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# Comparative Performance Analyses of GPS Receivers under High-Dynamic Conditions

**Byung-Moon Kwon* Ji-Hyeon Moon** Hyung-Don Choi*** Gwang-Rae Cho******

*Control System Department, Korea Aerospace Research Institute, Daejeon 305-333, Korea*
*(* Tel: +82-42-860-2992; e-mail: bmkwon@kari.re.kr, ** Tel: +82-42-860-2597;*
*e-mail: mjhdust@kari.re.kr, *** Tel: +82-42-860-2421; e-mail: hdchoi@kari.re.kr)*
***** KSLV Program Office, Korea Aerospace Research Institute, Daejeon 305-333, Korea*
*(Tel: +82-42-860-2411; e-mail: gwcho@kari.re.kr)*

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**Abstract:** The KSLV-I GPSR that is the first GPS receiver utilized on a satellite launch vehicle developed by KARI should operate normally under harsh environments such as extremely high vibration and shock, wide operating temperature range as well as high-dynamic conditions. Several extensive terrestrial tests have been already done in order to verify performance of the KSLV-I GPSR before flight. This paper deals with comparative performance analyses between the KSLV-I GPSR and other two GPS receivers without velocity and altitude restrictions under high-dynamic conditions. The tracking capability and accuracy of the GPS receivers are compared using a GPS signal simulator with various scenarios like a centrifuge, a satellite launch vehicle, and a spacecraft.

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## 1. INTRODUCTION

Onboard GPS receivers for satellite launch vehicles should have a capability to provide precise position, velocity, and timing information during all flight missions. The GPS receivers, therefore, must have a capability to maintain lock under harsh environments such as extremely high vibration and shock, wide operating temperature range as well as high-dynamic conditions characterized by supersonic velocities, tens of g's of acceleration, and several tens of g's per second of jerk (Cunningham *et al.* [2000] and Lung *et al.* [1995]).

The KSLV(Korea Space Launch Vehicle)-I GPSR that is the first GPS receiver utilized on a satellite launch vehicle, designated KSLV-I, developed by KARI(Korea Aerospace Research Institute) has been performed several extensive terrestrial tests including various environmental tests to ensure the capability to maintain lock (Choi *et al.* [2003~ 2007]).

As one of the terrestrial tests, the KSLV-I GPSR was tested under high-dynamic conditions using a GPS signal simulator which is usually used to evaluate tracking capability and accuracy of GPS receivers. This paper provides a detailed performance assessment and comparison of the KSLV-I GPSR and currently available two GPS receivers for both their tracking capability and accuracy under high-dynamic conditions. In order to simulate high-dynamic conditions, three scenarios like a centrifuge, a satellite launch vehicle, and a spacecraft that are representative high-dynamic applications are used in the tests.

The layout of this paper is organized as follows: In Section 2, the GPS receivers used in the tests are explained. In Section 3, a hardware configuration for the tests and various scenarios representative high-dynamic conditions are described. Performances of the GPS receivers are analyzed in Section 4. The concluding remarks and further works are given in Section 5.

## 2. GPS RECEIVERS FOR TESTS

Civilian GPS receivers could not deliver valid navigation information at velocities greater than 1,000knots (about 514m/sec) or altitudes greater than 60,000ft (about 18,228m) because of the export license restrictions. It is, therefore, difficult to obtain a GPS receiver without restrictions about velocity and altitude for high-dynamic tests. There are two COTS(Commercial-Off-The-Shelf) GPS receivers, PolaRx2 and DL-V3, without restrictions in KARI. The PolaRx2 and DL-V3 receivers deactivated velocity and altitude limitations have been provided by Septentrio, Belgium, and NovAtel, Canada, respectively, with permission of local governmental authorities. The performance of the KSLV-I GPSR was compared with the PolaRx2 and DL-V3 receivers.

