Implementation of Open Source Software NavIC L1 Transmitter and Receiver

Satheesh Kumar Simhachalam
PhD Scholar
EE Department, IIT Hyderabad
Telangana, India - 502284
gadepall@ee.iith.ac.in

Dr G.V.V.Sharma
Associate Professor
EE Department, IIT Hyderabad
Telangana, India - 502284
gadepall@ee.iith.ac.in

Dr. Kuchi Kiran Kumar
Professor
EE Department, IIT Hyderabad
Telangana, India - 502284
kkuchi@ee.iith.ac.in

***Abstract*—This paper presents an open source software implementation of NavIC L1 transmitter and receiver for SPS singal used for civilian purposes. It describes signal chacteristics, various singal processing blocks of both transmitter & receiver and channel modelling details. Simulation results are presented using random Navigation data genereated at transmitter end and verifying the same at receiver end.**

***Index Terms*—NavIC, SPS singal, BCH, LDPC, BOC signal, Navigation (NAV) message, Acquisition, Tracking, Encoder, Decoder, Demodulator**

I. Introduction

NavIC is an independent regional navigation satellite system developed and maintained by Indian Space Research Organisation (ISRO). It provides accurate position and timing services to users in India as well as the region extending upto 1500 km from its boundary. NavIC provides two types of services, namely, Standard Positioning Service (SPS) and Restricted Service (RS) with a position accuracy of better than 20m over the primary service area and timing accuracy better than 50ns.

The current NavIC satellite constellation comprises of six operational navigation satellites, out of which one satellite has civilian L1 band (1575.42 MHz) transponder providing SPS service for low power receivers. ISRO has plans to launch more satellites with L1 band, in future. SPS signals from NavIC are interoperable with other GNSS systems like GPS and GLONASS etc.

The Government of India mandated all mobile device manufatures to have support for navigation using NavIC in all the devices being used in India. Hence, there is a growing need for NavIC software implementations. [1] describes open source software implementation for Galileo signal, however, for Navic L1, no such implementation was found in the literature survey. So, this paper focuses on building an open source software implementation of Navic L1 transmitter (to simulate Navic L1 signal) and NavIC L1 receiver for SPS services.

The scope of implementation (done in Python) is limited to generating an SPS baseband signal, sending baseband signal (without a carrier) thorugh transmitter module, mixing it with channel modelling module and verifying that the same navigations bits are received at the output of the receiver module.

II. System Overview

The block diagram of the system is shown in Figure 1. Navigation data is randomly generated and subframes & master frames are created as per the frame structure described in subsequent sections. The transmitter module creates the required baseband signal as per the modulation scheme, with relevant channel encoding schemes and error correction & detection schemes. Channel modelling module adds various modelling parameters and AWGN noise to the baseband signals for different satellites, forming a composite signal. The receiver module receives the composite signal, processes it to extract the navigation data, that was originally sent.

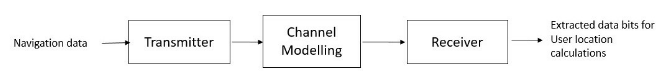

Fig. 1: System Overview

III. Software Implementation of Transmitter

The NavIC transmitter is simulated to send baseband signal to the channel as shown in Fig 2.

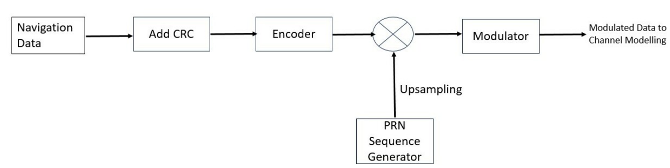

Fig. 2: Transmitter Block diagram

A. Modulation Scheme

The SPS signal is modulated using Synthesized Binary Offset Carrier (SBOC) modulation scheme [2], comprising of data signal and pilot signal. Both these signals contain BOC(1,1) and BOC(6,1) components. In this modulation scheme, data channel BOC(6,1) component is generated by interplexing data channel BOC(1,1), pilot channel BOC(1,1) and pilot channel BOC(6,1) components. Subsequently, the data and the pilot signals are quadrature multiplexed with each other with power sharing of 41.82% and 58.18%, respectively for each of the signals to provide the constant envelope modulation.

