An open-source MATLAB software-defined receiver for multi-frequency GNSS joint Tracking

User Manual

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Introduction

In time-varying GNSS signal environments impacted by multipath propagation, ionospheric scintillation, and interference, multi-frequency joint tracking enhances signal tracking sensitivity, accuracy, and robustness. This paper presents an open-source multi-frequency joint tracking software-defined receiver (MJTL_SDR) built on the MATLAB platform. The receiver implements two technical approaches: Doppler-aided multi-frequency joint tracking and Kalman filter-based multi-frequency joint tracking, while integrating the single-frequency independent tracking module as baseline. The software is designed to provide researchers with an experimental platform for systematic comparisons between multi-frequency joint tracking and standard single-frequency tracking method under unified data and configuration conditions, facilitating mechanism research and performance evaluation of multi-frequency tracking across diverse scenarios. Additionally, the software features a clear architecture and user-friendly design, enabling users to rapidly implement and validate self-developed baseband signal processing algorithms for multi-frequency tracking. This paper elaborates in detail on the implementation architecture and processing workflows of each tracking algorithm. Through real data collected in urban static scenarios and open-sky dynamic scenarios, the effectiveness and engineering practicability of the proposed multi-frequency joint tracking methods are comprehensively validated.

Requirements

MJTL_SDR is currently developed and tested in MATLAB environments on Windows platforms. It can also work on a Linux operating system. It does not use any MATLAB toolboxes, all the SDR have been tested on MATLAB R2023a.

Main Functionalities

MJTL_SDR is very easy to use. This section presents the usage via an example. The MJTL_SDR directory structure is as follows.

./Setting	Parameter configurations of the receiver
./Acquisition	Signal acquisition function
./Tracking	Signal tracking function
./Navigation	Functions related to NAV data decoding and PVT computation
./Common	Common functions between different SDR receivers
./Figplot	Plotting functions for tracking and navigation results
./Data	Storage path for IF signals
./Result	Storage path for acquisition and tracking results
./mainSDR.m	Starting function of the receiver

Startup

A demo dataset is available for download. The compressed file package contains two folders: TestData and TestResult. The TestData folder stores the GPS L1/L5 IF signals, which were collected in an urban area in Lujiazui Central Business District using LabSat3 wideband. The sampling frequency and IF are 30.69 MHz and 0 MHz, respectively. The TestResult folder contains the corresponding capture trace results for the test data. Before using the sample dataset, please unzip the data files. Copy the IF signals into the “Data” folder and configure the IF signals parameters within the “initSettings_L1/L5.m” function. Finally, run the “mainSDR.m” function to begin processing.

The mainSDR.m file is the main program. This software offers four operational modes selected via the sys parameter:

- sys = 1: GPS L1 single-frequency signal Standard Tracking Loop (STL).
- sys = 5: GPS L5 single-frequency signal Standard Tracking Loop (STL).
- sys = 6: GPS L1+L5 multi-frequency Doppler-Aided Joint Tracking Loop (DAJTL).
- sys = 7: GPS L1+L5 Kalman Filter-based Joint Tracking Loop (KFJTL).

```
-----------------------------------------------------------------------------------------
Welcome to:  MJTL_SDR
An open-source MATLAB code for GPS L1+L5 joint tracking
The code was improved by Huazhong University of Science and Technology.
-----------------------------------------------------------------------------------------

Choosing SDR mode: "1" -- L1 standard tracking Loop
                   "5" -- L5 standard tracking Loop
                   "6" -- Doppler-aided multi-frequency tracking Loop (DAJTL)
                   "7" -- Kalman filter-based multi-frequency tracking Loop (KFJTL):
fx Input: |
```

Figure 1. Tracking mode selected in the MATLAB Command Window.

Initialization

To process the raw IF data, the first step is to initialize necessary parameters for acquisition, tracking, positioning. During the initialization stage, in single-frequency mode, parameters for the L1 and L5 signals can be configured separately in initSettingsL1.m and initSettingsL5.m. In dual-frequency mode, both frequency bands must be set simultaneously, with the L1 signal serving as the primary reference, and common parameters are unified in initSettingsDual.m. Some important initialization parameters are listed in Table 1:

Table 1. Initialization parameters.