### *2.1 KSLV-I GPSR (Choi et al. [2003~2007])*

The KSLV-I GPSR is to provide real-time navigation information for range safety and raw measurement data for post-flight evaluation of the vehicle performance using L1, C/A code signal with an output rate of 10Hz. Stable carrier tracking at high dynamics is ensured by 3rd-order PLL(Phase Locked Loop) with 2nd-order FLL(Frequency Locked Loop) assisted. The GPS receiver with 3rd-order PLL filter will track a constant phase acceleration but deviate in the presence of a phase jerk. The bandwidths of PLL and FLL filters are 18Hz and 4Hz, respectively. Elevation mask angle of the KSLV-I GPSR is configured as 0.0° in order to have wide FOV(Field Of View).

The KSLV-I GPSR has confirmed to survive in the satellite launch vehicle environments through extensive terrestrial

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tests including humidity, high and low temperatures, vacuum, sinusoidal and random vibrations, shocks, electromagnetic radiation and susceptibility, etc. To maintain good GPS visibility for all flight trajectory and attitude of the satellite launch vehicle, the KSLV-I GPSR has triple RF front-ends, which are connected to three distinct GPS antennas, respectively. Each RF front-end is connected to an independent correlator chip that can be assigned to 12 tracking channels, independently. The KSLV-I GPSR, therefore, can track maximum 12 GPS satellite signals per one GPS antenna and process the signals from triple antennas, simultaneously. To maintain lock continuously, all information about acquired GPS satellite signals between tracking channels of each antenna is shared.

When the satellite launch vehicle is stand-by on the launch pad, the KSLV-I GPSR will be connected to GSE(Ground Support Equipment) on the ground using RS-422 serial communication through the umbilical cable to check and control the KSLV-I GPSR. The KSLV-I GPSR will be connected to the telemetry system through MIL-STD-1553B inside of the satellite launch vehicle. The navigation data and raw measurements will be transmitted to ground using S-band downlink after lift-off. All data of the KSLV-I GPSR in the tests described in this paper were logged using only RS-422 serial communication.

### *2.2 PolaRx2 (Septentrio [2005])*

The PolaRx2 receiver from Septentrio Satellite Navigation, Leuven, Belgium, is a general purpose 48-channel dual-frequency GNSS receiver with output rates of up to 10Hz. It has already been used in a variety of static and dynamic applications including onboard of trains, bulldozers, boats, helicopters, and airplanes (Septentrio [2005]). The first flight test with the PolaRx2 receiver for a technology demonstration micro-satellite is currently planned for 2008 as a part of On-Orbit Verification Program in DLR(German Aerospace Centre) (Montenbruck *et al.* [2006]).

The PolaRx2 in the tests has one antenna input, but available in versions with multiple antenna inputs (Septentrio [2005]). The PolaRx2 was configured in the tests as follows:

| | |
|---|---|
| • Channel Configuration | Single Frequency |
| • Elevation Mask | 0.0° |
| • Receiver Dynamics | Off |
| • Tracking Mode | Dynamic |
| • Output Rate | 10Hz |

The performance and hardware specifications of the PolaRx2 can be founded in Septentrio [2005]. Dynamic range of the PolaRx2 in technical specifications is 4g and 3g/sec for the acceleration and jerk, respectively, that is very low level to use the PolaRx2 as a navigation sensor of a satellite launch vehicle even though the limitations of velocity and altitude is removed.

### *2.3 DL-V3 (NovAtel [2006])*

The DL-V3 receiver from NovAtel Inc., Calgary, Canada, is a general purpose OEMV-3-based triple-frequency 72-channel GNSS receiver with output rates of up to 20Hz. The DL-V3 provides flexible connectivity through serial, USB, Ethernet, and Blutooth interfaces (NovAtel [2006]). All data of the DL-V3 in the tests were logged using USB interfaces. The DL-V3 was configured in the tests as follows:

| | |
|---|---|
| • Elevation Mask | 0.0° |
| • Output Rate | 10Hz |

The performance and hardware specifications of the DL-V3 can be founded in NovAtel [2006].

## 3. TEST Configuration

For the tests described in this paper, the test components were set-up like Fig. 1. The GPS signal simulator is a Spirent Communications' model GSS6560 that has 12 independent channels at L1 with C/A code modulation (Spirent [2004]). The host vehicle trajectory parameters required to perform the simulation can be input to GSS6560 as a data file or a model. No broadcast ephemeris errors, clock dithering, or multipath errors have been applied in the simulations. The GSS6560 was operated using three different scenarios in order to compare the performance of the GPS receivers under various high-dynamic conditions. One is a centrifuge and the others are a satellite launch vehicle and a spacecraft which are representative high-dynamic applications. It is assumed in this simulation that all GPS satellites above local horizontal 0° are located in FOV of GPS receivers, where the local horizontal is defined as a plane perpendicular to the earth's surface passing through the vehicle (Spirent [2004]).

