath channel model

G. Arul Elango *, G.F Sudha

Department of Electronics and Communication, Pondicherry Engineering College, Puducherry, India

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Abstract

The need for GPS data simulators have become important due to the tremendous growth in the design of versatile GPS receivers. Commercial hardware and software based GPS simulators are expensive and time consuming. In this work, a low cost simple novel GPS L1 signal simulator is designed for testing and evaluating the performance of software GPS receiver in a laboratory environment. A typical real time paradigm, similar to actual satellite derived GPS signal is created on a computer generated scenario. In this paper, a GPS software simulator is proposed that may offer a lot of analysis and testing flexibility to the researchers and developers as it is totally software based primarily running on a laptop/personal computer without the requirement of any hardware. The proposed GPS simulator allows provision for re-configurability and test repeatability and is developed in VC++ platform to minimize the simulation time. It also incorporates Rayleigh multipath channel fading model under non-line of sight (NLOS) conditions. In this work, to efficiently design the simulator, several Rayleigh fading models viz. Inverse Discrete Fourier Transform (IDFT), Filtering White Gaussian Noise (FWFN) and modified Sum of Sinusoidal (SOS) simulators are tested and compared in terms of accuracy of its first and second order statistical metrics, execution time and the later one is found to be as the best appropriate Rayleigh multipath model suitable for incorporating with GPS simulator. The fading model written in 'MATLAB' engine has been linked with software GPS simulator module enable to test GPS receiver's functionality in different fading environments.

Keywords: GPS signal simulator; Rayleigh fading; Non line of sight (NLOS); Sum of sinusoids (SOS)

1. Introduction

The GPS system has become the fundamental technology for position determination. It has enabled many applications in various areas. Due to its widespread use, much research is being done to develop low cost, small size and efficient GPS receivers. GPS simulators which provide the real time environment of the GPS satellite system become

* Corresponding author.
E-mail addresses: arulelango2012@gmail.com, arulelango2000@yahoo.co.in (G.A. Elango).
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the need of the hour. The two approaches for obtaining GPS signals are either collecting the set of real GPS signal measurements from a commercial front-end or by using software GPS signal simulators to generate the digitized IF GPS signal (Tang et al., 2006; Meng et al., 2002; Hu et al., 2009). The GPS signal parameters are non stationary, time varying, weather and satellite health have an effect on the signal characteristics. Underneath these conditions to perform multiple tests in indiscriminately outlined conditions, it's essential to simulate and record the signals rather than collecting the live signal from the satellites each time. In the laboratory environment, software GPS simulators are gaining popularity for providing the excellent research tool for investigating and improving the receiver performance in a wide range of conditions. The software based GPS simulators have a provision to change the RF front end specifications like IF, sampling frequency, number of quantization bits and bit resolution of the ADC when compared to the hardware GPS simulators. Some commercially available simulators like Accord GPS correlator simulator, National Instruments GPS simulator tool kit for Labview, LabSat GPS engine simulators and Sprient Multichannel GPS simulators typically cost hundreds of thousands of dollars. Until now, the GPS simulators are very expensive and only affordable to researchers with a large R&D budget.

1.1. Related works

The two common way of designing the simulator are analog and digital one. In the analog version of simulator, the Doppler, spreading code and navigation messages are generated in the digital hardware like FPGA. The radio frequency part is liable for up-conversion and filtering the signal. Conversely in digital version of GPS simulator, FPGA hosts service functions to transfer the digital samples to the PC and a signal is totally generated on an IF in the digital part and converted to analog signal then up converted to RF signal. Magiera (2012) proposed a Software defined radio (SDR) based GPS simulator. In this SDR based simulator, the two modules of signal formation unit (SFU) namely, spectrum spreading module and Doppler time offset module are implemented in FPGA which is hardware dependent one and therefore the hardware complexity of realizing of new set of GNSS signals are quite high. Boopalan et al. (2002) and Prasad et al. (2003) proposed a hardware design for GPS signal simulators on a multi-SHARC parallel processing system. Though the hardware based GPS simulator allocates visible satellites to the channel and handles the channel simultaneously utilizing the DSP based parallel processing system however, in a typical development stage of a project, the cost of the GPS simulator is prohibitively expensive. Gao et al. (2012) built a FPGA based of GPS simulator comprises of 12 channels for GPS signal and 4 channels for GLONASS signal and reconfiguration of further new GNSS signals are not feasible. Wang et al. (2010) and Guo et al. (2009) introduced a MATLAB based simulator. Deng and Wang (2011) and Tan (2003) developed a SIMULINK based GPS simulator for testing GPS receivers. Most of the software simulators are designed in MATLAB suite environment which takes plenty of time to generate the signal. The simulation speed may be enhanced by using more efficient programming language such as assembly language but it is again processor dependent one and the hardware complexity also increases. Positioning error due to ephemeris data is around 1–5 m, this mainly occurs because of difference between the simulated and actual orbital position of a GPS satellite. These drawbacks will be carefully considered when a fully software based architecture is used. The fully software configuration is more demanding in terms of cost, architectural re-configurability, accuracy and speed. Table 1 gives a comparison of the three classifications of existing GPS simulators.

In this paper, three main contributions of the work are presented. First, by implementing the signal formation unit in software, the capability of the simulator to reconfigure to newer spreading codes of GNSS signals at affordable cost to researchers is accomplished. Second, the accuracy of navigation data generation in the PCU is improved and the simulation time is reduced. The simulator is developed in C (VC++ environment) with some channel module functions called in MATLAB run engine to speed up the operation with reduced time complexity. Thirdly, based on the evaluation of statistical characteristics of different fading models, the simulator incorporates a modified Jakes as an efficient Rayleigh multipath channel fading model under non-line of sight conditions. Another salient feature of the proposed simulator is that the statistical parameter analysis for a slow and fast receiver dynamics in terms of average fade duration and level crossing rate can also be performed.

The paper is structured as follows. Section 2 describes the main functional blocks of the simulator. The complete design flow, the algorithm description of the formation of the navigation data, modulation and the generation of composite GPS IF data are presented in Section 3. The verification of IF simulated signals is given in Section 4.

Table 1
Comparison of existing GPS simulators.

Parameters	Analog simulator	Digital simulator	Complete software based simulator
Design architecture hardware/software	Fully hardware	Software controlled hardware	Purely software
Signal formation unit (SFU) Implementation	In FPGA	In FPGA	Software (SIMULINK/MATLAB)
Spectrum spreading Doppler shift time offset			
Parameter computation unit (PCU) and data flow control unit (DFCU)	Hardware (DSP)	Software (SIMULINK/MATLAB)	Software (SIMULINK/MATLAB)
Adaptability to future GNSS signals	All Fixed channels – not re-configurable	Some channels fixed – not reconfigurable for all future signals like QZSS & IRNSS	Possible
Position accuracy	Good 5–7 m	7–10 m	Ephemeris error can be corrected by exploiting IEEE-754 format precision in generation of navigation data
Cost	High	High	Low
Simulation time	Low DSP based Parallel processors speedup the operation	Low	More can be minimized by employing whole simulator part in efficient programming language

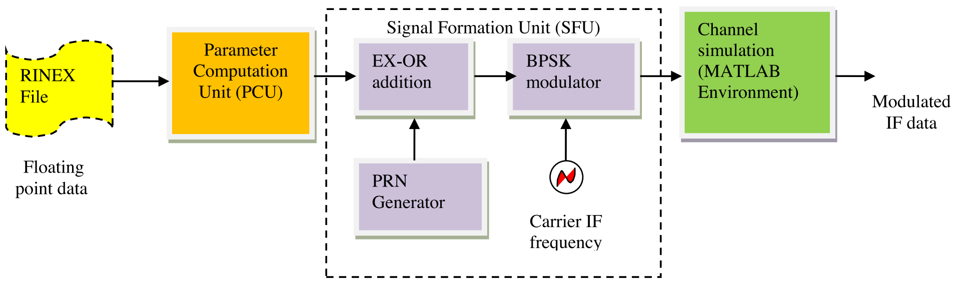

Fig. 1. Block diagram of software GPS signal simulator.

Finally, different the multipath channel impairments for a slow and fast moving receiver is compared and analyzed in Section 5.

2. Design flow of proposed L1 GPS signal simulator

The architecture of the proposed L1 GPS signal simulator comprises of four main functional blocks as shown in Fig. 1. In this simulator, the ephemeris data and pseudorange values collected from Receiver Independent Exchange Format (RINEX) file for six visible satellites based on the user trajectory are given as input to the source encoder block otherwise known as parameter computation unit. The source encoder is the initial block that performs operations such as conversion of floating point numbers to binary format which represents collecting the satellite clock information, clock correction etc. into relevant GPS frames. The 1500 bits GPS navigation data is modulo 2 added with the pseudorandom noise generator with the specified number of satellites available to the user listed in the file. The navigation data is modulated with the user assigned carrier IF frequency of several MHz. Finally taking into consideration the typical C/N_0 value of the GPS receiver as typically around 37–45 dB-Hz (Braasch and Van Dierendonck, 1999) the noise is added with the simulated data according to the bit error rate (BER).