1) Mathematical Equations: The mathematical representation [1], [2] of baseband navigation signals is as follows:

Pilot Signal:

$$S_{p,a}(t) = \sum_{i=-\infty}^{\infty} C_{p,s}(|i|_{1800}) \oplus \sum_{j=1}^{10230} C_{p,p}([j]) \cdot \\ \mathrm{rect}_{T_{c,p,p}}\left(t - iT_{c,p,s} - jT_{c,p,p}\right) \cdot sc_{p,a}(t,0) \quad (1)$$

$$S_{p,b}(t) = \sum_{i=-\infty}^{\infty} C_{p,s}(|i|_{1800}) \oplus \sum_{j=1}^{10230} C_{p,p}([j]) \cdot \\ \mathrm{rect}_{T_{c,p,p}}\left(t - iT_{c,p,s} - jT_{c,p,p}\right) \cdot sc_{p,b}(t,0) \quad (2)$$

where $C_{p,p}$ is pilot primary PRN code, $C_{p,s}$ is pilot secondary/overlay PRN code, $T_{c,p,p} = \frac{1}{1.023}\mu$s and $T_{c,p,s} = 10$ms. $|i|_L$ means i modulo L.

$S_{p,a}$ is sinBOC(1,1) component of pilot signal and $S_{p,b}$ is sinBOC(6,1) component of pilot signal.

The Binary NRZ sub-carrier is defined as:

$$sc_{p,x}(t,\varphi) = \mathrm{sgn}[\sin(2\pi f_{sc,x}t + \varphi)] \quad (3)$$

The subcarrier signals are sinBOC. Hence, the subcarrier phase $\varphi = 0$.

Data Signal:

$$S_{d,a}(t) = \sum_{i=-\infty}^{\infty} C_d(|i|_{10230}) \oplus d_d([i]_{10230}) \cdot \\ \mathrm{rect}_{T_{c,d}}\left(t - iT_{c,d}\right) \cdot sc_{d,a}(t,0) \quad (4)$$

where $T_{c,d} = \frac{1}{1.023}\mu$s and $[i]_L$ means the integer part of $\frac{i}{L}$.

The interplexed component $S_{d,b}(t)$ is given by:

$$S_{d,b}(t) = \sum_{i=-\infty}^{\infty} C_d(|i|_{10230}) \oplus d_d([i]_{10230}) \cdot \\ \mathrm{rect}_{T_{c,d}}\left(t - iT_{c,d}\right) \cdot sc_{d,b}(t,0) \quad (5)$$

The above equation can also be represented as

$$S_{d,b}(t) = S_{p,a}(t) \cdot S_{p,b}(t) \cdot S_{d,a}(t) \quad (6)$$

The Binary NRZ sub-carrier is defined as:

$$sc_{d,x}(t,\varphi) = \mathrm{sgn}[\sin(2\pi f_{sc,x}t + \varphi)] \quad (7)$$

The subcarrier signals are sinBOC. Hence, the subcarrier phase $\phi = 0$.

$f_{sc,a}$ is Sub-carrier frequency of $sc_{p,a}$ and $sc_{d,a}$ sub-carriers and equal to 1.023 MHz. $f_{sc,b}$ is Sub-carrier frequency of $sc_{p,b}$ and $sc_{d,b}$ sub-carriers and equal to 6.138 MHz.

Ranging code C_d, defined in (4) and (5), includes only primary code of data channel.