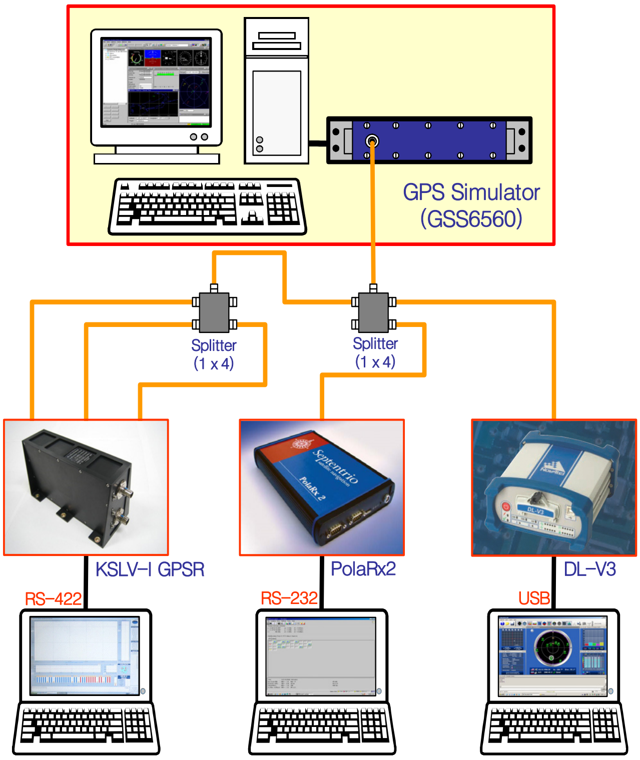

Fig. 1. Test Configuration

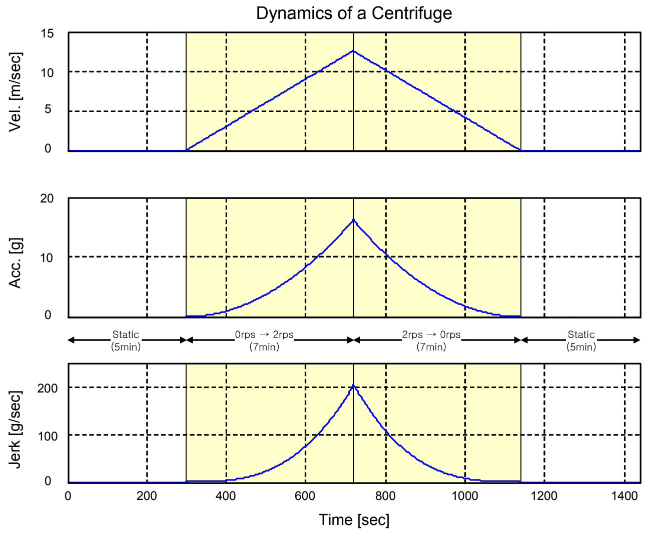

Fig. 2. Dynamics of a Centrifuge

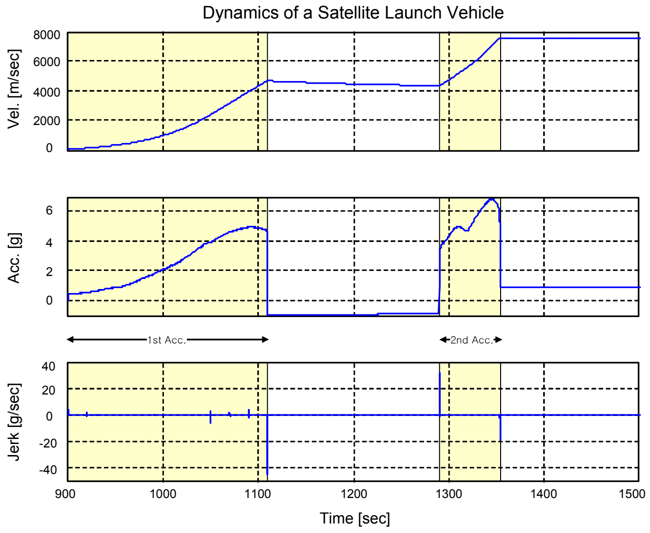

Fig. 3. Dynamics of a Satellite Launch Vehicle

Based on the specified GPS constellation data and the test trajectories, true navigation data has been computed for comparison with the actual navigation data from GPS receivers.