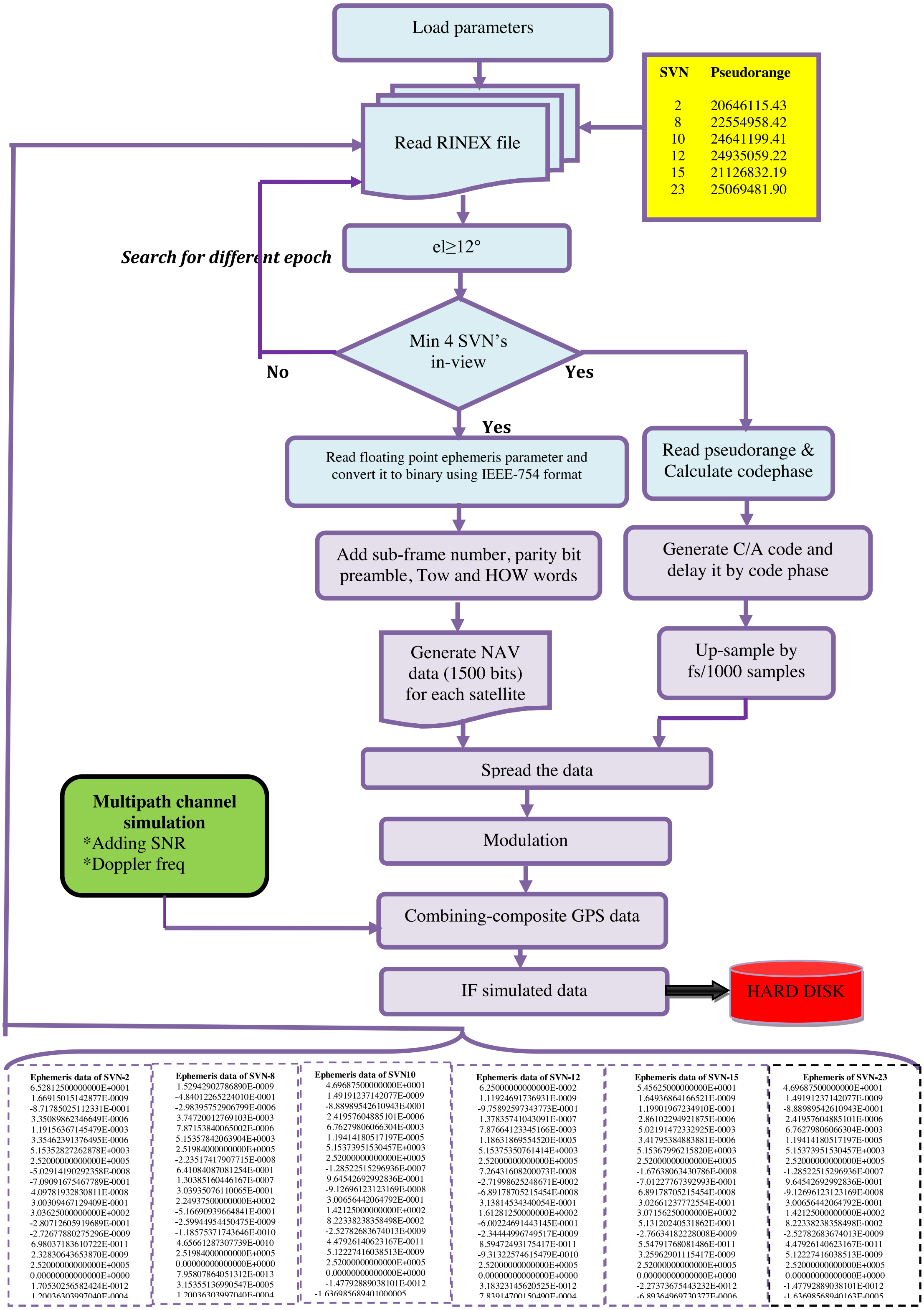

Fig. 2. Complete design flow of proposed software GPS simulator.

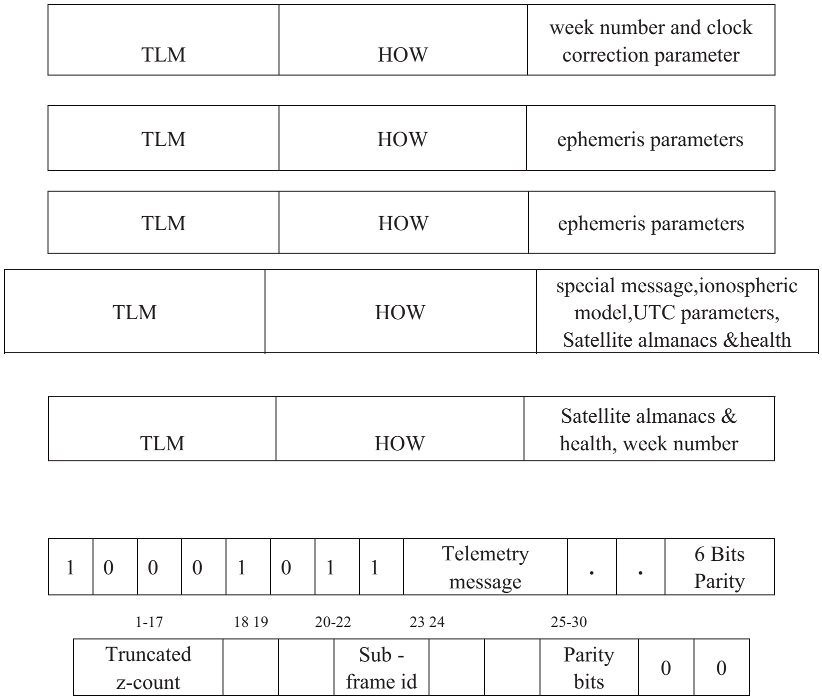

Fig. 3. (a) GPS Navigation Message Structure (subframe1-5). (b) TLM and HOW words.

3. Detailed functional description of parameter computation unit

The complete design flow of the proposed software GPS simulator is shown in Fig. 2. The detailed description of each stage is explained in the following sections.

3.1. Selection of visible satellites

The visible satellites are chosen from the user trajectory. This can be computed from the three scenarios namely static, moving along a straight line and moving along a circular path with constant velocity (Li et al., 2008). At any point of time on the surface of earth minimum 4 satellites should be visible to the user. In such a way that, the determination of visible satellites are chosen from the RINEX file based on fixing the threshold value of 12° elevation angle. The ephemeris data contains the information about the subframe parameters. To place the 21 ephemeris values into GPS frame format, one should know about the standard GPS navigation message format. Out of five subframes, the first three subframes from four or more satellites are needed to find the user location. The Fig. 3a shows the standard data format of a GPS system. The last 2 subframe contains the information about the almanac data. The first two words of all the subframes contain the telemetry (TLM) and Hand Over Word (HOW). Each word contains 30 bits and the message is transmitted from bit 1 to 30. These two words are shown in Fig. 3b. The TLM word starts with an 8-bit preamble, followed by 16 reserved bits and 6 parity bits, apparently the reserved bits are set to 1. The bit pattern of the preamble will be used to match the navigation data to detect the starting of a subframe (Tsui, 2000).

3.2. Conversion the ephemeris and pseudorange decimal values into binary subframe data

The ephemeris parameters location and their corresponding scale factors are given in the Table 2. The decimal ephemeris values are converted to equivalent IEEE-754 floating point binary format in order to preserve the accuracy of the data conversion in the PCU block of the simulator. Keeping this in mind 8, 16 and 32 bits precision are used. The sign bit, exponent, mantissa are selected as per the precision type used in the simulation. The general IEEE 754 format is used as $(-1)^s \times (1 + \text{fraction}) \times 2^{\text{exp}-\text{bias}}$. The precision type and their equivalent data format is given in

Table 2
Ephemeris parameters used in GPS navigation data formation.

Frame number	Ephemeris parameters	Location	No of bits	Scale factor	Precision (bits)
Subframe-1	T_{GD}—satellite group delay differential	197–204	8	2^{-31}	8
	t_{oe}—satellite clock correction	219–234	16	2^{4}	16
	af_2—satellite clock frequency drift	241–248	8	2^{-55}	8
	af_1—satellite clock drift	249–264	16	2^{-43}	16
	af_0—satellite clock offset	271–292	22	2^{-31}	32
Subframe-2	C_{rs}—cosine harmonics correction terms to the orbit radius	369–384	16	2^{-5}	16
	Δ_n—mean motion difference	391–406	16	2^{-43}	16
	M_0—mean anomaly at reference epoch	407–414;421–444	32	2^{-31}	32
	C_{uc}—sine harmonics correction terms to the argument of latitude	451–466	16	2^{-29}	16
	e_s—eccentricity	467–474;481–504	32	2^{-33}	32
	C_{us}—sine harmonics correction terms to the argument of latitude	511–526	16	2^{-29}	16
	$\sqrt{a_s}$—square root of semi major axis	527–534;541–564	32	2^{-19}	32
	t_{oe}—ephemerides reference week	571–586	16	2^{4}	16
Subframe-3	C_{ic}—cosine harmonics correction terms to the angle of inclination	661–676	16	2^{-29}	16
	Ω_e—longitude of the ascending node of the orbit plane at weekly epoch	677–684;691–714	32	2^{-31}	32
	C_{is}—sine harmonics correction terms to the angle of inclination	721–736	16	2^{-29}	16
	i_o—longitude of node at weekly epoch	737–744;751–774	32	2^{-31}	32
	C_{rc}—sine harmonics correction terms to the orbit radius	781–796	16	2^{-5}	16
	ω_0—argument of perigee	797–804;811–834	32	2^{31}	32
	Ω—rate of node's right ascension	841–864	24	2^{-43}	32
	idot—rate of inclination angle	879–892	14	2^{-43}	16

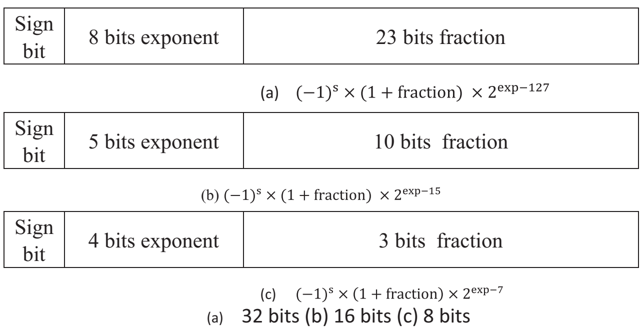

Fig. 4. IEEE 754 format precision type used in PCU block.