Parameter		Description
Raw data parameters	*msToProcess*	Number of milliseconds to be processed
	numberOfChannels	Number of channels to be used for signal processing
	skipNumberOfBytes	Move the starting point of processing in byte
	fileName	Raw data file name
	fileRoute	Raw data file route
	fileType	Data size: ‘int8’, ‘int16’
	dataType	Raw data type: 1 - 8 bit real samples S0, S1, S2, ... 2 - 8 bit I/Q samples I0, Q0, I1, Q1, I2, Q2, ...
Signal parameters	*IF*	Intermediate frequency
	samplingFreq	Sampling rate
	codeFreqBsis	Code frequency
	carrFreqBasis	Carrier frequency
	codelength	Code length
Acquisition parameters	*acqSatelliteList*	PRNs to be searched
	acqSearchBand	Single sideband around IF to search for satellite signal
	acqSearchStep	Frequency search step for coarse acquisition

	acqThreshold	Acquisition threshold
	acqNonCohTime	Non-coherent integration times for acquisition
Tracking parameters	*pilotTRKflag*	Enable use of pilot channel for tracking: 0 - Off 1 - On
	dllDampingRatio	DLL damping ratio
	dllNoiseBandwidth	DLL noise bandwidth
	CorrelatorSpacing	Correlator spacing between the Early and Late code
	pllDampingRatio	PLL damping ratio
	pllNoiseBandwidth	PLL noise bandwidth
	intTime	Integration time for DLL and PLL
	CNo.accTime	Accumulation interval in Tracking
	CNo.VSMinterval	Accumulation interval for computing VSM C/No
Navigation parameters	*navSolPeriod*	Period for calculating pseudoranges and position
	elevationMask	Elevation mask to exclude signals from satellites at low elevation
	useTropCorr	Enable use of tropospheric correction: 0 - Off 1 - On
	truePosition.E	True position of the antenna in UTM system (if known).
	truePosition.N	
	truePosition.U	
Common parameters	*c*	The speed of light
	startOffset	Initial signal travel time

Acquisition

In the acquisition stage, the MJTL_SDR dual-frequency receiver offers two approaches to obtain code delay and Doppler frequency parameters of visible satellites: independent L1/L5 acquisition and L1-aided L5 acquisition. In single-frequency mode, the acquisition results for the L1 and L5 signals can be obtained separately through acquisitionL1.m and acquisitionL5.m. This software will first acquire the visible satellites, outputting the satellite number, Doppler frequency and code phase of L1 and L5 in the command window, as shown in Figure 2.

```
Starting acquiring satellites...
GPS L1 C/A signal satellite acquisition result:
(. . . . . . . . . 10 . 12 . . 15 . . 18 . . . . 23 24 25 . . . . . . 32 )

*=========*=====*===============*===========*=============*========*
| Channel | PRN |   Frequency   |  Doppler  | Code Offset | Status |
*=========*=====*===============*===========*=============*========*
|       1 |  10 | +2.52500e+03 |    2525   |    48492    |    T   |
|       2 |  12 | +2.30000e+03 |    2300   |    27885    |    T   |
|       3 |  15 | -2.25000e+03 |   -2250   |    21384    |    T   |
|       4 |  18 | -3.07500e+03 |   -3075   |    26474    |    T   |
|       5 |  23 | +5.75000e+02 |     575   |     7435    |    T   |
|       6 |  24 | -2.15000e+03 |   -2150   |     4636    |    T   |
|       7 |  25 | +3.50000e+03 |    3500   |    13882    |    T   |
|       8 |  32 | +1.97500e+03 |    1975   |    22818    |    T   |
|       9 | --- | ------------ |   -----   |   ------    |   Off  |
|      10 | --- | ------------ |   -----   |   ------    |   Off  |
*=========*=====*===============*===========*=============*========*
```

(a) L1 signal acquisition results

```
Starting acquiring satellites...
GPS L5C signal satellite acquisition result:
(. . . . . . . . . 10 . . . . . . . 18 . . . . 23 24 . . . . . . . 32 )

*=========*=====*===============*===========*=============*========*
| Channel | PRN |   Frequency   |  Doppler  | Code Offset | Status |
*=========*=====*===============*===========*=============*========*
|       1 |  10 | +1.87500e+03 |    1875   |    17801    |    T   |
|       2 |  18 | -2.30000e+03 |   -2300   |    26475    |    T   |
|       3 |  23 | +4.25000e+02 |     425   |     7435    |    T   |
|       4 |  24 | -1.60000e+03 |   -1600   |     4636    |    T   |
|       5 |  32 | +1.47500e+03 |    1475   |    22818    |    T   |
|       6 | --- | ------------ |   -----   |   ------    |   Off  |
|       7 | --- | ------------ |   -----   |   ------    |   Off  |
|       8 | --- | ------------ |   -----   |   ------    |   Off  |
*=========*=====*===============*===========*=============*========*
```

(b) L5 signal acquisition results

Figure 2. Acquisition results under single-frequency mode shown in MATLAB command window.