The satellite signals generated by the GPS simulator are supplied to the GPS receivers simultaneously through two 1×4 active splitters. All GPS receivers are rebooted in cold start conditions at the start of the tests.

### *3.1 Centrifuge Scenario*

The first scenario employed in the tests is a rotational motion like a centrifuge that has a centre point at constant latitude and longitude with a radius of about 1m, and fixed altitude of 100m. The magnitudes of angular velocity, centripetal acceleration and jerk are increased monotonically from 0rps to 2rps and decreased inversely like Fig. 2. Centrifuge testing, though the centrifuge motion does not model a missile or satellite launch vehicle trajectories, provides a means to obtain GPS data in a high-dynamic environment accompanied by accurate reference data. The monotonic characteristic of the dynamics also can help to determine a threshold of the GPS receiver performance under dynamic environments (Cunningham *et al.* [2000] and Kwon *et al.* [2006]). The magnitude of the maximum velocity, acceleration, and jerk is approximately 12.54m/sec, 16.07g, and 202.14g/sec at time 720.0sec, respectively. The jerk level is extremely large compared to the levels of the velocity or acceleration.

### *3.2 Satellite Launch Vehicle Scenario*

Another representative high-dynamic application is a satellite launch vehicle that has extremely high velocity, acceleration, and jerk. An example of a satellite launch vehicle's dynamics during flight mission is shown in Fig. 3 that is a 2nd test scenario used in this paper. In the scenario, the satellite launch vehicle is lift-off at time 900sec and has two periods of acceleration phase. The first and second peaks of the jerk in the scenario are about -44.2g/sec and 31.3g/sec that are appeared at the end of 1st acceleration phase and at the beginning of 2nd acceleration phase, respectively.

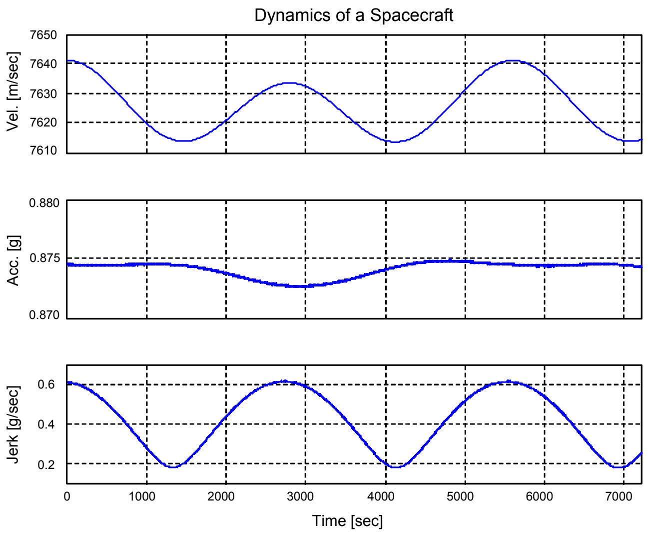

Fig. 4. Dynamics of a Spacecraft

### *3.3 Spacecraft Scenario*

The last scenario is for applications of a spacecraft. A complete description of the orbital simulation scenario is found in Montenbruck and Holt [2002]. The scenario is summarized as follows:

| | |
|---|---|
| • Semi-major Axis | 6823.0km |
| • Eccentricity | 0.001 |
| • Inclination | 87° |
| • Longitude of Ascending Node | 135° |
| • Argument of Perigee | 0.0° |
| • Mean Anomaly | 0.0° |

The modelled spacecraft is assumed to fly in a 450km alti-

Table 1. Dynamic Conditions at Loss and Recovery of Navigations (Centrifuge Scenario).

