Performance Analysis of the GPS Receiver under High Acceleration and Jerk Environments

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Abstract

The GPS receiver developed by KARI for the satellite launch vehicle should operate under severe dynamic environments such as high acceleration and jerk. Several terrestrial tests including the outdoor centrifuge test are planed in order to verify performances of the GPS receiver before flight. This paper deals with preliminary test results of the GPS receiver using a GPS signal generator before the centrifuge test that is a performance test of the GPS receiver using live GPS satellite signals. Test methods of the GPS receiver for the satellite launch vehicle under high centripetal acceleration and jerk utilizing a GPS signal generator are described. The simulation results are also analyzed in this paper.

Keywords: GPS Receiver, Satellite Launch Vehicle, Centrifuge, Centripetal Acceleration, Jerk.

1. Introduction

The application of GPS(Global Positioning System) to satellite launch vehicles presents different challenges compared with satellites or earth-surface user navigations [1, 2]. The primary technical challenge to use GPS for satellite launch vehicles is due to the bad GPS visibility by the restriction on the placement of antennas, harsh environment for the on-board equipments as well as severe dynamic conditions characterized by hypersonic velocities, tens of g's in acceleration and jerk on the order of tens of g's per second [1-3]. In spite of the difficulties, the use of GPS for the launch vehicles has been endeavored continuously since the GPS for space applications has performance advantages and cost effectiveness.

To guarantee the GPS receiver has sufficient FOV(Field of View) for all flight trajectory and attitude of the launch vehicle, the GPS receiver for the satellite launch vehicle developed by KARI(Korea Aerospace Research Institute) has triple RF front-ends that will be connected to 3 GPS antennas, individually [4]. Triple GPS antennas will provide uninterrupted coverage during all flight mission of the satellite launch vehicle. The GPS receiver is to provide navigation data of the vehicle as well as GPS satellites raw data at every 0.1 second using L1, C/A code signal. The navigation data and the raw data are to be used for one of the onboard information for range safety and for the post-flight evaluation of the vehicle performance, respectively.

Even though the enormous size of the satellite launch vehicles, the placement of the GPS antenna is practically subject to severe constraints [1, 2]. For KSLV-I which is the satellite launch vehicle is being developed by KARI as an example, 3 GPS antennas are placed on the joint section between 1st-stage and 2nd-stage like Fig. 1. The joint section is a cylindrical surface with large diameter but tens of centimeters wide. Furthermore, the neighborhood objects such as the other antennas like S-band, C-band, UHF and various cowls that should be also placed on the joint section could shade the GPS antennas from satellites. The performance of the GPS receiver can be degraded due to the high power signals transmitted from S-band or C-band antennas. It is, therefore, recommended that the GPS antennas are installed separately from the other antennas as far as possible.

It is very important to install the GPS antennas on the satellite launch vehicle properly since the GPS receiver data cannot be obtained even though the receiver operates normally due to the insufficient GPS satellite signals. Note that the placement of 3 GPS antennas on KSLV-I is not separated equally. Selection of the placement is considered flight attitude of the vehicle as well as opening direction of the nose fairing. The GPS antennas are looking sideways on the launch pad, but have a vertical FOV after lift-off according to the flight attitude.

Several terrestrial tests including the outdoor centrifuge test are planed in order to verify performance of the GPS receiver before flight. This paper deals with preliminary test results of the GPS receiver using a GPS signal generator before the centrifuge test that is a performance test of the GPS receiver using live GPS satellite signals. Test methods of the GPS receiver for the satellite launch vehicle under high centripetal acceleration and jerk utilizing a GPS signal generator are described. The simulation results are also analyzed in this paper.