The L1 and L5 signals broadcast by GPS satellites originate from the same onboard atomic clock, resulting in synchronized code phases and proportional carrier Doppler frequencies relative to carrier frequencies. Therefore, after fine acquisition of the L1 signal, the code delay and Doppler frequency for L5 can be directly derived, reducing the search space from a large two-dimensional (code delay × Doppler) problem to a one-dimensional code-phase search. Since the Doppler component is largely eliminated, correlation only needs to be performed at the correct code phase. This significantly shortens cold-start or re-acquisition time and improves receiver startup speed and real-time performance. This software will first acquire the visible satellites, outputting the satellite number, Doppler frequency and code phase of L1 and L5 in the command window, as shown in Figure 3.

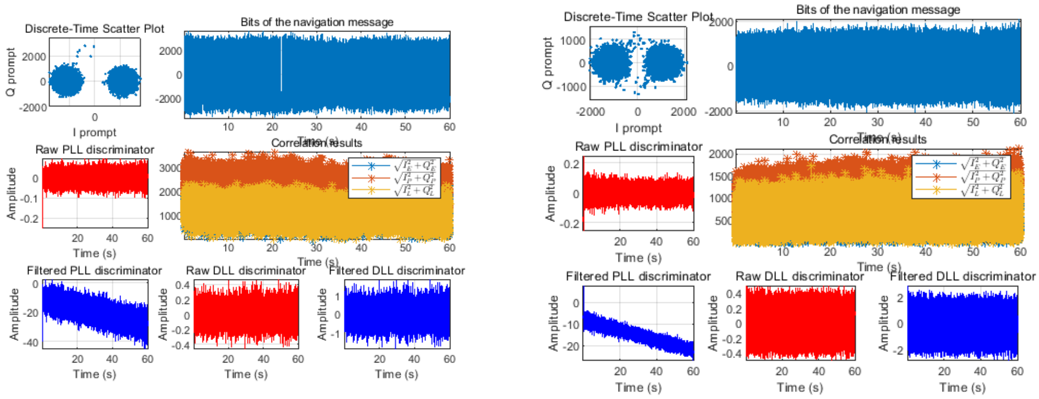
```
Starting acquiring satellites...
GPS L1 C/A signal satellite acquisition result:
(. . . . . . . . . 10 . 12 . . 15 . . 18 . . . . 23 24 25 . . . . . . 32 )
GPS L5C signal satellite acquisition result:
(. . . . . . . . . 10 . . . . . . . 18 . . . . 23 24 . . . . . . . 32 )

*=========*=====*==============*============*================*==============*==============*================*========*
| Channel | PRN | L1 Frequency | L1 Doppler | L1 Code Offset | L5 Frequency |  L5 Doppler  | L5 Code Offset | Status |
*=========*=====*==============*============*================*==============*==============*================*========*
|       1 |  10 | +2.5250e+03 |     2525   |      48492     | +1.8856e+03 |    1886      |     17801      |      T |
|       2 |  18 | -3.0750e+03 |    -3075   |      26474     | -2.2963e+03 |   -2296      |     26475      |      T |
|       3 |  23 | +5.7500e+02 |      575   |       7435     | +4.2938e+02 |     429      |      7435      |      T |
|       4 |  24 | -2.1500e+03 |    -2150   |       4636     | -1.6055e+03 |   -1606      |      4636      |      T |
|       5 |  32 | +1.9750e+03 |     1975   |      22818     | +1.4748e+03 |    1475      |     22818      |      T |
*=========*=====*==============*============*================*==============*==============*================*========*
```

Figure 3. L1-aided L5 acquisition results shown in MATLAB command window.

The acquisition result is saved in the current folder with the name of "acqResults _ raw data file name.mat". This software checks the existence of acquisition results of this raw data file according to its name, so that users have no need to acquire signals repeatedly in further development.