The composite SBOC modulated signal $S(t)$ is generated by quadrature multiplexing of data and pilot signals, as given below:

$$S(t) = [\alpha S_{p,a}(t) - \beta S_{p,b}(t)] + j[\gamma S_{d,a}(t) + \eta S_{d,b}(t)] \quad (8)$$

where $\alpha = \sqrt{\frac{6}{11}}$, $\beta = \sqrt{\frac{4}{110}}$, $\gamma = \sqrt{\frac{4}{11}}$ and $\eta = \sqrt{\frac{6}{110}}$

The baseband composite SBOC modulated signal $S(t)$ can also be denoted as:

$$S(t) = S_I(t) + jS_Q(t) \quad (9)$$

Based on (9), the band-pass representation of the SBOC modulated navigation signal $(S_{RF}(t))$ at L1 band is defined as follows:

$$S_{RF}(t) = S_I(t) \cdot \cos(2\pi f_{L1}t) - S_Q(t) \cdot \sin(2\pi f_{L1}t) \quad (10)$$

where f_{L1} is equal to 1575.42 MHz.

B. Navigation Message structure

The NavIC L1 Master Frame [2] is of 1800 symbols long made of 3 subframes. Subframe 1 consists of 52 symbols, Subframe 2 is composed of 1200 symbols, and Subframe 3 is comprised of 548 symbols. The master frame structure is shown in Figure 3.

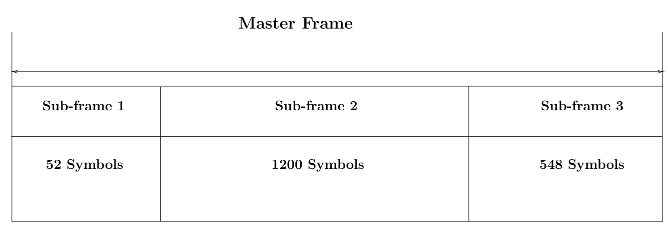

Fig. 3: Master Frame Structure

The subframe structure is as shown in Figure 4 [2].

Subframe 1 consists of 9 bits that are BCH encoded into 52 symbols. Subframe 2 has a total of 600 bits, comprising 576 bits for primary navigation parameters and 24 bits for CRC. Subframe 3 contains a total of 274 bits, with 250 bits for secondary navigation parameters and 24 bits for CRC. Both subframe 2 and subframe 3 are separately encoded using rate $\frac{1}{2}$ Quasi Cyclic LDPC codes. This results in 1200 symbols for subframe 2 and 548 symbols for subframe 3 as shown in Figure 4.

The CRC of data signal follows 24Q polynomial for subframe 2 and subframe 3. Any burst errors during the data transmission are corrected by interleaving. In matrix interleaving, input symbols are filled into a matrix column-wise and read at the output row-wise. Subframe 2 and subframe 3 are together interleaved using 46 columns $\times$ 38 rows.

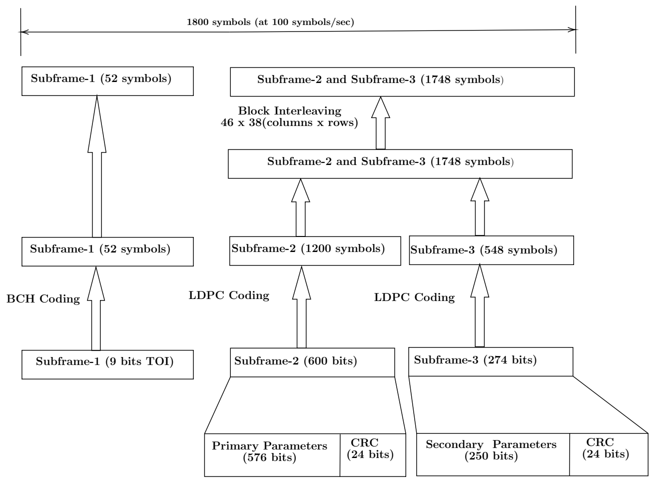

Fig. 4: NavIC L1 SPS Subframe Structure

C. PRN Codes

Each satellite is assigned a unique PRN ranging code number, termed as PRN ID. The L1 SPS PRN ranging codes for both pilot and data channels associated to a PRN ID "i" are all distinct, independent and are time-synchronized codes. Both these ranging codes have a period of 10230 chips which translates to 10 milliseconds in length when operating at a chipping rate of 1.023 Mcps.