| Receiver | Loss of Navigation | | | | Recovery of Navigation | | | |
|---|---|---|---|---|---|---|---|---|
| | Time [sec] | Vel. [m/sec] | Acc. [g] | Jerk [g/sec] | Time [sec] | Vel. [m/sec] | Acc. [g] | Jerk [g/sec] |
| PolaRx2 | 447.8 | 4.42 | 1.99 | 8.81 | 1009.9 | 3.89 | 1.54 | 6.01 |
| DL-V3 | 562.7 | 7.85 | 6.29 | 49.44 | 889.1 | 7.50 | 5.74 | 43.09 |

tude near circular, polar orbit, which resembles that of the Champ and Grace satellites (Montenbruck and Holt [2002]). This scenario has dynamic conditions such as extremely high velocities but very low accelerations and jerks like Fig. 4 that is typical dynamics of spacecrafts. The spacecraft scenario used in this paper is run over two hours.

Benchmark testing results of spaceborne GPS receivers for LEO(Low Earth Orbit) satellite are founded in Montenbruck *et al.* [2006], Montenbruck and Holt [2002], and Holt *et al.* [2003].

## 4. PERFORMANCE OF GPS RECEIVERS

### *4.1 Centrifuge Scenario*

In the centrifuge scenario, the KSLV-I GPSR maintains the signal lock continuously for full range of the test. The PolaRx2 and DL-V3, however, loses the lock and can not even provide navigation data during dynamic conditions like Table 1. It can be seen that PolaRx2 is more sensitive to the dynamics than DL-V3.

Navigation errors of the GPS receivers are shown in Fig 5. The KSLV-I GPSR shows good accuracy performance but step errors in position solution exhibit when new satellite signals are acquired. Relatively large errors in position solution of the KSLV-I GPSR are appeared when the satellite signals with low elevation angle nearly 0° are used in the computation. Large velocity errors of the KSLV-I GPSR are observed around maximum dynamic condition.

The PolaRx2 has the excellent position accuracy but somewhat larger velocity errors at static and under lower dynamic conditions. The PolaRx2 outputs some unavailable values as the position and velocity data when the navigation data can not be provided.

The DL-V3 has excellent position and velocity accuracies at static and under lower dynamic conditions. The velocity computed in DL-V3, however, becomes large in proportion to the dynamics of a centrifuge. Velocity computation algorithm of the DL-V3 is required some improvements in order to use for the applications with rotational motion. Navigation information of the DL-V3 around at the loss and recovery of navigation is unsettled because of inconstant lock status. It is noted that the DL-V3 keeps the past position and velocity values when the navigation data can not be provided. These values are eliminated in Fig. 5 intentionally.

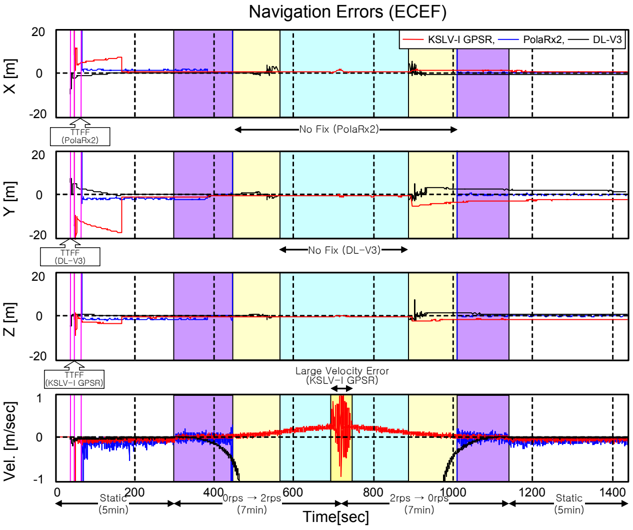

Fig. 5. Navigation Errors (Centrifuge Scenario)

The TTFF(Time To First Fix) is roughly 1 minute for all GPS receivers used in the tests including initial self-test. It is noted that the TTFF in the centrifuge scenario is occurred at the static.