The layout of this paper is organized as follows: In Section 2, the characteristics of the GPS receiver for the satellite launch

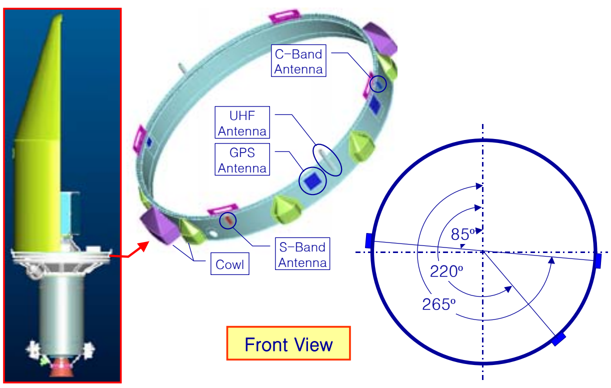

Figure 1. Placement of the GPS Antennas on KSLV-I.

vehicle are described. In Section 3, the GPS simulator scenario in order to generate high acceleration and jerk using rotational motion is presented. The GPS receiver performance under centrifuge motion is analyzed in Section 4. The concluding remarks and further works are given in Section 5.

2. Description of the GPS Receiver

The GPS receiver for the satellite launch vehicle is designed in order to operate normally in the severe environments such as thermal, vacuum, humidity, electromagnetic, vibration, shock, and dynamic conditions such as extremely high altitude, velocity, acceleration and jerk. In order to verify performance of the GPS receiver under these circumstances on the ground before flight, the environmental tests for qualification should be accomplished during the development phase.

Hardware architecture of the GPS receiver is shown in Fig. 2 [4]. To provide spherical coverage, the receiver is connected to 3 distinct GPS antennas mounted on the surface of the vehicle. The GPS antenna is an omni-directional RHCP(Right Hand Circular Polarization) active patch antenna with LNA(Low Noise Amplifier) [4]. Each antenna is connected individually to an RF front-end driven by a common 10MHz reference oscillator. Triple RF front-ends are connected to independent correlator chips that can be assigned independently to 12 tracking channels respectively. The GPS receiver, therefore, can track maximum 12 GPS satellite signals per GPS antenna and can process the signals from 3 distinct antennas, simultaneously. To maintain continuous lock, all information about the GPS satellite signals between tracking channels from each antenna should be shared.

Same GPS satellite signals could be received from 2 different antennas simultaneously because FOV of each antenna is overlapped. In this case, the signal used for calculation of the navigation data can be basically selected from the antenna with largest SNR(Signal to Noise Ratio). This antenna is referred to the master antenna for the satellite signal. The master antenna is assigned to individual GPS signal based on the SNR. The SNR of the GPS satellite signals in an antenna is generally large when the elevation angle of the GPS satellite is large and *vice versa* since the SNR is mainly a function of the elevation angle of the satellite [5]. The master antenna transfer occurs at the point that the SNR of the current master antenna is less than 1dB of the SNR of the highest non-master antenna. It is noted that the similar algorithm for antenna selection was used in Reference [5]. The difference between algorithms used in Reference [5] and this paper is update rate of the master antenna selection, *i.e.* the master antenna selection is occurred every 15 second in Reference [5] but every 0.1 second in this paper.

Stable carrier tracking at high dynamics is ensured by a 3rd-order PLL(Phase Locked Loop) with 2nd-order FLL(Frequency Locked Loop) assisted [4]. The GPS receiver with 3rd-order loop will track constant phase acceleration but deviate in the presence of a phase jerk. The bandwidth will be selected with considering about the tracking capability of the GPS receiver under dynamics. It should be confirmed whether the receiver could operate normally over the satellite launch vehicle dynamics.

When the satellite launch vehicle is stand-by on the launch pad, RS-422 will be used for connecting with GSE(Ground Support Equipment) on the ground through the umbilical cable and checking the condition of the GPS receiver. When the satellite launch vehicle is on flight, the GPS receiver will be connected to the telemetry system through MIL-STD-1553B RT mode. The navigation data and GPS satellites raw data will be transmitted to ground using S-band downlink.

3. GPS Simulator Scenario

GPS signal generators provide a safe, convenient and cost effective means to test GPS receivers in the laboratory. They also generate accurate GPS signals under high dynamics and provide repeatable testing method of the GPS receiver under various user scenarios. The GPS signal generator used in the test described in this paper is Spirent Communications GSS6560 which has 12 independent channels at L1 with C/A code modulation [6]. The vehicle trajectory parameters that are required to perform the simulation are read by GSS6560 as a data file or a model. These parameters include the vehicle position, velocity, acceleration, jerk, attitude, *etc*.