Furthermore, the pilot channel's primary PRN code is modulated with a secondary overlay code with a length of 1800 and a period of 18s at a rate of 100 chips per second. The overlay codes for each satellite are distinct and independent. Thus, the PRN code structure for the L1 pilot component is that of a tiered code, that is generated by XOR-ing the primary pilot code with the secondary or overlay code. This is shown in Figure 5 [2].

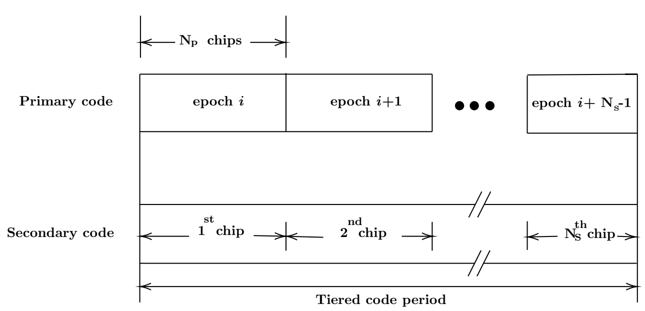

Fig. 5: Tiered code structure and timing relationship between primary and secondary codes

IV. Channel Modelling

The following parameters are modelled in the satellite communication channel:

1) Doppler shift
2) Delay
3) Power scaling and
4) Thermal noise at the receiver

A. Doppler shift

Due to relative motion between the satellites and the receiver, the transmitted signals undergo a frequency shift before arriving at the receiver. This shift in frequency is called Doppler shift.

The Doppler shift is introduced by muliplying the satellite signal with a complex exponential,

$$x_{Shift}\left[n\right] = x\left[n\right]e^{-2\pi j\left(f_c + f_{Shift}\right)nt_s} \tag{11}$$

where, $x_{Shift}\left[n\right]$ = Doppler shifted signal
$x\left[n\right]$ = Satellite signal
t_s = Sampling period

B. Delay

Since there is a finite distance between the satellite and the receiver, the signal at the reciever is a delayed version of the transmitted signal. This delay is given by

$$D_s = \frac{d}{c}f_s \tag{12}$$

where,
D_s = Total delay in samples
d = Distance between satellite and receiver
c = Speed of light
f_s = Sampling rate

The total delay on the satellite signal is modeled in two steps. First,to introduce the static delay, the samples are read from a queue whose size is the desired static delay length. To introduce the variable delay, the signal is passed throughan all-pass FIR filter with an almost constant phase response. Its coefficients are calculated using the delay value required.

C. Power Scaling

When a transmitting antenna transmits radio waves to a receiving antenna, the radio wave power received is given by,

$$P_r = P_t D_t D_r \left(\frac{1}{4\pi\left(f_c + f_{Shift}\right)D}\right)^2 \tag{13}$$

where,
P_r = Received power
P_t = Transmitted power
D_t = Directivity of transmitting antenna
D_r = Directivity of receiving antenna
D = Total delay in seconds

To scale the received signal as per the received power calculated,

$$x_{Scaled}\left[n\right] = \frac{\sqrt{P_r}}{\mathrm{rms}\left(x\left[n\right]\right)}x\left[n\right] \tag{14}$$

D. Thermal noise

The thermal noise power at the receiver is given by,

$$N_r = kTB \tag{15}$$

where,

N_r = Noise power in watts
k = Boltzmann's constant
T = Temperature in Kelvin
B = Bandwidth in Hz

AWGN (Additive White Guassian Noise) samples with zero mean and variance N_r are generated and added to the satellite signal to model thermal noise at receiver.

V. Software Implementation of Receiver

The block diagram of the receiver is as shown in Figure 6.