Fig. 4. While implementing the frame synchronization module in software GPS receiver the reverse operation has to be performed in the data decoding part i.e., floating point binary values are converted to decimal and multiplied with the corresponding scale factor. If the scaled number is greater than or equal to zero, then the digits are placed in the particular location of the frame. Else 2's complement is taken.

3.2.1. Algorithm description of forming GPS navigation data Format

Once the satellites orbital parameters have been converted and placed into corresponding bit location of navigation data, the next step of inclusion of frame number information for identifying the frame location, 8 bits preamble (10001011) addition for finding the start of every subframe and parity bit generation for the purpose of parity bit matching in every 30 bits (word) is required to construct the complete 1500 bits of GPS navigation data. This section shows the steps involved in formation of 1500 bits navigation data.

```
Definition:
Bit index is the position of the beginning bit, j-all in view Satellite Vehicle Number from1-N.
TLMmsg[16]={1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0}

Step1: Adding preamble bits to each subframe:
Bit index <1500
if (bit index (mod 300=0)){
    data [SVN j][bit index+1]=1
    data [SVN  j][bit index+2]=0
    data [SVN j][bit index+3]=0
    data [SVN j][bit index+4]=0
    data [SVN j][bit index+5]=1
    data [SVN j][bit index+6]=0
    data [SVN j][bit index+7]=1
    data [SVN j][bit index+8]=1
bit index = bit index +8;}

Step 2: Adding subframe ID number:
if(bit index=50){
data [SVN j][bit index]=0          }
data[SVN j][bit index+1]=0         } Subframe-1
data [SVN j][bit index+2]=1}       }
if(bit index=350){
data [SVN j][bit index]=0          }
data [SVN j][bit index+1]=1        } Subframe-2
data [SVN j][bit index+1]=0        }
if (bit index=650){
data [SVN j][bit index]=0          }
data [SVN j][bit index+1]=1        } Subframe-3
data [SVN j][bit index+2]=1}       }
if (bit index=950){
data [SVN j][bit index]=1          }
data [SVN j][bit index+1]=0        } Subframe-4
data [SVN j][bit index+2]=0}       }
if (bit index=1250){
data [SVN j][bit index]=1          }
data [SVN j][bit index+1]=0        } Subframe-5
data [SVN j][bit index+2]=1}       }

Step 3: Adding Telemetry message
    if (bit index =9& bit index =309& bit index =609 & bit index =909& bit index =1209)
    data [SVN j] [TLM msg +bit index]=TLM msg [bit index]

Step 4: Adding TLM reserved bits
    if (bit index =22& bit index =23)
    data [SVN j][ bit index +1]=1;
    if(bit index =322& bit index =323)
    data[SVN j][ bit index +1]=1;
    if(bit index =622& bit index =623)
    data[SVN j][ bit index +1]=1;
    if(bit index =922& bit index =923)
    data[SVN j][ bit index +1]=1;
    if(bitindex =1222& bit index=1223)
    data[SVN j][ bit index +1]=1;

Step 5: Adding TOW in HOW word
Step 6: Adding parity bits at the end of every 30 bits
```

The algorithm used here for adding the parity bits is based on the parity encoding equations given in the reference (Tsui, 2000). The equations are calculated from a parity matrix given below.

123456789101112131415161718192021222324

$$H=\begin{bmatrix}
1&1&1&0&1&1&0&0&0&1&1&1&1&1&0&0&1&1&0&1&0&0&1&0\\
0&1&1&1&0&1&1&0&0&0&1&1&1&1&1&0&0&1&1&0&1&0&0&1\\
1&0&1&1&1&0&1&1&0&0&0&1&1&1&1&1&0&0&1&1&0&1&0&0\\
0&1&0&1&1&1&0&1&1&0&0&0&1&1&1&1&1&0&0&1&1&0&1&0\\
1&0&1&0&1&1&1&0&1&1&0&0&0&1&1&1&1&1&0&0&1&1&0&1\\
0&0&1&0&1&1&0&1&1&1&1&0&1&0&1&0&0&0&1&0&0&1&1&1
\end{bmatrix}$$

3.3. Delay calculation

The code phase value of every SVN is calculated from the pseudo range (ρ) values which are read from the RINEX file. The flow chart in Fig. 5 indicates the steps involved for calculating the delay in C/A code experienced by all-in view SVN's used in the GPS signal generation.

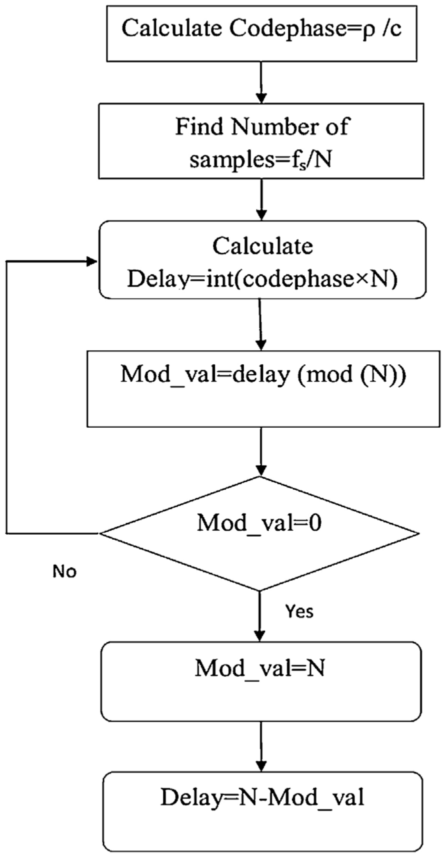

Fig. 5. Flowchart for delaying the up sampled C/A code.

Table 3
Codephase values used for delaying the *C*/*A* code.

SVN	Code phase (chips)	Doppler frequency (Hz)
2	839	–
8	187	3000
10	577	4500
12	140	2500
15	432	6000
23	119	5500

The codephase values of all-in view SVN’s 2, 8,10,12,15 and 23 are calculated from the pseudorange values given in Fig. 2 and their respective C/A code are delayed by the number of bits as specified in the Table 3.

3.4. Signal formation unit—spreading the data

For spreading the data, 30 s of 5 subframe data for 6 sets of Satellite are obtained by 1023 bits i.e., 1 ms C/A code are spreaded with navigation data and repeated 20 times since the navigation data duration is 20 ms. Then the resultant bit sequence is again repeated 1500 times for obtaining the 1page i.e., 30 s duration of 5 subframe data (30,000 ms/20 ms = 1500bits). As shown in Fig. 6, the bitwise ex-or operation is performed for 1500 bits navigation data with the 1023 bits of C/A code. Then the resultant 1023 bit sequence is repeated 20 times till the last bit of navigation data. This procedure is used to spread data length of 30,690,000 bits for one SVN. Likewise the same operation is performed for all-in view SVN’s. Finally the spreading data is stored in a file format. Since this huge

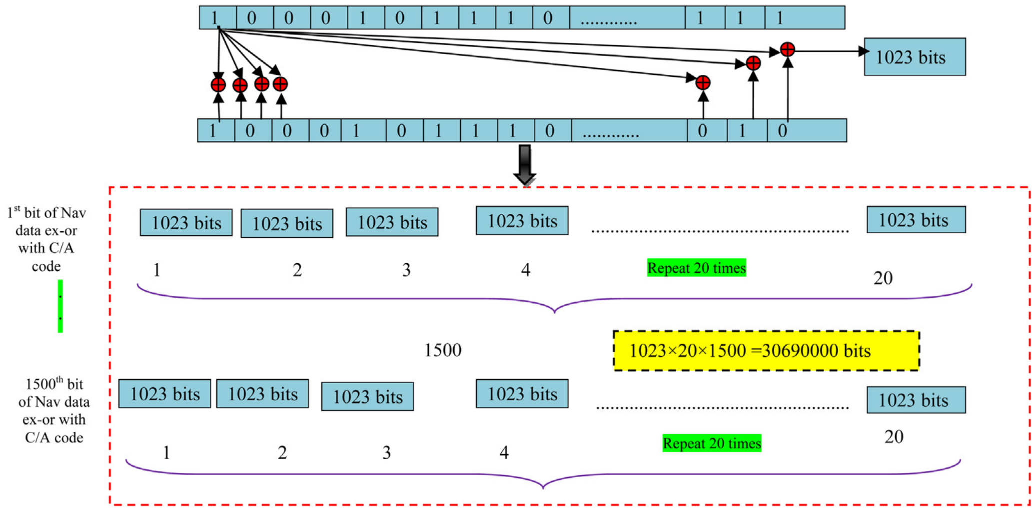

Fig. 6. spreading of GPS data.