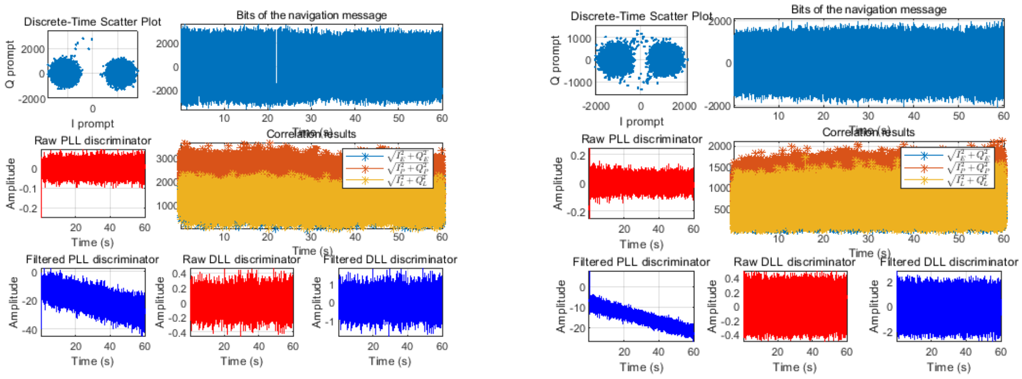
Tracking

During the tracking stage, MJTL_SDR provides three configurable tracking algorithm architectures: the single-frequency tracking algorithms are implemented in trackingL1.m and trackingL5.m, the Doppler-aided joint tracking algorithm is implemented in trackingDopAid.m, and the Kalman filter-based multi-frequency joint tracking algorithm is implemented in trackingDualKF.m. Once a tracking method is selected, the receiver enters a high-precision continuous tracking phase based on the coarse code phase and carrier Doppler results obtained from the acquisition stage, thereby acquiring precise code and carrier phases. Here, the DLL employs a normalized non-coherent early-minus-late envelope discriminator, while the second-order PLL uses a two-quadrant arctangent phase discriminator. To fully decode the five subframes, at least 30 seconds of data must be tracked. Conventional tracking results are saved in the current folder in the format "trkResults_(DA/KF)+original data filename+.mat". Figure 4 shows the STL tracking results of PRN 10. As seen in the top right panel in Figure 4, the navigation bit steam can be found in the in-phase output of the prompt channel. Similarly, Figure 5 and Figure 6 show the tracking results of DAJTL and KFJTL method, respectively.