### *4.2 Satellite Launch Vehicle Scenario*

All GPS receivers used in the tests maintain the signal lock continuously for the satellite launch vehicle scenario. Navigation errors of the GPS receivers after lift-off are shown in Fig. 6 and Table 2.

The KSLV-I GPSR shows good navigation accuracy even though the relatively large errors in position solution are appeared when the satellite signals with low elevation angle are used in the computation regardless of the dynamics. Maximum position error of the KSLV-I GPSR is about -5.3m that is appeared at the lift-off due to the satellite signal with low elevation angle. The PolaRx2 has also good position accuracy under the satellite launch vehicle dynamics. The PolaRx2, however, has the maximum position error about -17.2m and the maximum velocity error about 8.5m/sec at the beginning of 2nd acceleration phase. It is noted that the instantaneous peaks of the navigation errors are appeared in the PolaRx2 and DL-V3 at the dynamics with the instantaneous extremely large jerk. The DL-V3, on the contrary of the other GPS receivers, has the large position errors, relatively, after lift-off. This phenomenon is seems to be occurred due to the large velocities not accelerations or jerks. The velocity accuracy of the DL-V3 is strikingly different from its position accuracy. The DL-V3 has most notable velocity accuracy over full range of the flight mission in the scenario except at the point of large jerks.

It can be shown at a glance in Fig. 6 that the KSLV-I GPSR and PolaRx2 seem to have the large velocity errors over periods of acceleration phase. The phenomenon, however, is a kind of computational latency that is originally occurred due to the velocity is computed using Doppler values typically derived from differences in consecutive carrier phase measurements. Note that the time latency of the veloc-

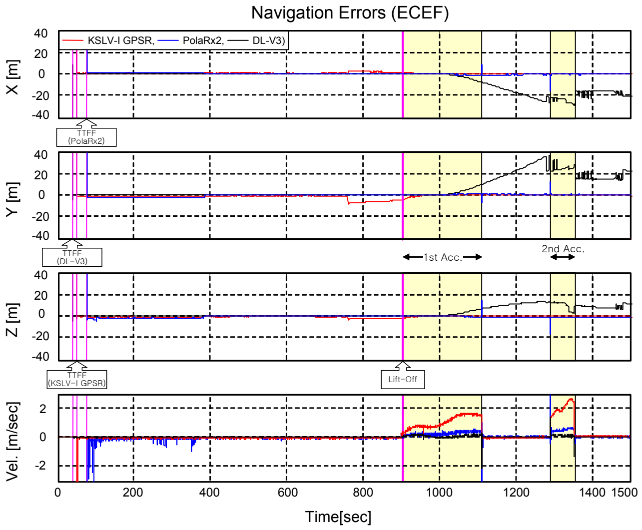

Fig. 6. Navigation Errors (Satellite Launch Vehicle Scenario)

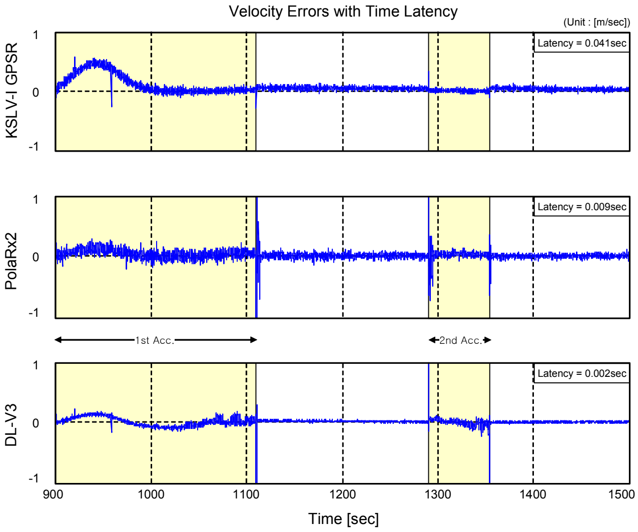

Fig. 7. Velocity Errors reckoned with Time Latency (Satellite Launch Vehicle Scenario)