In order to generate vehicle scenario with high acceleration and jerk, the rotational motion like Fig. 3 is considered. Although the rotational motion does not trajectory model of a satellite launch vehicle, the centrifuge test can provide means to obtain GPS data in a high-dynamic environment [3]. The rotational motion has a center point at constant latitude and longitude with a radius of about 1m, and fixed altitude of 1,000m. In this case, the latitude and longitude are sinusoidal trajectories with respect to time like Fig. 4. The magnitudes of angular velocity, centripetal acceleration and jerk are increased monotonically from 0rps to 2rps and decreased inversely like Fig 5. The maximum dynamics is appeared at time 470 second. The monotonicity characteristic of the dynamics can help to decide the value of the threshold for the performance of the GPS receiver under dynamic environments even though the dynamics is a rotational motion not a translational motion. Maximum velocity, acceleration and jerk are approximately 12.57m/sec,

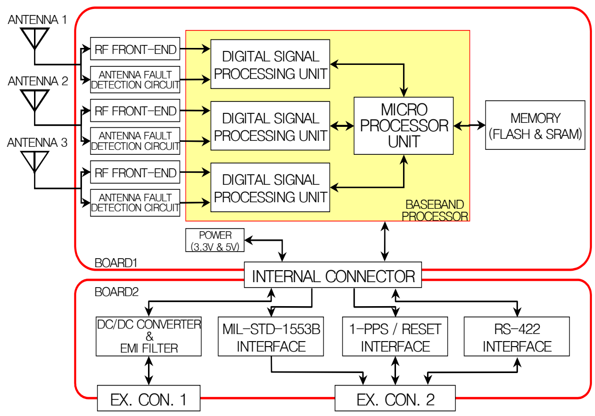

Figure 2. GPS Receiver for Satellite Launch Vehicle.

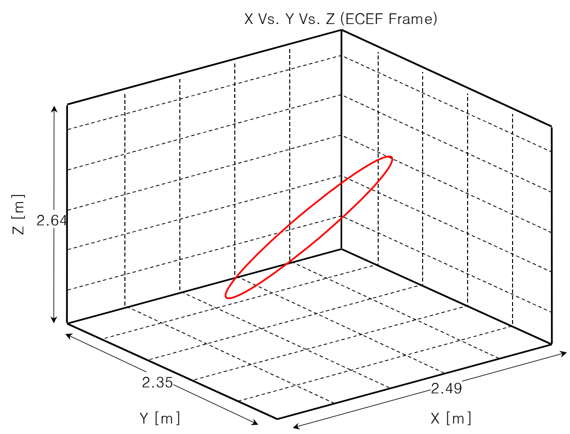

Figure 3. Rotational Motion in ECEF Coordinate Frame.

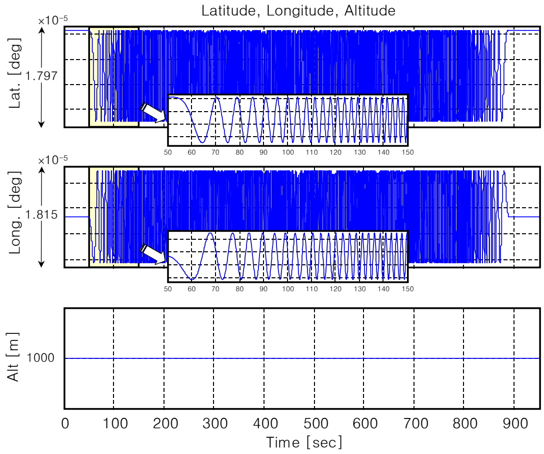

Figure 4. Latitude, Longitude and Altitude in the Scenario.