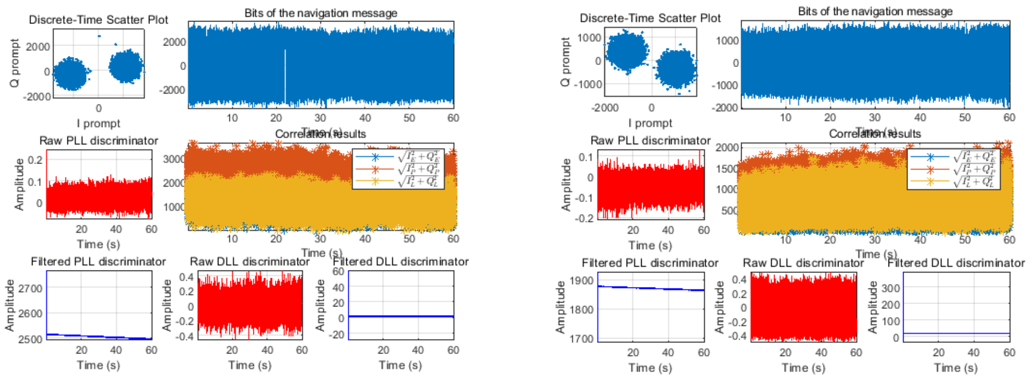
(a) L1 signal (b) L5 signal

Figure 4. STL tracking results of PRN 10



(a) L1 signal (b) L5 signal

Figure 5. DAJTL tracking results of PRN 10

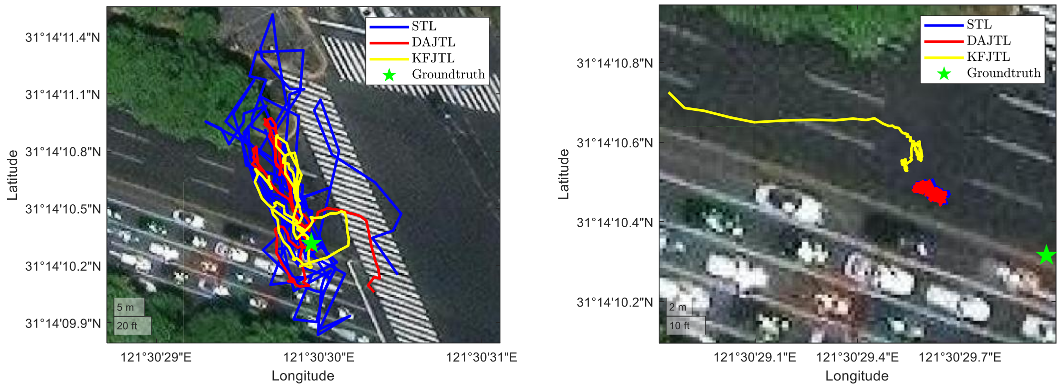


(a) L1 signal (b) L5 signal

Figure 6. KFJTL tracking results of PRN 10

Positioning

Navigation solutions are calculated using a unified least-squares estimation positioning method to ensure that different tracking strategies are evaluated fairly under the same framework. Figure 7 shows the horizontal positioning results of STL, DATL, KFJTL.



(a) L1 signal (b) L5 signal

Figure 7. Horizontal positioning results in the static test plotted on a Google map

Contact Information

This is the first version of this software. Please do not hesitate to contact us if you come across any bugs or have any comments, suggestions or corrections. We will reply you by e-mail as soon as possible.

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Appendix A Reasoned criteria to tune the Kalman filter

When using a KF architecture, there are three covariance matrices that have to be tuned in order to achieve proper performances, namely the initial estimate error covariance $\mathbf{P}_{ini,k}$, the process noise covariance Q_k and the measurement noise covariance $\mathbf{R}_k$. The measurement-noise covariance can be determined based on the coherent integration interval and the signal-to-noise ratio. The process-noise covariance matrix adopted in this paper follows the formulation from. Different combinations of process-noise and measurement-noise covariance will result in different steady-state bandwidths for the tracking loop. The process-noise vector at the k-th epoch can be expressed as:

$$\mathbf{w_k} = \begin{bmatrix} w_{code,1} & w_{code,2} & w_{carr,1} & w_{carr,2} & w_{freq} & w_{acc} \end{bmatrix}_k \tag{1}$$

where $w_{code,1}$ and $w_{code,2}$ denote the code-phase noise induced by ionospheric delay variations for the two frequency bands, $w_{carr,1}$ and $w_{carr,2}$ represent the process noise of clock offset for the two frequency bands, respectively. Additionally, w_{freq} represent the process noise of clock drift caused by the oscillator, and w_{acc} is the acceleration noise in the line-of-sight direction associated with receiver dynamics. The covariance matrix of the process noise is given by:

$$\mathbf{Q_k} = \mathbf{E}\left[\mathbf{w_k} \cdot \mathbf{w_k^T}\right]$$

$$= \begin{bmatrix}
S_{c,1}T + \frac{S_d\beta_1^2T^3}{3} & \frac{S_d\beta_1\beta_2T^3}{3} & \frac{S_d\beta_1T^3}{3} & \frac{S_d\alpha\beta_1T^3}{3} & \frac{S_d\beta_1T^2}{2} & 0 \\
\frac{S_d\beta_1\beta_2T^3}{3} & S_{c,2}T + \frac{S_d\beta_2^2T^3}{3} & \frac{S_d\beta_2T^3}{3} & \frac{S_d\alpha\beta_2T^3}{3} & \frac{S_d\beta_2T^2}{2} & 0 \\
\frac{S_d\beta_1T^3}{3} & \frac{S_d\beta_2T^3}{3} & S_{b,1}T + \frac{S_dT^3}{3} + \frac{S_aT^5}{20} & \frac{S_d\alpha T^3}{3} + \frac{S_a\alpha T^5}{20} & \frac{S_dT^2}{2} + \frac{S_aT^4}{8} & \frac{S_aT^3}{6} \\
\frac{S_d\alpha\beta_1T^3}{3} & \frac{S_d\alpha\beta_2T^3}{3} & \frac{S_d\alpha T^3}{3} + \frac{S_a\alpha T^5}{20} & S_{b,2}T + \frac{S_d\alpha^2T^3}{3} + \frac{S_a\alpha^2T^5}{20} & \frac{S_d\alpha T^2}{2} + \frac{S_a\alpha T^4}{8} & \frac{S_a\alpha T^3}{6} \\
\frac{S_d\beta_1T^2}{2} & \frac{S_d\beta_2T^2}{2} & \frac{S_dT^2}{2} + \frac{S_aT^4}{8} & \frac{S_d\alpha T^2}{2} + \frac{S_a\alpha T^4}{8} & S_dT + \frac{S_aT^3}{3} & \frac{S_aT^2}{2} \\
0 & 0 & \frac{S_aT^3}{6} & \frac{S_a\alpha T^3}{6} & \frac{S_aT^2}{2} & S_aT
\end{bmatrix} \tag{2}$$