Table 2. Navigation Errors during Flight. (Satellite Launch Vehicle Scenario)

| Errors | | | KSLV-I GPSR | PolaRx2 | DL-V3 |
|---|---|---|---|---|---|
| MEAN | ECEF – X [m] | | 3.967e-2 | -4.468e-1 | -12.365 |
| | ECEF – Y [m] | | -8.657e-2 | 3.606e-1 | 13.769 |
| | ECEF – Z [m] | | -1.341e-1 | -7.860e-1 | 6.767 |
| | Vel. [m/sec] | Reckon without Latency | 5.723e-1 | 1.279-1 | 2.770e-2 |
| | | Reckon with Latency | 5.789e-2 | 1.496e-2 | 2.603e-3 |
| R95 | ECEF – X [m] | | 6.046e-1 | -9.692e-1 | -25.752 |
| | ECEF – Y [m] | | -1.832 | 9.213e-1 | 31.267 |
| | ECEF – Z [m] | | -8.186e-1 | -1.427 | 12.837 |
| | Vel. [m/sec] | Reckon without Latency | 1.939 | 4.885e-1 | 1.393e-1 |
| | | Reckon with Latency | 3.696e-1 | -1.273e-1 | 1.150e-1 |
| MAX | ECEF – X [m] | | 1.598 | -15.736 | -28.982 |
| | ECEF – Y [m] | | -5.243 | 12.889 | 36.740 |
| | ECEF – Z [m] | | -2.307 | -17.169 | 13.685 |
| | Vel. [m/sec] | Reckon without Latency | 2.661 | 8.678 | -2.185 |
| | | Reckon with Latency | 5.584e-1 | 8.414 | -2.180 |

ity computed in the DL-V3 is provided to improve the results. Velocity errors reckoned with the time latency are shown in Fig. 7. Great difference occurred due to the latencies in some milliseconds can be shown in Fig. 7. The latency is necessarily considered in order to more accurate velocity data with respect to the time tag particularly in the dynamics with high acceleration like the satellite launch vehicle. The latency values of GPS receivers in Fig. 7 were computed by trial and error even though the DL-V3 provides the latency itself. The latency provided by the DL-V3 during the test is 0.15sec. If the latency 0.15sec is applied, however, the larger velocity error is occurred. The KSLV-I GPSR has 0.041sec as the latency, which is larger than the PolaRx2 by 4.5 times, approximately.

All GPS receivers used in the tests has the TTFF under 80sec, approximately, that is also occurred at the static.

### 4.3 *Spacecraft Scenario*

All GPS receivers used in the tests maintain the signal lock continuously for the spacecraft scenario. Navigation errors of the GPS receivers are shown in Fig. 8 and Table 3.

Position and velocity errors of the KSLV-I GPSR and the PolaRx2 are fairly small for all periods. The instantaneous peak navigation errors of the PolaRx2 appeared in the previous scenario due to the large jerk do not occurred. The KSLV-I GPSR, on the contrary, has some peak velocity errors as the maximum -1.4m/sec, approximately. The DL-V3 is appeared many periods of abnormal operations and provides position data with large errors. It, however, still has excellent velocity error in all test period. It is noted in the test using the spacecraft scenario that absolute value of the velocity error according to the latency is insignificant because of the low acceleration of the dynamics.

The TTFF in the spacecraft scenario is occurred during the dynamics of a spacecraft, *i.e.* the extremely high velocity, which differs from the previous scenarios. The DL-V3 receiver showed the longest TTFF despite of large number of tracking channels. The KSLV-I GPSR, PolaRx2, and DL-V3 has the TTFF as 168.4sec, 110.0sec, 326.1sec, respectively, in the spacecraft scenario.

## 5. CONCLUSIONS

This paper analyzed the performance test results for the three GPS receivers focused on both the tracking capability and navigation data accuracy under representative high-dynamic conditions such as centrifuge, satellite launch vehicle, and spacecraft.