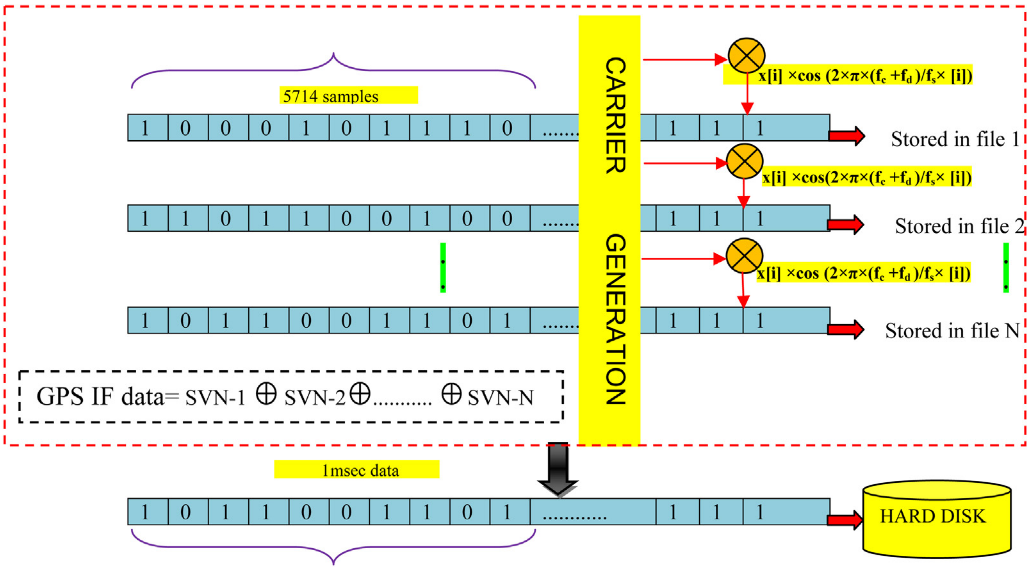

Fig. 7. Procedure for combining all-in view SVN's spread data to create digitized IF GPS data.

number of bit spreading is difficult in MATLAB, the implementation of GPS IF signal simulator is carried out in VC++ platform which is more feasible and faster. The spreading codes used in the future GNSS signals can be easily reprogrammed using this SFU unit.

3.5. Modulation and generation of composite GPS signal

This module shown in Fig. 7 generates the composite GPS signal from the all-in view SVN's. As per the sampling frequency assigned by the user, the spread data is sampled at f_s Hz for 1 ms period. Hence the stored spread data in a file of every 1023 bits are replaced by $f_s/1000$ samples i.e., the 1023 bit sequence is up-sampled at a rate of $f_s/1000$ samples, then it is modulated on to an IF frequency of f_c Hz aided with adoppler frequency of f_d Hz. The modulated GPS data is computed by multiplying the in-phase component with an up-sampled spread data $x[i] \times \sin\,(2 \times \pi \times [(f_c \pm f_d)/f_s \times i]$ where ($i = 0$ to $f_s/1000$). The spread data for all-in view SVN's are combined by doing bitwise OR operation. This is the final version of digitized IF GPS data which is streamed on to a hard drive to test the functionality of GPS receivers.

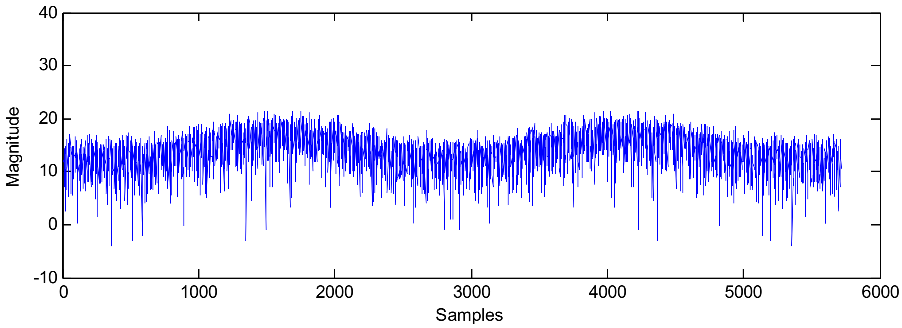

Fig. 8. Spectrum of GPS IF signal generated by GPS simulator.

4. Verification of the generated IF signal using software GPS simulator

The simulator has a provision of changing the IF frequency from 1.5 MHz to 8 MHz. For simulation purpose, the IF frequency is set as 1.6205 MHz and the sampling frequency is fixed at 5.714 MHz. Based on the afore mentioned procedures the digitized IF GPS data has been generated and the spectrum is plotted for the digitized IF data in Fig. 8. From this it is infered that the GPS signal generation is correct and the centre frequency is located around 1.6205 MHz .The performance of the acquisition module in software GPS receiver is tested for all-in view SVN's (2, 8,10,12,15 and 23) used in the GPS signal generation. The acquisition results of SVN-2, 8, 12 and 23 plotted in Fig. 9 show distinct peaks and their corresponding codephase are exactly matched with the values used in signal generation. The sky plot of six all-in view satellites distribution is plotted in Fig. 10.

The simulator output for each stage and the inputs required from the user end and the outputs at every stage are given in this section. During simulation the break points are set to display the output.

4.1. Horizontal positioning error computation—simulated versus actual data

The relative error between the actual data and the simulated data is given by the equations

$$\Delta_n = (\mathrm{Lat1} - \mathrm{Lat2})\, a_s\, (1 - e_s)\, (1 + 3\left(\frac{e_s}{2}\right)^2 \left[\frac{\sin(\mathrm{Lat1} + \mathrm{Lat2})}{2}\right]^2 \tag{1}$$

where e_s—WGS-84 earth eccentricity squared, a_s—earth semi-major axis in meters

$$\Delta_e = (\mathrm{Long1} - \mathrm{Long2})\, a_s \cos(\mathrm{Lat1}) \left[1 + \left(\frac{e_s}{2}\right)^2 \left(\frac{\sin(\mathrm{Lat1} + \mathrm{Lat2})}{2}\right)\right]^2 \tag{2}$$

$$\mathrm{Horizontalpositioningerror\,(HOPE)} = \sqrt{{\Delta_n}^2 + {\Delta_e}^2} \tag{3}$$

The ephemeris data collected from the RINEX file available in the IISC station website database (http://www.sonel.org/spip.php?page=gps&idStation=701) of Lat/Lon: 13.02120018°/77.57039642° is used for GPS IF signal generation. It has been tested with the software GPS Receiver in order to compute the positioning error of the user. The simulated results of Lat/Lon 13.02120107° and 77.57039599° are observed and the horizontal position error of 6.1640 m is calculated. This shows that the ephemeris error of 0.836 m is reduced compared to conventional approach (7 m) owing to the use of 8, 16 and 32 bits precision IEEE-754 floating point decimal to binary conversion in the source encoder block of the simulator. The East, North and Up positioning error of the simulated data is plotted in Fig. 11.

5. Rayleigh fading channel model for GPS signal

Multipath propagation is one of the most challenging problems encountered in GPS receiver design. It is the major error source which affects the receiver positioning upto 10 m (Borre et al., 2007). The two most common channel distributions are the Rayleigh fading and the Ricean fading. When the transmitter is far away from the receiver, it

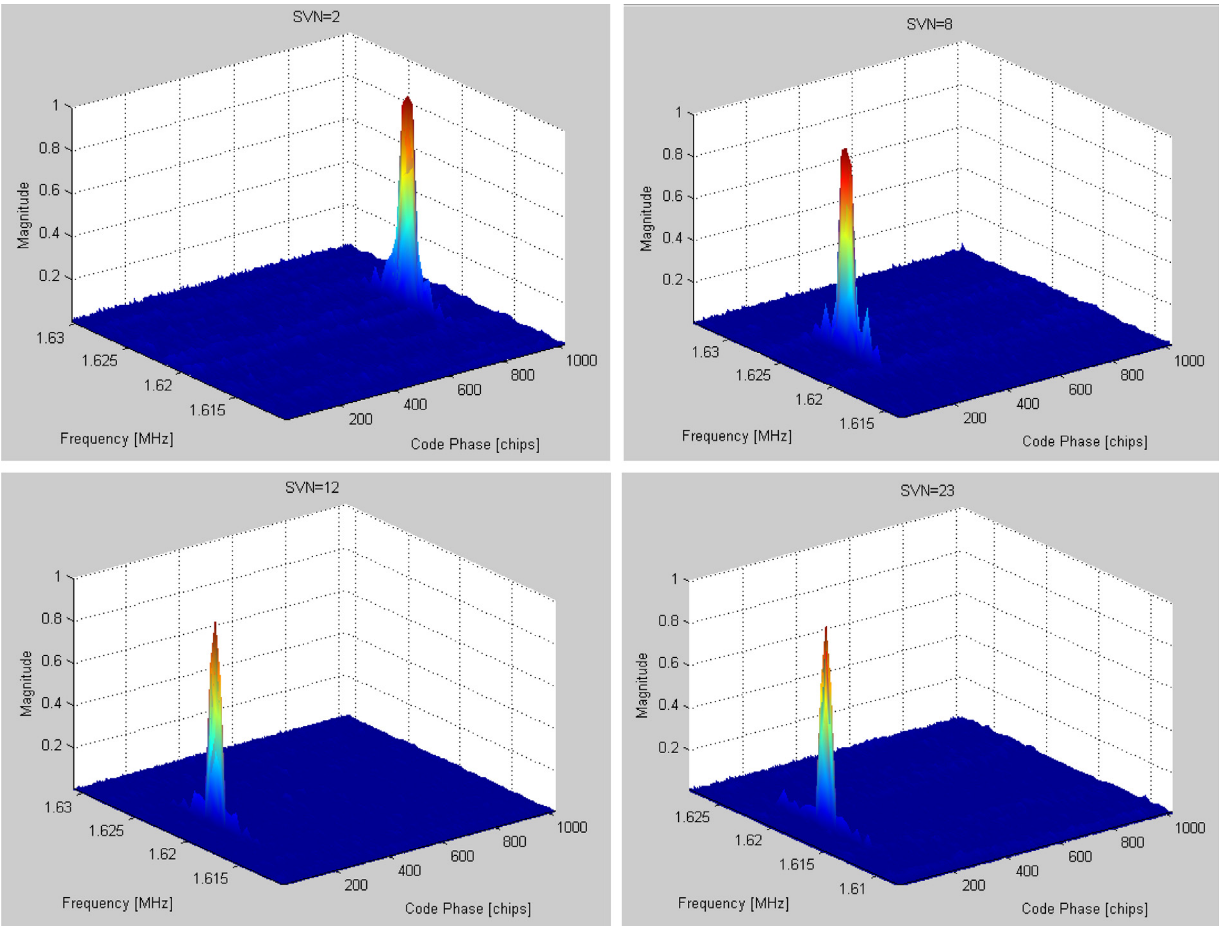

Fig. 9. Acquisition results of SVN-2, 8, 12 and 23.