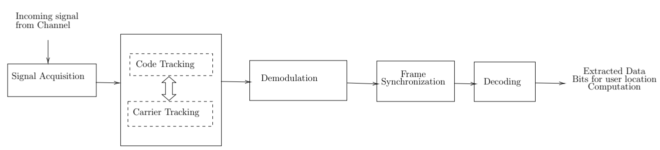

Fig. 6: The Block Level Architecture for Receiver

The signal processing chain at the receiver is divided into five steps:

1) Acquisition
2) Tracking
   a) Carrier Tracking
   b) Code Tracking
3) Demodulation
4) Frame synchronisation
5) Channel decoding

A. Acquistion

A generic NavIC L1 SPS signal is defined by its complex baseband equivalent, $S_T(t)$, the digital signal at the input of an Acquisition block can be written as:

$$x_{IN}[k] = A(t)\hat{s}_T(t-\tau(t))e^{j(2\pi f_D(t)t+\Phi(t))}\Big|_{t=kT_s} + n(t)\Big|_{t=kT_s} \tag{16}$$

where f_D is Doopler shift frequency, τ is PRN Code delay,Φ is Phase shift and $n(t)$ is AWGN noise.

The role of the acqusition block is to examine the presence/absence of signals coming from a given satellite. In the case of signal being present, it should provide coarse estimations of the Code delay (τ) and the Carrier Doppler shift (f_D), yet accurate enough to initialize the carrier and code tracking loops.

1) Implementation of PCPS Acquisition: The Parallel Code Phase Search (PCPS) algorithm [1], [3] is used in Acquisition block and is shown in Figure 7. in the 2-dimnesional search, the frequency bin having maximum input signal power is determined as coarse doppler frequency (f_D). The index at which the peak power is present in that frequency bin is termed as coarse Code delay (τ). These values are passed to the Tracking module. If the Input signal power is less than a threshold, then the satellite is considered to be non-visible. Under low SNR conditions, samples from 2-3 successive coherent integration periods can be added to have a better acquisition sensitivty.

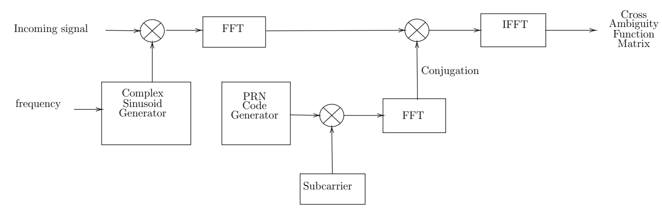

Fig. 7: PCPS algorithm flow

B. Tracking

The role of tracking block [5] is to refine coarse estimations and follow signal synchronization parameters: code phase, Doppler shift and carrier phase and extract the baseband signal. It performs the following 3 functions to decipher the baseband signal from the incoming signal as shown in figure 8. The tracking algorithm specified in [1] is used in this work.

1) Carrier and code wipeoff
2) Pre-detection integration
3) Baseband signal processing

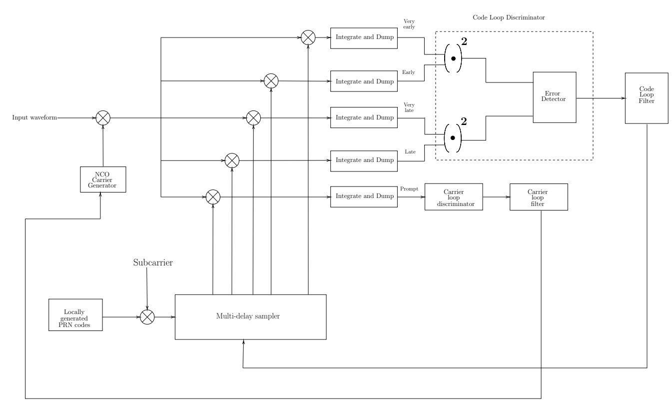

Fig. 8: Tracking block diagram

1) Carrier and code wipeoff: **Carrier wipeoff:** Referring to the Figure 8, first, the incoming signal is stripped off the carrier (plus carrier Doppler) by a local replica carrier (plus carrier Doppler) signals. The replica carrier (including carrier Doppler) signals are synthesized by the carrier numerically controlled oscillator (NCO). In closed loop operation, the carrier NCO is controlled by the carrier tracking loop in the receiver processor.