where $S_{c,1}$ and $S_{c,2}$ correspond to the power spectral densities (PSDs) of the code-tracking loop noise for the two frequency bands, respectively. $S_{b,1}$ and $S_{b,2}$ denote the products of the square of the carrier frequency and the PSD of w_{clk} for each band, S_d is the product of the square of the carrier frequency of the f_1 and the PSD of w_{freq}, S_a represents the PSD of w_{acc}.

The observation noise vector $\mathbf{v_k}$ can be expressed as:

$$\mathbf{v_k} = \begin{bmatrix} v_{\tau,1} & v_{\varphi,1} & v_{\tau,2} & v_{\varphi,2} \end{bmatrix}_k \tag{3}$$

where $v_{\tau,1}$ and $v_{\tau,2}$ denote the observation noise of the code phase discriminator for the two frequency bands, $v_{\varphi,1}$ and $v_{\varphi,2}$ denote the observation noise of the carrier phase discriminator for the two frequency bands respectively. The covariance matrix of the observation noise can be expressed as:

$$\mathbf{R_k} = \mathbf{E}\left[\mathbf{v_k} \cdot \mathbf{v_k^T}\right] = \begin{bmatrix} \sigma_{\tau1,k}^2 & 0 & 0 & 0 \\ 0 & \sigma_{\varphi1,k}^2 & 0 & 0 \\ 0 & 0 & \sigma_{\tau1,k}^2 & 0 \\ 0 & 0 & 0 & \sigma_{\varphi2,k}^2 \end{bmatrix} \tag{4}$$

where $\sigma_{\tau1,k}^2$ and $\sigma_{\tau2,k}^2$ are variances of code phase discriminator's observation noise. $\sigma_{\varphi1,k}^2$ and $\sigma_{\varphi2,k}^2$ are variances of carrier phase discriminator's observation noise.

$$\begin{aligned} \sigma_{\tau i,k}^2 &= \frac{d_i T}{4T \cdot (C/N_0)_{i,k}} \left(1 + \frac{2}{(2-d_i)T \cdot (C/N_0)_{i,k}} \right) \\ \sigma_{\varphi i,k}^2 &= \frac{T}{2T \cdot (C/N_0)_{i,k}} \left(1 + \frac{1}{2T \cdot (C/N_0)_{i,k}} \right) \end{aligned} \tag{5}$$

where d_i is the spacing between the early and late local replica codes of the i-th frequency signal, and $(C/N_0)_{i,k}$ the i-th carrier signal carrier-to-noise density ratio (C/N0) at the k-th epoch.

The initial estimate error covariance can be expressed as:

$$\mathbf{P}_{ini,k} = \begin{bmatrix} P_{code,1} & 0 & 0 & 0 & 0 & 0 \\ 0 & P_{code,2} & 0 & 0 & 0 & 0 \\ 0 & 0 & P_{carr,1} & 0 & 0 & 0 \\ 0 & 0 & 0 & P_{carr,2} & 0 & 0 \\ 0 & 0 & 0 & 0 & P_{freq} & 0 \\ 0 & 0 & 0 & 0 & 0 & P_{acc} \end{bmatrix}_k \tag{6}$$

where $P_{code,1}$ and $P_{code,2}$ are the initial code phase errors are related to code phase search accuracy and signal-to-noise ratio, $P_{carr,1}$ and $P_{carr,2}$ are the initial carrier phase error, P_{freq} is the initial frequency error depends on the frequency search accuracy during acquisition and bit synchronization, P_{acc} is the variance of the acceleration based on the dynamics of the vehicle.