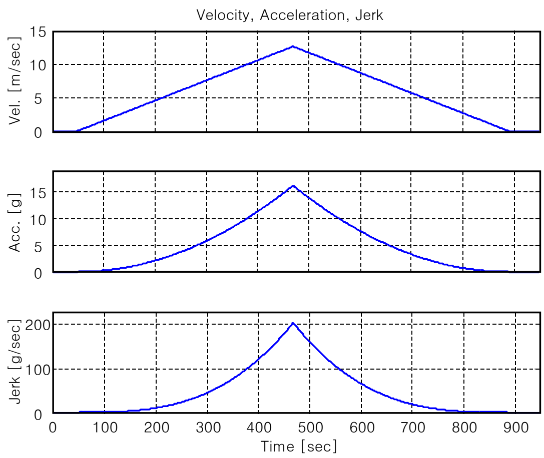

Figure 5. Velocity, Acceleration and Jerk in the Scenario.

16.08g and 202.06g/sec, respectively. The jerk level is extremely large compared to the levels of the velocity or acceleration. It is noted that the centrifuge test equipment that belongs to KARI can generate the rotational motion used in this paper. This equipment was designed and fabricated for software developments and verification tests of the GPS receiver using live GPS satellite signals. KARI, therefore, is going to accomplish outdoor centrifuge test of the GPS receiver using live GPS satellite signals.

4. Performance of the GPS Receiver

The performance of the GPS receiver under dynamics is analyzed in this section. It is especially focused on the performance at time when the GPS receiver loses the signal locks, where the signal lock means a status that the receiver uses the signal for calculation of the navigation data. The GPS receiver runs at the initial position during enough time to track GPS satellite signals before the scenario of the GPS signal simulator is started. Only one antenna port of the GPS receiver is connected to the GPS signal generator and the other two antenna ports are terminated.

4.1 GPS Satellite Signals and Fix Mode

The number of satellite signals used for calculation of the navigation data and fix mode of the GPS receiver are shown in Fig. 6. Total 11 signals are used for calculation of the navigation

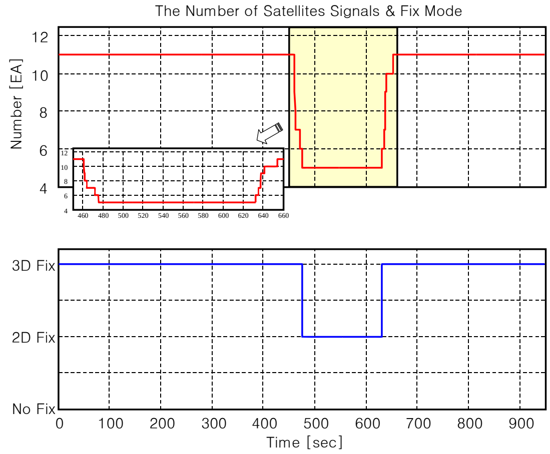

Figure 6. Number of Satellite Signals and Fix Mode.

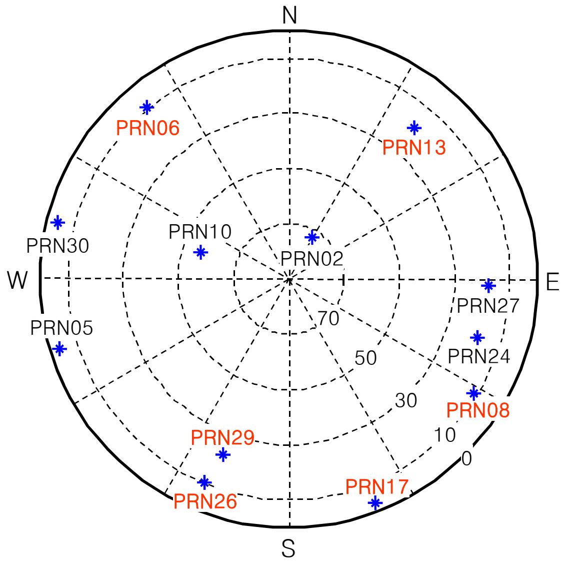

Figure 7. GPS Constellation at 460.8 Second.