Code wipeoff: ACF of BOC signal contains 2 locals maximas, apart from having a global maxima at 0^{th} chip delay. To detect these maximas, the received signal is correlated with Very Early(VE), Early(E), Prompt(P), Late(L) and Very Late(VL) local replica codes (plus code Doppler) synthesized by a multi-delay sampler. In the closed loop operation, the code NCO is controlled by the code tracking loop in the receiver processor. E and L are typically separated in phase by 0.3 chips. VE and VL are separated by 1.2 chips. The prompt replica code phase is aligned with the incoming satellite code phase producing maximum correlation if it is tracking the incoming satellite code phase. Any misalignment in the replica code phase with respect to the incoming code phase produces a difference in the vector magnitudes of the VE,E,L and VL correlated outputs so that the amount and direction of the phase change can be detected and corrected by the code tracking loop.

2) Pre-detection and integration: Extensive digital predetection integration and dump processes occur after the carrier and code wiping off processes. Figure 8 shows five complex correlators required to produce five components, which are integrated and dumped to produce VE,E,P,L,VL vesions of the signal.

3) Baseband signal processing: This entails Carrier tracking and Code tracking using Phase locked loop (PLL), Frequency locked loop (FLL) and Delay locked loop (DLL).

Phase locked loop(PLL)

The carrier loop discriminator defines the type of tracking loop as a PLL, a Costas PLL (which is a PLL-type discriminator that tolerates the presence of data modulation on the baseband signal), or a frequency lock loop (FLL). Carrier tracking loop tracks the frequency and phase of the received signal by detecting the phase error between replicated signal and incoming signal. This error is fed through loop filter to Carrier NCO so as to adjust its frequency and phase to synchronize with incoming signal in both frequency and phase. For very low phase error detected, navigation data is accurately extracted.

$$\text{Phase error}_{pilot} = ATAN2(I_P, Q_P) = \tan^{-1}\left(\frac{I_P}{Q_P}\right) \tag{17}$$

Frequency locked loop

PLLs replicate the exact phase and frequency of the incoming signal to perform the carrier wipeoff function. FLLs perform the carrier wipeoff process by replicating the approximate frequency, and they typically permit the phase to rotate with respect to the incoming carrier signal. The algorithm used in FLL discriminator is $\frac{\text{ATAN2}(cross, dot)}{t_2 - t_1}$. The frequency error is given by

$$\text{Frequency error} = \frac{\phi_2 - \phi_1}{t_2 - t_1} \tag{18}$$

The phase change $\phi_2 - \phi_1$ between two adjacent samples of I_P and Q_P at times t_2 and t_1 is computed. This phase change in a fixed interval of time is proportinal to frequenct error in the carrier tracking loop. The error is fed to carrier NCO through a loop filter to adjust the frequency to lock to the right frequency.

Delay locked loop: Post the carrier signal synchronization, received code samples are synchronized by aligning with locally replicated code samples by shifting right or left. To determine the direction of shift, the I and Q outputs are multiplied with prompt code (PRN code which is phase aligned), E and VE code (prompt PRN code shifted by some samples to the left) and L,VL code (prompt PRN code shifted by some samples to the right) resulting in corresponding I and Q channel respectively. Following algorithm is used to lock the code phase.

$$E_K = \sqrt{VE^2 + E^2} \tag{19}$$

$$L_K = \sqrt{VL^2 + L^2} \tag{20}$$

$$\text{DLL Discriminator}(\epsilon) = \frac{1}{2}\frac{E_K - L_K}{E_K + L_K} \tag{21}$$

If the replica code is aligned, then the E & L and VE & VL envelopes are equal in amplitude and no error is generated by the discriminator. If the replica code is misaligned, then code phase error is sensed by code discriminator. This error is filtered and then applied to the code loop NCO, where the output code shift is increased or decreased as necessary to correct the replica code generator phase with respect to the incoming signal code phase.