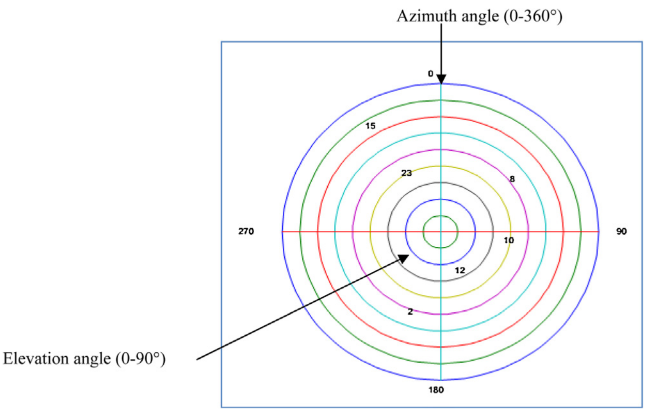

Fig. 10. Sky plot for all-in view satellites.

does not have a clear line of sight. So in the absence of a line of sight, all the multipath components have roughly the same amplitude, then the envelope of the received signal is Rayleigh distributed. But when there is a single dominant stationary signal present, such as the LOS when the transmitter and receiver are relatively close to each other,then the fading envelop is Ricean one. Nakagami fading distribution is used only when there is not one but two or three dominant components from different directions. The latter two distributions seldom arise in the GPS channel scenario

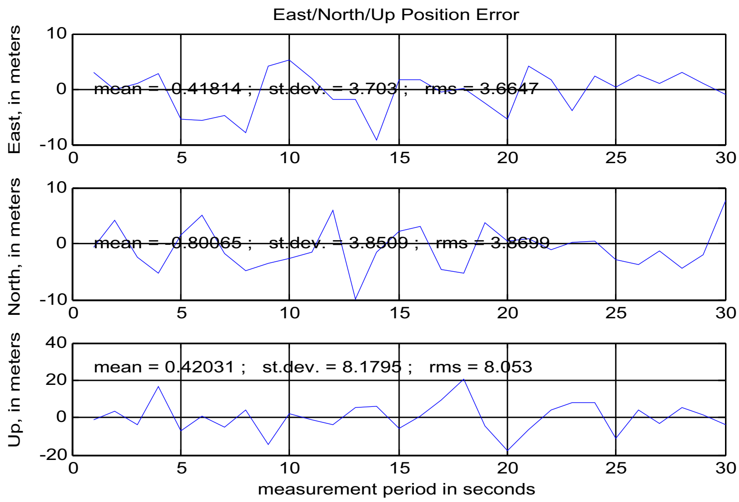

Fig. 11. Navigation error in Easting, Northing and Uping co-ordinates.

in the indoor environment. The Rayleigh fading is widely used model among others during severe multipath conditions. Rao et al. (2013) demonstrated a GPS Ricean fading model in urban environment. Under the non-line-of-sight (NLOS) situation the proposed GPS simulator is implemented.

Inorder to test the various multipath mitigation algorithms like adaptive blind equalization approach (Zhao et al., 2013), wavelet transform approach (Mosavi and Azarbad, 2013) deconvolution approach (Dragunas and Borre, 2011) and sparse reconstruction based algorithm (Xiang et al., 2013) at the receiver side especially in the tracking stage, it is essential to incorporate a multipath channel model into the GPS simulator. Cynthia Junqueir et al. (2002) implemented a Clark fading model of multipath signal generation while designing their GPS signal simulator. Byun et al. (2002) developed a MUSTARD simulator (Multipath Simulator Taking into Account Reflection and Diffraction) which recommends the best antenna type, location, and orientation within the surrounding objects. Djebouri and Djebbouri (2004) implemented a tapped delay line model of the frequency-selective fading to test their averaging correlation algorithm for fast GPS satellite signal acquisition.

The Clarke model has been used to characterize Rayleigh fading channel since from past 3 decades and it has got a widespread acceptance hence it is referred to as a reference model. But, the computational inefficiency results to look for an alternative model. Different Rayleigh fading simulators presented in the literature are respectively, Inverse Discrete Fourier Transform (IDFT) (Young) method, Filtering White Gaussian Noise (FWGN) method and modified Sum of Sinusoidal (SOS) method (modified Jakes). The more detailed description of the IDFT and FWFN methods are available in the literatures (Skima et al., 2014a,b; Özen et al., 2011). In our paper, for FWFN case, an Autoregressive (AR) model is used for filtering the white Gaussian noise. The recently developed modified Jakes fading channel simulator is chosen to characterize the channel and it is developed in this work due to the less computational burden i.e., re-computation of parameters is not required for every change in doppler frequency.

In the modified SOS model, the received signal is given as the superposition of waves (Pop and Beaulieu, 2001).

$$R(t) = \Re\{E_0 \sum_{n=1}^{N} C_n \exp j(\omega_m t \cos A_n + \varphi_n) e^{j\omega_c t}\} \tag{4}$$

where E_0—amplitude of the cosine wave

$C_n = \sqrt{2}/N$—attenuation of the path and distribution of C_n:$2ae^{-a^2}$ where $[0 \leq C_n \leq 1]$

$A_n = \frac{2\pi n + \left(\frac{\theta}{32}\right) - 3\pi/2}{4N}$, $n = 1, 2. \ldots N$—angle of the arrival of nth path. $\theta \sim \cup\,[-\pi, \pi]$

φ_n—phase shift undergone by nth path and distribution of φ_n:. $\varphi_n \sim \cup\,[-\pi, \pi]$

ω_c—transmitted cosine's radian frequency.

ω_m—transmitted doppler radian frequency shift,$\omega_m = 2\pi v_m/\lambda_c$ where λ_c is the wavelength of transmitted cosine wave.

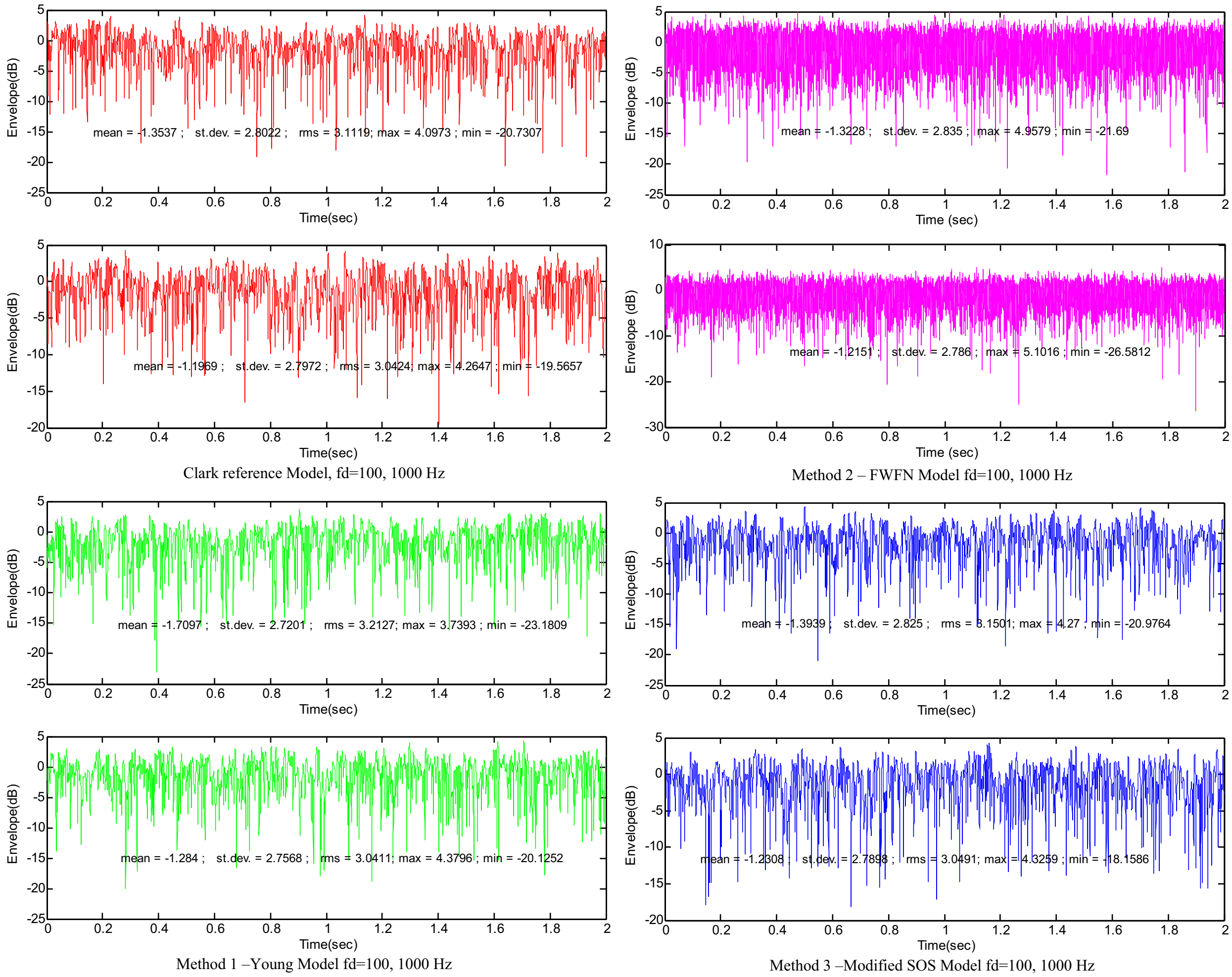

Fig. 12. Envelope of the GPS signal for slow ($f_m = 100$ Hz) and fast ($f_m = 1000$ Hz) fading scenarios.