Table 1. Azimuth and Elevation Angles of GPS Satellites at 460.8 Second. (Unit: [deg])

PRN	2	5	6	8	10	13
Azimuth	29.0	-107.0	-39.8	121.5	-73.1	39.8
Elevation	73.0	3.1	9.3	11.2	56.8	18.7
PRN	17	24	26	27	29	30
Azimuth	159.1	107.1	-157.5	91.9	-159.6	-76.2
Elevation	3.2	18.6	10.5	17.7	22.2	3.6

data in 3D fix mode and minimum 5 signals are kept locking continuously over all test time. The GPS receiver operates as 2D fix mode during 157.1 seconds from 475.6 second to 632.6 second due to the bad DOP(Dilution of Precision) of the GPS satellites used for calculation of the navigation data. The GPS receiver loses the lock before the receiver drop down to 2D fix mode from 3D fix mode. When the GPS receiver loses the lock of the satellite signal, PRN29 that is the first satellite lost lock, at 460.8 second, the GPS constellation is shown in Fig. 7 that has azimuth and elevation angles like Table 1. Highlighted satellites in Fig. 7 and Table 1, PRN6, PRN8, PRN13, PRN17, PRN26, PRN29, are lost the lock during the test that is shown in Fig. 8 in detail. It is noted that the satellites lost of lock have a low elevation angle.

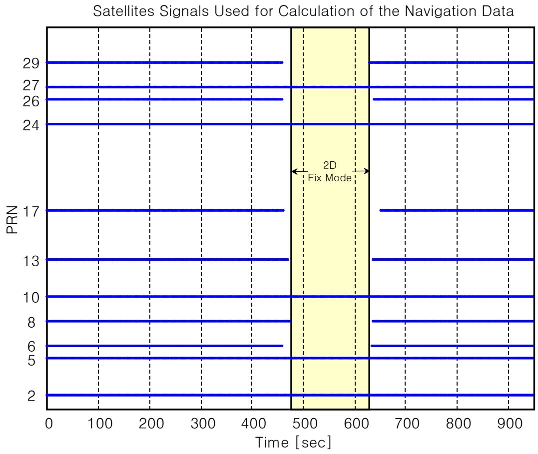

Figure 8. Satellite Signals Used for Calculation of Navigation Data.

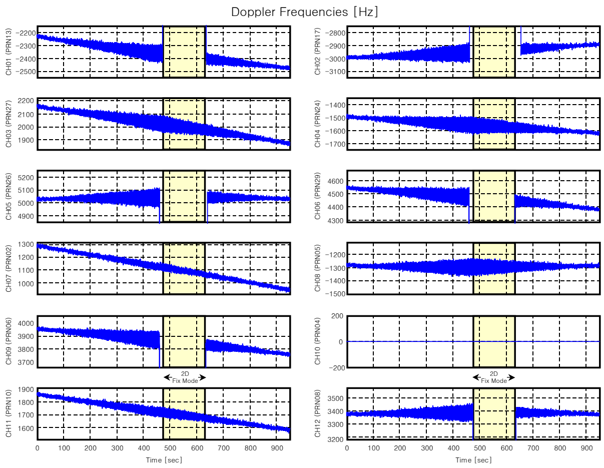

Figure 9. Doppler Frequencies.

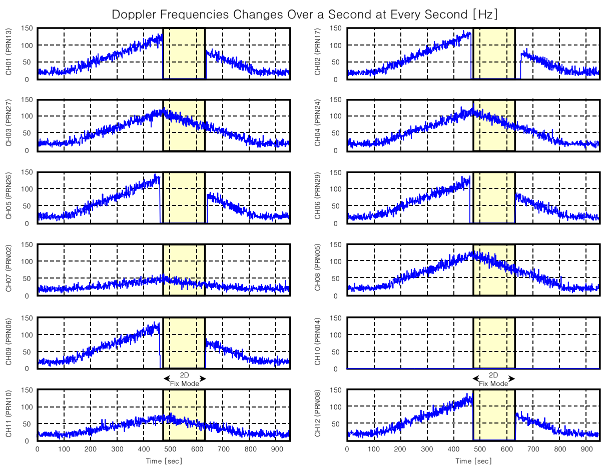

Figure 10. Changes of the Doppler Frequency Shift Over a Second at Every Second.