When tracking loop is in locked state, I_P component of Data channel will carry Data sysmbols and Q_P of Pilot channel will carry pilot overlay codes.

C. Demodulation

After the aquisition and tracking have been performed, the received data is mapped back using BPSK demodulation, mapping -1 to binary 1 and $+1$ to binary 0. Data symbols and Pilot overlay codes are obtained after demodulation process.

D. Frame synchronisation

The start of master frame for a given satellite is determined using correlation of recevied pliot overlay bits with locally generated pilot's overlay bits. The index at which the maximum correlation output is present is considered as the start of master frame. The same index is used to decode the data symbols.

E. Decoding

Demodulated data is first separated into subframes using the frame index. Subframe 1 is decoded using Maximum-likelihood method (BCH decoding). Subframes 2 and 3 are deinterleaved and decoded using belief propagation (LDPC decoding) [6]. CRC is calculated to verify if there are any errors.

1) Process: The high-level diagram of the channel decoding process in NavIC L1 is shown in Figure 9.

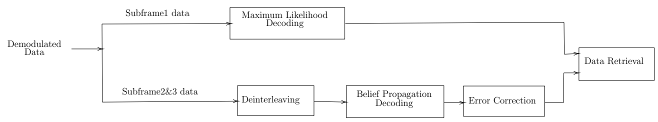

Fig. 9: The Block Level Architecture for Channel decoding

VI. Simulation results

A. Transmitter

The simulation of transmitter starts with generating Pilot PRN codes(primary and secondary) & Data PRN codes for 4 satellites and upsampling them with sampling frequency F_s of 4MHz. Navigation bits for Master frames are randomly generated, CRC is padded and necessary encoding and interleaving are carried out to generate symbols for 3 subframes. 36 seconds of sample data is generated for each of the satellites(36×4M samples). Baseband signal for each of the satellites is generated as per the modulation scheme. For each of these signals, doppler shift (between -5000Hz to 5000Hz), code delay($0 - 10230$) and power scaling are applied. The composite signal is generated by adding all these 4 signals. AWGN noise (-20dB to 0dB) is added to this signal resulting in an SPS L1 signal. This simulated sigaml is transmitted (without carrier) through the channel.

B. Receiver

The symbol period of 10ms is considerd as Integration period at the receiver end. In the receiver module, Acquisition block reads 10ms of received samples (N= 40,000) and finds out visible satellites and coarse Doppler shift (F_d) & coarse Code delay(τ) using PCPS algorithm. Frequency search band of -5000Hz to 5000Hz with a step size of 80Hz is used for this purpose. PCPS output shown in Figure 10 for a satellite, depicts received signal for various doppler frequencies and code delay.

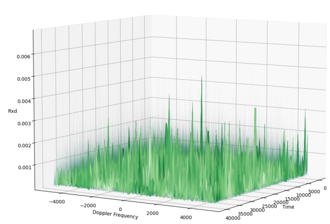

Fig. 10: Received signal Power vs Frequency & Code delay

Acquisition results for 4 satellites are as shown below

Acquisition results for **PRN ID 2**
Peak to noise ratio= 16.82
Status:True Doppler:520 Delay/Code−Phase:301
Acquisition results for **PRN ID 3**
Peak to noise ratio= 10.93
Status:True Doppler:1320 Delay/Code−Phase:588
Acquisition results for **PRN ID 4**
Peak to noise ratio= 14.46
Status:True Doppler:3800 Delay/Code−Phase:426
Acquisition results for **PRN ID 6**
Peak to noise ratio= 17.74
Status:True Doppler:4920 Delay/Code−Phase:313