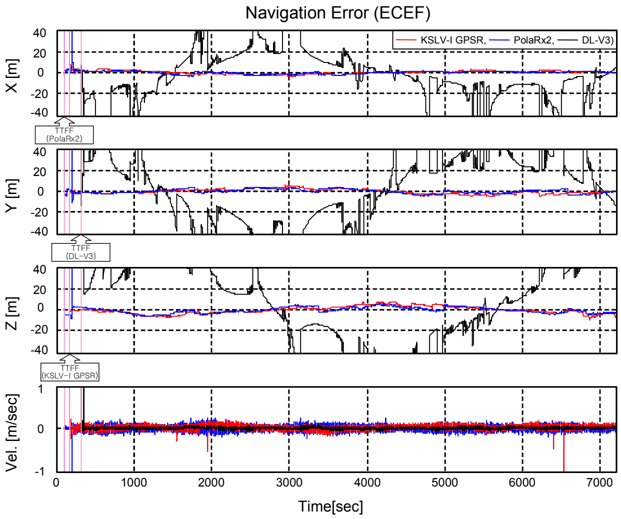

Fig. 8. Navigation Errors (Spacecraft Scenario)

Table 3. Navigation Errors during Flight.
(Spacecraft Scenario)

| Errors | | | KSLV-I GPSR | PolaRx2 | DL-V3 |
|---|---|---|---|---|---|
| MEAN | ECEF – X [m] | | 1.970e-1 | 2.477e-2 | -1.002 |
| | ECEF – Y [m] | | -1.713e-1 | -6.309e-2 | 2.510 |
| | ECEF – Z [m] | | -3.651e-1 | -5.146e-1 | 13.273 |
| | Vel. [m/sec] | Reckon without Latency | 1.941e-2 | 4.829e-3 | 3.366 |
| | | Reckon with Latency | 1.952e-2 | 4.852e-3 | 3.371 |
| R95 | ECEF – X [m] | | 2.772 | -2.176 | 56.487 |
| | ECEF – Y [m] | | 4.256 | -3.721 | 98.911 |
| | ECEF – Z [m] | | -6.695 | -5.074 | -171.066 |
| | Vel. [m/sec] | Reckon without Latency | 8.462e-2 | -8.564e-2 | -3.485e-2 |
| | | Reckon with Latency | 8.418e-2 | 8.565e-2 | 3.485e-2 |
| MAX | ECEF – X [m] | | 2.772 | -2.176 | 56.487 |
| | ECEF – Y [m] | | 4.256 | -3.721 | 98.911 |
| | ECEF – Z [m] | | -9.719 | -6.742 | -250.091 |
| | Vel. [m/sec] | Reckon without Latency | -1.337 | 2.560e-1 | 8.464e-2 |
| | | Reckon with Latency | -1.336 | 2.559e-1 | 8.468e-2 |

Among the three GPS receivers tested, the KSLV-I GPSR has an excellent capability to maintain the signal lock for all scenarios considered in this paper. Navigation data computed in KSLV-I GPSR is also good for all tests, but appeared relatively large errors when the satellite signals with low elevation angle are used in the computation. Large velocity errors appeared around maximum dynamic condition of the centrifuge scenario, but that is not concerned because of the dynamic level at that time does not appear in the satellite launch vehicles. Some peaks of the velocity error are occurred in the spacecraft scenario regardless of the dynamics.

The PolaRx2 shows excellent performance in the test scenarios of the spacecraft and the satellite launch vehicle except at the presence of the instantaneous jerk. In the centrifuge scenarios, however, it can be seen that the PolaRx2 is very sensitive to the rotational dynamics. Some peaks of the navigation data from the PolaRx2 are occurred at the point of large jerk in the satellite launch vehicle scenario.

The DL-V3 has notable velocity accuracy for all dynamics except the centrifuge. The position error, on the contrary, is very large when the DL-V3 exposed high-velocity environments. Eventually some periods of abnormal operation in the spacecraft scenario was appeared. We made some inquiries about the behaviour of the DL-V3 to NovAtel and another export license to acquire new firmware for the DL-V3 is in progress.

It is noted that the KSLV-I GPSR is a single-frequency GPS receiver, but the PolaRx2 and DL-V3 receivers are not. Since the GPS simulator used in this paper broadcasts only single-frequency, the PolaRx2 and DL-V3 receivers did not utilize their all capabilities.

Launch of KSLV-I is presently scheduled at the end of 2008. The KSLV-I GPSR will be tested using additional high-dynamic conditions before flight. It is also required further research to evaluate raw measurement accuracy of the KSLV-I GPSR as given in Montenbruck *et al.* [2002] and Holt *et al.* [2003].

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