Doppler frequency shifts of the satellite signals calculated in the GPS receiver are shown in Fig. 9. The Doppler frequency shifts are not large, but the changes of the Doppler frequency shifts are large and they become larger particularly during the high dynamic period. The differences between maximum and minimum Doppler frequency shifts over a second at every second are shown in Fig. 10. It can be seen that the GPS receiver loses the lock of the signal when the change of the frequency shift is larger than 130Hz, approximately. The larger change of the frequency shift, the faster loss of lock is. The maximum changes of the Doppler frequency shifts of the signal over all test time are given in Table 2. It is more obvious that the GPS receiver loses the lock of the signal with the larger change of the Doppler frequency shift. PRN24 is locked continuously even though the 1st maximum change of the frequency shift is large that seems to be an instantaneous situation since 2nd and 3rd maximum frequency changes are smaller than 130Hz.

Table 2. Maximum Changes of the Doppler Frequency Shift.

Ch. #	PRN	Doppler Frequency Change					
		Time [sec]	1st Max. [Hz]	Time [sec]	2nd Max [Hz]	Time [sec]	3rd Max [Hz]
1	13	454	132	470	131	467	130
2	17	436	142	437	138	461	137
3	27	478	125	477	122	470	118
4	24	475	135	428	126	471	123
5	26	443	143	441	140	447	136
6	29	460	137	431	136	458	131
7	2	477	62	463	60	471	59
8	5	478	127	489	126	458	125
9	6	440	137	458	133	454	130
10	4	0	0	0	0	0	0
11	10	504	80	474	77	502	76
12	8	453	136	475	136	474	131

The dynamics level at the points of loss of lock and recovery of lock is given in Table 3. The levels of velocity and acceleration are not severe compared to the jerk level. The jerk level about 180g/sec gives rise to loss of lock of the satellites having large change of the Doppler frequency shift. Recovery of lock is occurred at the lower dynamics level.

Table. 3. Dynamics Level at Loss of Lock and Recovery of Lock.

PRN	Loss of Lock				Recovery of Lock			
	Time [sec]	Vel. [m/sec]	Acc. [g]	Jerk [g/sec]	Time [sec]	Vel. [m/sec]	Acc. [g]	Jerk [g/sec]
6	461.1	12.29	15.39	189.25	635.7	7.61	5.90	44.96
8	475.6	12.40	15.67	194.37	637.8	7.55	5.81	43.85
13	472.1	12.51	15.93	199.33	637.6	7.56	5.82	43.96
17	463.8	12.38	15.60	193.01	654.5	7.05	5.06	35.71
26	461.9	12.32	15.45	190.36	641.4	7.44	5.64	42.00
29	460.8	12.29	15.37	188.84	632.7	7.70	6.04	46.56

4.2 Navigation Data

The navigation data of the GPS receiver is not serious concern in this paper because the position boundary of the scenario is smaller than the error boundary of the receiver. Pseudorange measurements are similar to the static navigation in the scenario used in this paper. The navigation accuracy of the GPS receiver will be investigated under the other various scenarios through the GPS signal generator [4].

In 2D fix mode, the receiver calculates only latitude and longitude without altitude which has the previous value. The position error in ECEF(Earth-Centered Earth-Fixed) coordinate frame are shown in Fig. 11 that have obviously small errors. The velocity, however, has a very large error according to the dynamics like Fig. 12 because it depends on the Doppler frequency. The velocity is calculated somewhat lower than that of the scenario. This phenomenon is an enigma and need more

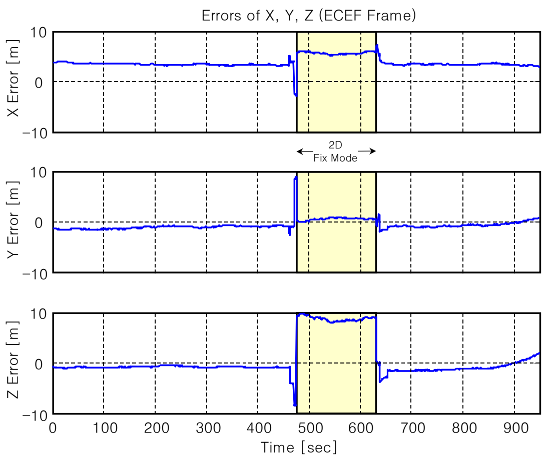

Figure 11. Position Error.