The tracking loop runs for 3600 times (36×100 symbols/sec) to process received samples for each satellite. Tracking loop uses the following parameters:

1) Buffer size for power estimation = 10
2) $CN0_{min}$ = 25
3) Phase lock detector threshold = 0.85
4) Lock fail counter threshold = 25
5) Lock counter threshold = 20
6) PLL Noise Bandwidth = 18 Hz
7) FLL Noise Bandwidth = 2 Hz
8) DLL Noise Bandwidth = 2 Hz
9) SNR = -10db

Figure 11 shows tracking output for a satellite detailing Frequency, Phase and Code delay error and NCO output values.

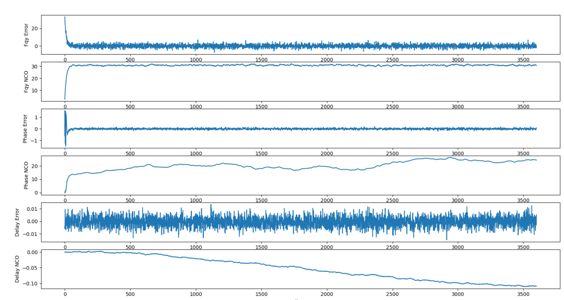

Fig. 11: Tracking output

Figure 12 shows, for a satellite, NAV bits transmitted and received for Subframes 1,2 and 3. For subframe 1, all 9 bits are shown while for subframes 2 and 3, first 24 bits are shown.

VII. Future work

The current work has focused on proper reception of NavIC L1 SPS baseband signal. In future work, the receiver should be fed with I and Q samples from a NavIC L1 simulator (ISRO had built a simulator) to calculate user location. Subsequetly, when a minimum of 4 NavIC satellites with L1 band are available in constellation, the receiver has to be tested with real time data received from satellite.

VIII. Conclusions

In this paper, we presented open source implemnetation in Python of generating SPS NavIC L1 baseband signal, transmitting it through a modelled channel and processing the

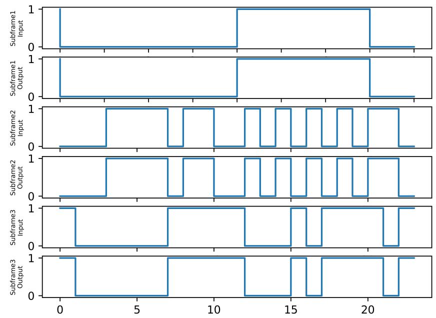

Fig. 12: NAV bits transmitted and received

received data for accurate reception. Various singal processing blocks like Acquisition, trackng and decoding etc are discussed in detail. The open source code and documentation is available at https://github.com/satheeshsimha/navic-1/tree/main/L1.

REFERENCES

[1] Carles Fernández-Prades,Javier Arribas,Luis Esteve,David Pubill,Pau Closas, ”An open source Galileo E1 software receiver”, Published in: 2012 6th ESA Workshop on Satellite Navigation Technologies (Navitec 2012) & European Workshop on GNSS Signals and Signal Processing held from 05-07 December 2012.

[2] NavIC Signal In Space ICD for SPS in L1 frequency, V1.0, October 2022,https://www.isro.gov.in/media_isro/pdf/Publications/Vispdf/Pdf2017/1a_messgingicd_receiver_incois_approved_ver_1.2.pdf

[3] GNSS SDR documention on Acquisition, https://gnss-sdr.org/docs/sp-blocks/acquisition/

[4] GNSS SDR documentation on Tracking, https://gnss-sdr.org/docs/sp-blocks/tracking/

[5] Elliott D. Kaplan and Christopher J. Hegarty, ”Understanding GPS Principles and Applications”, 3^{rd} edition

[6] Lingxia Zhou, Meixiang Zhang, Satya Chan 2 and Sooyoung Kim, ”Review and Evaluation of Belief Propagation Decoders for Polar Codes”, Symmetry2022, 14, 2633. https://doi.org/10.3390/sym14122633