Where scale factors $\tilde{X}_c(t)$ and $\tilde{X}_s(t)$ are given as

$$\tilde{X}_c(t) = \frac{2}{\sqrt{N}}\left(\sqrt{2}\cos B_{M+1}\cos\omega_m t + 2\sum_{n=1}^{M}\cos B_n \cos\omega_n t\right)$$
$$\tilde{X}_s(t) = \frac{2}{\sqrt{N}}\left(\sqrt{2}\sin B_{M+1}\cos\omega_m t + 2\sum_{n=1}^{M}\sin B_n \cos\omega_n t\right) \quad (5)$$

B_M—bank of low frequency oscillators used.

$$R(t) = \tilde{X}_c(t)\cos\omega_c t + j\tilde{X}_s(t)\sin\omega_c t$$

In this modified Jakes fading model, the simulated GPS signal is represented as the superposition of finite number of waves.The phase is uniformly distributed and the amplitude is Rayleigh distributed. For mobility modeling, it is assumed that the receiver moves at speed v_m. The envelope of the faded GPS signal for 2 s duration of fade at two different Doppler frequencies at $f_m = 100$ Hz and 1000 Hz are simulated for all the models and it is plotted in Fig. 12. The normalized amplitude of GPS signal varies with respect to time when the receiver is moving with a higher Doppler frequency of 1000 Hz. The mean variation and standard deviation of the GPS transmitted signal using modified Jakes model envelope has a bear resemblance to with the Clark reference model. The Histogram plot of the envelope i.e., absolute value of $R(t)$ is shown in Fig. 13 which resembles the Rayleigh distribution. The Rayleigh envelope of the

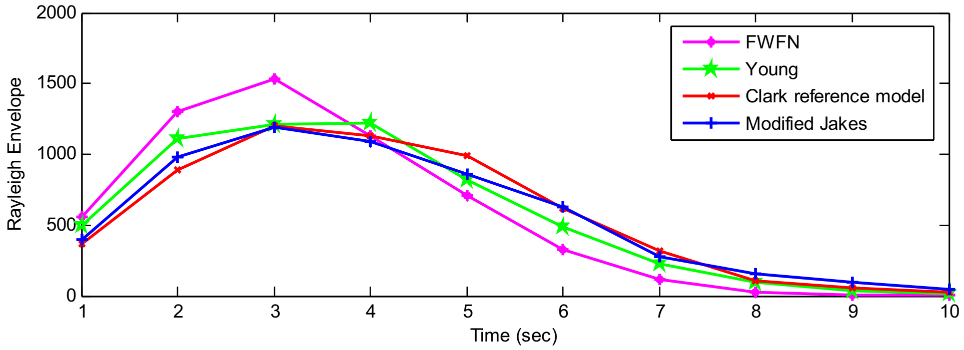

Fig. 13. Histogram plot of the envelope of different fading models tested in GPS simulator.

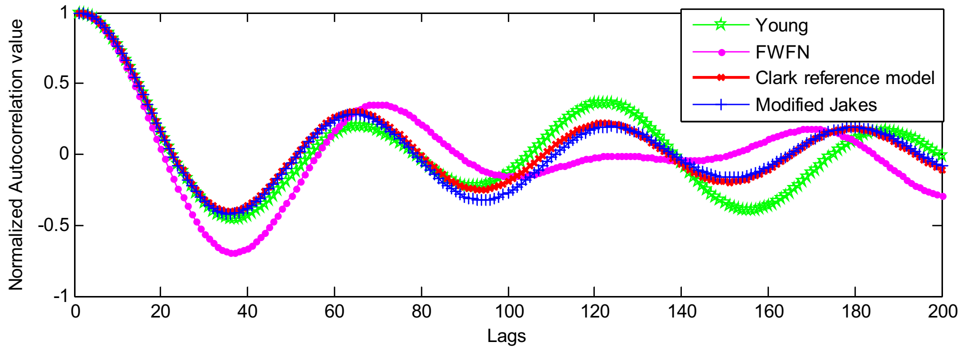

Fig. 14. Autocorrelation plot of different fading models tested in GPS simulator.

modified Jakes fading model closely fits with the Clark reference model and the other two models noticeably deviate from the envelope of the reference model. It is observed that for Modified Jakes fading model, the simulated Auto correlation function (ACF) Rxx (τ) closely matches with the autocorrelation properties of Clark reference model compared to other methods. We can see clearly from Fig. 14 that the Modified Jakes model reproduces the desired ACF more accurately than FWFN and Young models.

5.1. Comparison of different Rayleigh fading simulators tested for GPS signal

There is a need for generating best multipath Rayleigh model in the software GPS simulator in terms of accuracy of their statistical parameters for providing precise position. The existing simulators available in the literature do not have the detailed comparison so far about the Rayleigh model implemented in the GPS signal simulator. In this section the Young, FWFN and modified SOS types of Rayleigh fading model are simulated and compared with the Clark's reference model with respect to their first and the second order statistical metrics. The simulation is carried out for 5714 samples with a Doppler frequency of 100 Hz.

5.1.1. First order metric

The accuracy of the envelope of the PDFs of the reference process to the simulated process is given by Skima et al. (2014a)

$$\text{Kullback-Leibler divergence}\,(\text{KL}-\text{D})_{P||Q} = \sum\nolimits_i P\,(i)\,ln\frac{P\,(i)}{Q\,(i)} \tag{6}$$

where $P\,(i)$ and $Q\,(i)$ are respectively the reference and simulated probability density function envelopes.

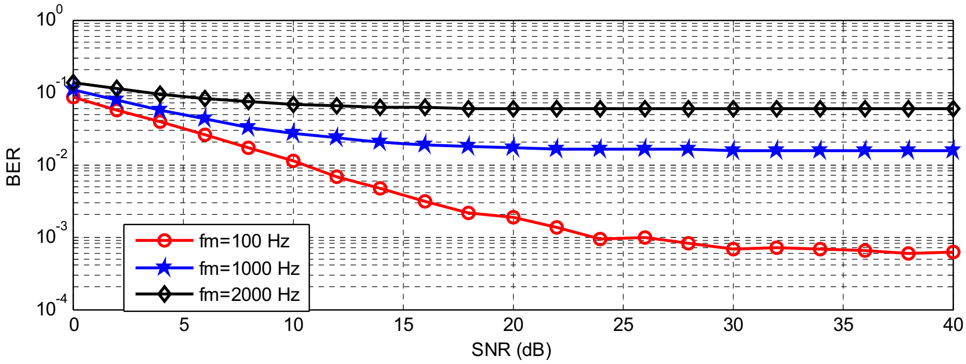

Fig. 15. BER versus SNR of fast and slow moving receiver.

5.1.2. Second order metric

The mean and maximum power margin of the fading model available in the literature are (Skima et al., 2014a)

$$\begin{aligned} \text{Meanpowermargin} &= G_{\text{mean}} = \frac{1}{\sigma_x^2 M}\text{trace}\left(C_x C_{\hat{x}}^{-1} C_x\right) \\ \text{Maximumpowermargin} &= G_{\text{max}} = \frac{1}{\sigma_x^2}\max\left(\text{diag}\left(C_x C_{\hat{x}}^{-1} C_x\right)\right) \end{aligned} \tag{7}$$

where σ_x^2 is the variance of the reference distribution, $C_{\hat{x}}^{-1}$ is the inverse of the covariance matrix of any length M subset of adjacent samples produced by the Rayleigh fading generator, and C_x corresponds to the simulated covariance matrix of ideally distributed samples. These values are expressed in dB. Good performance measure ensures 0 dB for both the metrics. To compute this 2nd order metrics an autocorrelation sequence length of 200 is taken, and the σ_x^2 set to unity. The time average correlations required for estimating the covariance matrix C_x were calculated based on 5714 generated samples. The simulation results were averaged over 10 independent trials.

The mean deviation between two power spectral densities (PSDs) is given as (Skima et al., 2014a)

$$\text{Mean error of PSD} = J_d = \frac{1}{N_{\text{PSD}}}\Sigma_{n=-N_{\text{PSD}}/2}^{N_{\text{PSD}}/2-1}|S^{\text{ref}}\left(\frac{n}{N_{\text{PSD}}}\right) - S^{\text{sim}}\left(\frac{n}{N_{\text{PSD}}}\right)| \tag{8}$$

where N_{PSD} is the number of points in the PSD. S^{ref} and S^{sim} are reference PSD, the simulated PSD process.

The performance of the three fading models is tested using afore mentioned four metrics. The simplest appropriate and accurate multipath model for GPS simulator under non line of sight is found based on the first and the second order statistics as depicted in Table 4. Taking in to account the Clark's model as the reference one while comparing with other three models, although Young model provides good second order statistics (G_{mean} and G_{max}) compared to Jakes and FWFN models but, here all samples are generated with a single Fast Fourier Transform (FFT) which requires huge memory storage hence, it is unable to perform a sample-by sample simulation. The best performance is achieved within modified SOS model when the quantity of sinusoid is more, the $G_$mean and $G_$max values worth quite well and comes closer to zero dB. The value of KL-D i.e., theoretical Rayleigh envelope is exactly matched with the simulated one in the modified SOS model with nominal number of sinusoids (N = 64) (see Fig. 13) and also the mean error PSD conjointly achieved lower value. One vital observation can be viewed from the Table 4 that the significant increase of filter order also does not improve much in the metrics values in the case of FWFN. The simulation is carried out at 1.46 GHz processor with 1 GB memory in MATLAB; the average computation time is calculated for all the three cases. Hence from the Table 4, one can conclude that the modified SOS model with N = 64 is the ideal choice for obtaining the better statistical characteristics.