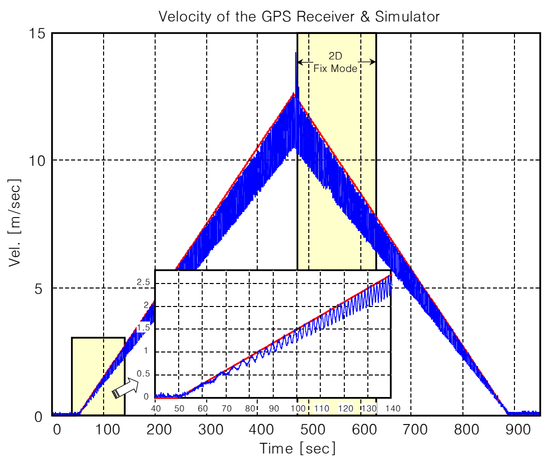

Figure 12. Velocity Error.

Table 4. Navigation Error during 3D Fix Mode.

Latitude Error [$\times 10^{-5}$deg]			
Mean	RMS	R95	Max.
0.706	1.116	1.426	-10.761
Longitude Error [$\times 10^{-5}$deg]			
Mean	RMS	R95	Max.
-2.306	2.332	-2.750	-5.702
Altitude Error [m]			
Mean	RMS	R95	Max.
-2.749	2.852	-3.490	-5.470
X Error (ECEF Frame) [m]			
Mean	RMS	R95	Max.
3.333	3.371	3.758	7.253
Y Error (ECEF Frame) [m]			
Mean	RMS	R95	Max.
-0.858	1.154	-1.550	8.873
Z Error (ECEF Frame) [m]			
Mean	RMS	R95	Max.
-0.907	1.252	-1.558	-8.453
Velocity Error [m/sec]			
Mean	RMS	R95	Max.
0.488	0.723	1.622	2.184

※ The velocity error is calculated for all test intervals including 2D fix mode.

analysis to solve the puzzle. Position error during the GPS operates as 3D fix mode and velocity error over all test time are given in Table 4. It can be seen that the position error is small but the velocity error is slightly large.

5. Conclusion

This paper analyzes the performance test result of the GPS receiver for the range safety of KSLV-I using the GPS signal generator. The rotational motion scenario is used in this paper to generate vehicle scenario having high acceleration and jerk with monotonicity characteristic. The GPS receiver loses the lock of the satellite signals with high Doppler frequency change over 130Hz, approximately, near at the maximum dynamics level in the scenario.

It is required further research to perform the centrifuge test using live GPS satellite signals that is the similar to the simulation scenario used in this paper. There are also plans to accomplish performance tests of the GPS receiver using various trajectory models of satellite launch vehicles before flight.

Reference

1. J. Leung, G. Schipper, G. T. Tseng, P. Wildhagen, "GPS Applications to Launch Vehicles," *Proceedings of 51st ION Annual Meeting*, Jun. 1995, pp. 293-302.
2. M. Santina, J. Leung, G. Smit, J. Tekawy, G. T. Seng, J. McKay, S. Bandel, "GPS-Based Launch Vehicle Tracking Using a Common Multi-Patch Antenna Configuration," *Proceeding of 8th ION International Technical Meeting*, Sep. 1995, pp. 1885-1893.
3. J. P. Cunningham, P. K. Khoe, B. R. Hermann, A. G. Evans, J. H. Merts, "Evaluation of GPS Receiver Performance Under High-Dynamic Conditions," *ION-GPS-2000*, Sep. 2000, pp. 2051-2060.
4. Hyung-Don Choi *et al.*, *Technology Development for Improving Accuracy and Reliability of an Avionic System for a Satellite Launcher (I ~ IV)*, Korea Aerospace Research Institute, 2003 ~ 2006.
5. D. Yale, A. Ndili, J. Li, E. Ng, E. Bean, S. Buchman, "Rolling GPS Receiver Development and Verification Test for Space Application," *ION-GPS-1999*, Sep. 1999, pp. 857-864.
6. *DGP00686AAA: SimGEN (Including SimLOCATE) User Manual*, Spirent Communications, Jan. 2004.