5.1.3. BER versus SNR for slow and fast receiver dynamics

In our simulation we used 64 sinusoids to generate the channel where the real and imaginary parts of the complex channel are defined by the sinusoids and their phase shifted versions. The plot in Fig. 15 shows the variation caused by the channel as f_m is changed. On increasing f_m the channel becomes fast varying and causes more signal distortion.

Table 4
Performance comparison of Young, FWFN and modified Jakes fading model with reference to the Clark model implemented in GPS signal.

Metrics	Young fading simulator	FWFN fading simulator			Modified Jakes fading simulator					
		Filter order = 50	Filter order = 100	Filter order = 150	$N = 8$	$N = 16$	$N = 32$	$N = 64$	$N = 128$	$N = 256$
G_{mean}	0.0858	8.4469	2.07250	0.4379	6.4848	0.0545	0.0337	0.1841	0.0278	0.0165
G_{max}	1.0303	86.9652	14.5203	3.5693	27.6878	0.6771	0.3072	0.2638	0.2377	0.2182
KL-D	0.0004	1.92657	1.45661	1.4555	0.05568	0.07646	0.76873	0.00043	0.00042	0.00033
Mean error PSD	0.2215	0.92025	0.87028	0.63184	0.29482	0.23376	0.08979	0.01481	0.07583	0.02355
Computation time (s)	5.663801	3.938819	4.135673	4.543647	4.358840	5.196444	6.235781	6.703915	9.009290	10.0876

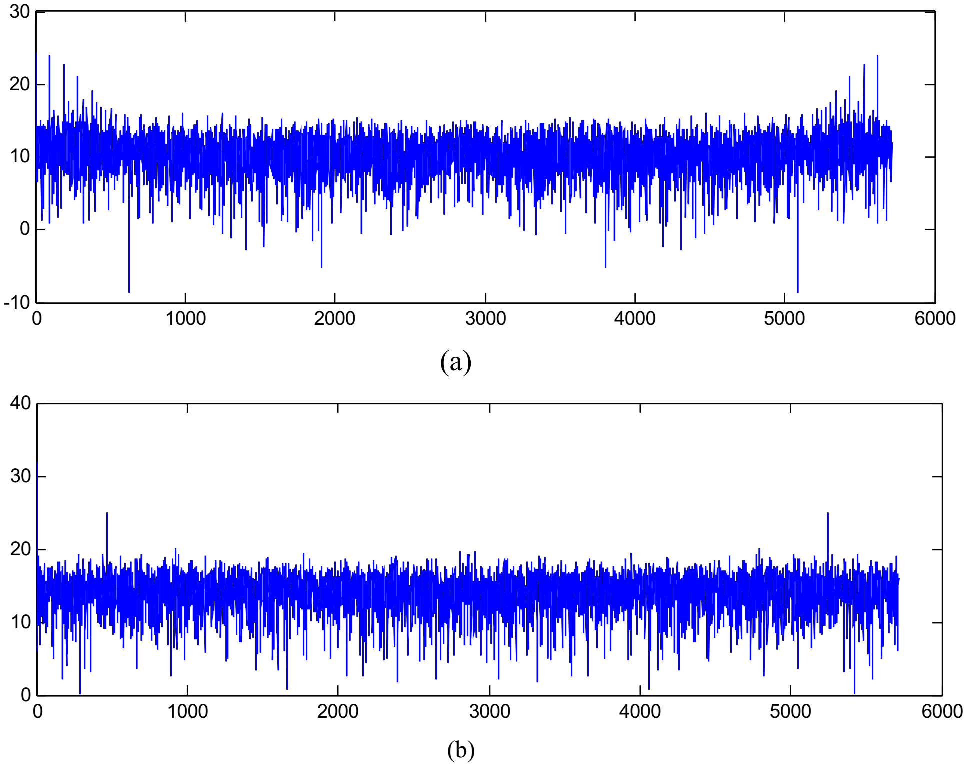

Fig. 16. Faded signal spectrum for different multipath scenarios. (a) f_m = 100 Hz, SNR = 2.0 dB (b), f_m = 1000 Hz, SNR = −12.0 dB.

The BER rate is quite high during fast receiver dynamics i.e., at higher Doppler rates the BER is in the order of 10^{-1}. If the SNR goes beyond 20 dB, the BER is minimum and maintained as constant while at lower SNR the BER is higher.

To design a GPS simulator with extremely low SNR, the provision of adding noise is required to test the weak signal enhancement algorithms in GPS acquisition stage. Usually in the laboratory environment the noise generation is carried out by a separate noise generator and combined with a signal conditioner unit in the hardware platform which is costlier and requires dedicated hardware components. For different multipath scenarios, the proposed simulator generates faded signal with addition of AWGN with different SNR. The spectrum of the faded GPS signal is plotted in Fig. 16a and b.

5.2. *Computation of statistical parameters*

In order to analyze the signal under various receiver dynamics, it is essential that statistical parameter need to be computed. The proposed GPS simulator with modified SOS Rayleigh fading model allows for computation of two parameters namely level crossing rate and average fade duration.

5.2.1. *Level crossing rate computation of slow and fast receiver dynamics*

Level crossing rate is defined as the expected rate at which the Rayleigh fading envelop normalized to the local root mean square signal level crosses a specified threshold level in the positive going direction (Du and Swamy, 2010). The Probability of envelop of the received signal does not exceed a specified value 'R' is given by $p\,(r \le R) = \int_O^R p\,(r)\,dr = 1 - e^{-\frac{r^2}{2\sigma^2}}$, where σ is r.m.s value of the envelope of the received signal. The level crossing rate is given as (Du and Swamy, 2010) $N_R = \sqrt{2\pi f_m \rho e^{-\rho^2}}$ Where $\rho = R/r_{rms}$ and $r_{rms} = \sqrt{2}\sigma$, here $\rho = 1$ (Threshold = r.m.s value). The level crossing rate of fast and slow fade scenarios are calculated using the envelope detector while a moving vehicle is under deep fade. Based on this definition the statistical parameters like how many times the envelope of the faded signal stay below a certain threshold, how long period the receiver is under deep fade and how the signal strength is varying

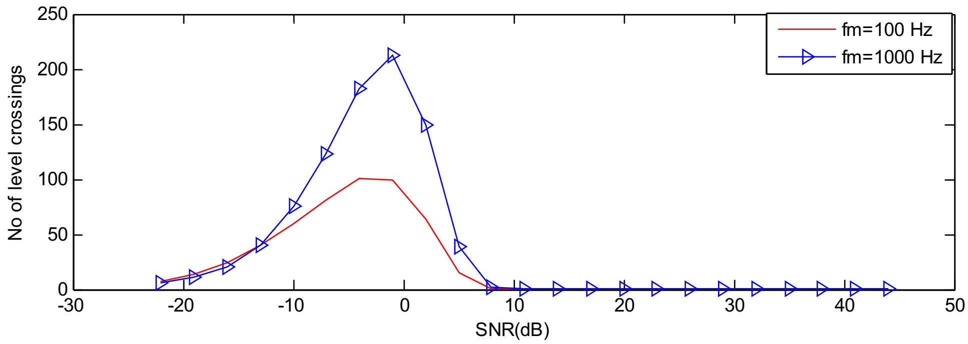

Fig. 17. Level crossing rate for slow and fast receiver dynamics.

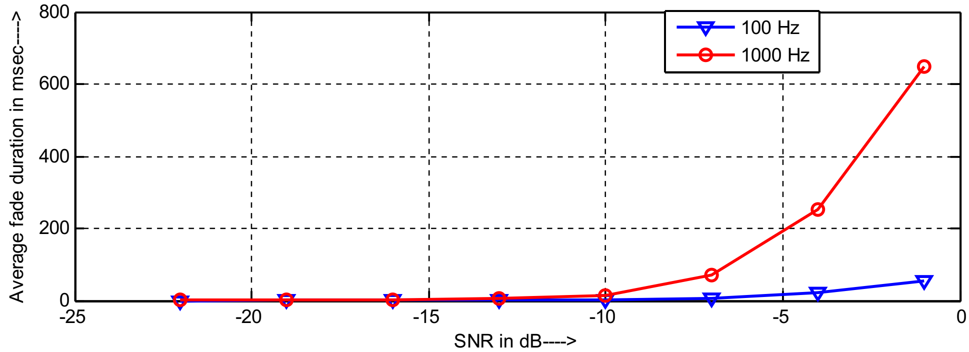

Fig. 18. Average fade duration for slow and fast receiver dynamics.

are calculated. The level crossing rate with Doppler frequency of 100 Hz has the maximum rate of 100 crossings and at higher Doppler frequency about 1000 Hz, the level crossing rate is increased two fold times as shown in Fig. 17.

5.2.2. Calculation of average fade duration for slow and fast receiver dynamics

The channel model has an option of analyzing the fade duration during the slow and fast receiver dynamics. Outage occurs when the envelope fades below a critical level for a long period and then the receiver synchronization is lost .The average fade duration is calculated as the total length of time that the envelop is below the threshold to the average number of crossings (Du and Swamy, 2010). The average time for which the received signal below the specified level 'R' is given by (Du and Swamy, 2010) $\tau = e^{-\rho^2 - 1} / \left(\rho f_{m\sqrt{2\pi}}\right)$. The simulation is carried out for the total time of 5 s duration for the calculation of average duration for slow and fast receiver dynamics at two different Doppler frequencies is shown in Fig. 18. In 100 Hz, the signal is under deep fade for 56 ms period, which is not a healthy scenario and this leads to burst errors. The GPS data rate is 50 bps, then the number bits received in-correctly at the receiver side would be around $56 \times 10^{-3} \times 50 = 3$ bits. At higher Doppler rate of 1000 Hz, the BER becomes still worsen (33 in-correct bits). Due to this burst error the lock will not be achieved in the Phase Locked Loop (PLL) and Delay Locked Loop (DLL) of the tracking stage of the receiver and the bit synchronization algorithm fails to extract the frame of the GPS data, hence the GPS receiver has to employ sophisticated algorithms to establish the lock and to compensate the PLL and DLL errors to demodulate the navigation data successfully.

5.3. Performance evaluation of the proposed simulator

The proposed simulator implemented with the novel complete software oriented architecture benefits all aspects of design parameters. The entire module is designed to cope with the addition of future GNSS signals with higher flexibility and re-configuration. The accuracy in navigation data generation compared with the other simulators is good since the parameter computation unit is implemented in software with IEEE-754 floating point conversion and also

Table 5
Performance comparison of proposed GPS simulator with others existing in the literature.

GPS simulators	Overall design hardware/software	Signal formation unit (SFU) implementation	Accuracy in generation of navigation data	Multipath channel model and noise generation	Simulation time
Gao et al. (2012)	Hardware	Hardware (FPGA)	Good	Separate hardware required	Not mentioned
Magiera (2012)	Partially hardware and software	Hardware (FPGA)	Not mentioned	Not incorporated	Not mentioned
Deng and Wang (2011)	Software	Software (SIMULINK)	Not mentioned	Not incorporated	Not mentioned
Hu et al. (2009)	Software (MATLAB & some key functions in 'C')	Software (MATLAB)	Not mentioned	Not incorporated	Not mentioned
Wang et al. (2010)	Software	MATLAB	Not mentioned	Not incorporated	20 s for 1 ms IF signal excluding Multipath
Guo et al. (2009)	Software	MATLAB	Not mentioned	Not incorporated	Not mentioned
Li et al. (2008)	Software (MATLAB & some key functions in 'C')	MATLAB	7 m	Not incorporated	Not mentioned
Proposed simulator	Software (only in 'C')	C (VC++ platform)	Good Horizontal position error 6.1640 m	Rayleigh multipath channel fading model under non-line of sight conditions with fast and slow receiver dynamics incorporated (MATLAB)	Low (12.34 s for 1 ms IF data) including Multipath

the simulation time 12.34 s (digitized IF signal generation time (5.636085 s) + channel simulation time (6.703915 s)) is greatly reduced. The proposed simulator outperforms in all aspects of architecture design, accuracy and simulation speed compared to others as shown in Table 5.

6. Conclusion

A novel complete software based GPS signal simulator is designed as per the user requirements with provision to reconfigure the parameters involved in the signal generation particularly the Signal Formation and Parameter Computation blocks implemented in software to cope up with realizing of future GNSS signals. This novel and simple software tool enables researchers to investigate and test the performance of the software GPS receiver's functionality in a laboratory environment whereas not employing expensive hardware equipments. The multipath channel effect is also incorporated which provides the real time scenario signal from GPS satellites. The aim of reducing the computational effort and improving the accuracy of the desired statistical properties of the simulator is achieved by implementing Modified SOS-based fading model with smaller number of sinusoids in GPS signal under non line of sight scenario. Furthermore the statistical parameters of level crossing rate and the average fade duration calculation for fast and slow receiver dynamics are helpful for analyzing the signal strength variation with reference to the speed of the vehicles while designing the different multipath mitigation algorithms in GPS receiver module.

References

Boopalan, G., Prasad, S.V.M.K., Ramakrishna, P.V., Vaidehi, V., Krishnan, C.N., Rajagopal, L.R., 2002. Hardware design for GPS signal simulators. In: NCC-2002, Jan 25–27, IIT Bombay, pp. 84–89, 23.

Borre, Kai, Akos, Dennis M., Bertelsen, Nicolaj, Rinder, Peter, Jensen, Soren Holdt, 2007. A Software Defined GPS and Galileo Receiver. Birkhäuser, Bostonin, ISBN-10 978-0-8176-4390-4.

Braasch, Michel S., Van Dierendonck, A.J., 1999. GPS receiver architecture and measurements. Proceedings of the IEEE vol. 87, 48–64.

Byun, Sung H., Hajj, George A., Young, Lawrence E., 2002. Development and application of GPS signal multipath simulator. Radio Sci. 37 (6), pp. 10-1–10-23.

Deng, Chao, Wang, Dan-Dan, 2011. Study and simulation of digital IF GPS signals. International Conference on Machine Learning and Cybernetics (ICMLC) vol. 2, 544–547.

Djebouri, D., Djebbouri, Djebbari M., 2004. Averaging correlation for fast GPS satellite signal acquisition in multipath Rayleigh fading channels. Microw. J. 47 (8), 66–82.

Dragunas, Kostas, Borre, Kai, 2011. Multipath mitigation based on de-convolution. J. Global Position. Syst. 10 (1), 79–88.

Du, Ke-Lin, Swamy, M.N.S., 2010. Wireless Communication Systems-From RF Systems to 4G Enabling Technologies. Cambridge University Press.

Gao, Yue-yun, Li, Yong-hong, Feng, Qiao-ling, Wang, Yu-long, 2012. Research of intermediate frequency GPS signal simulator based on FPGA. International Conference on Computer Science & Service System, 1095–1098.

Guo, Jiming, Wang, Wei, Chao, Baichong, 2009. Model of GPS IF signal and its simulation. Geo: Spat. Inform. Sci. 12 (2), 100–103.

Hu, Yongkang, Yang, Dongkai, Zhang, Yiqiang, Zhang, Qishan, 2009. Development of a software-based IF GPS signal simulator. Proceedings of the SPIE, International Conference on Space Information Technology vol. 7651, article id. 76513W.

Junqueir, Cynthia, Filho, Danilo Zanatta, Filho, João Batista Destro, Loiola, Murilo B., Romano, João Marcos T., 2002. A GPS simulator for analysis of channel impairments in practical scenarios. In: International Telecommunications Symposium, Natal, Brazil.

Li, Cheng Jun, Qian, Yi, Lu, Mingquan, Feng, Zhengming, 2008. The design and implement of GPS software simulation platform. 7th International Conference on System Simulation and Scientific Computing, ICSC 2008. Asia Simulation Conference, 186–191.

Magiera, J., 2012. Design and implementation of GPS signal simulator. International Conference on Localization and GNSS (ICL-GNSS), 1–4, 25–27.

Meng, Jian, Wang, Chunli, Li, Qiqin, 2002. Research of GPS simulation technique. Proceedings of 3rd International Conference on Microwave and Millimeter Wave Technology, 2002, 365–368.

Mosavi, M.R., Azarbad, M.R., 2013. Multipath error mitigation based on wavelet transform in L1 GPS receivers for kinematic applications. AEU: Int. J. Electron. Commun. 67 (10), 875–884.

Özen, Serdar, Arsal, Ali, Toker, Kadir Atilla, 2011. Hardware realization of a low-complexity fading filter for multipath Rayleigh fading simulator. Electr. Eng. 93 (June (2)), 83–90.

Pop, Marius F., Beaulieu, Norman C., 2001. Limitations of sum-of-sinusoids fading channel simulators. IEEE Trans. Commun. 49 (4).

Prasad, S.V.M.K., Vaidehi, V., Ramakrishna, P.V., Krishnan, C.N., Sarangaram, T.A., Boopalan, G., Nagalakshmi, N., Nappinnai, S., 2003. Design of a real-time GPS satellite signal simulator on the MULTISHARC parallel processing system. Navigation 50 (1), 57–64.

Rao, G. Sasi Bhushana, Sateesh Kumar, G., Kumar, M.N.V.S.S., 2013. GPS signal Rician fading model for precise navigation in urban environment. Indian J. Radio Space Phys. 42, 192–196.

Skima, M.A., et al., 2014a. A multi-criteria comparative analysis of different Rayleigh fading channel simulators. Int. J. Electron. Commun. (AEÜ), http://dx.doi.org/10.1016/j.aeue.2014.01.001.

Skima, Mohamed Ali, Boulaaba, Amira, Ghariani, Hamadi, 2014b. On the performance of the sum-of-sinusoids simulation models for Rayleigh fading channels. Recent Adv. Telecommun. Inform. Educ. Technol., ISBN: 978-1-61804-262-0.

Tan, Thiam Hock, 2003. Global Positioning System Signal Simulation, Thesis Report. Department of Information Technology and Electrical Engineering, University of Queensland.

Tang, Bin, Liu, Shushi, Tang, Weitao, Dong, Xurong, 2006. Design a L1 software GPS receiver based on IF GPS signal simulator. 8th International Conference on Signal Processing vol. 3, 16–20.

Tsui, James Bao-Yen, 2000. Fundamentals of Global Positioning System Receivers, A Software Approach, 2nd ed. Artech House, Boston.

Wang, Jun, Xi, Xiaoli, Liu, Jiangfan, 2010. The design of GPS IF signal software simulator. International Symposium on Signals Systems and Electronics (ISSSE) vol. 1, 1–3, 17–20.

Xiang, Fei, Liao, Guisheng, Zeng, Cao, Wang, Weiwei, 2013. A multipath mitigation discriminator for GPS receiver. AEU: Int. J. Electron. Commun. 67 (10), 839–847.

Zhao, Yun, Xue, Xiaonan, Zhang, Tingfei, 2013. Receiver-channel based adaptive blind equalization approach for GPS dynamic multipath mitigation. Chin. J. Aeronaut. 26 (2), 378–384.