Performance Assessment of Single and Dual Frequency, Commercial-based GPS receiver for LEO orbit

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ABSTRACT

Testing and qualification of a commercial dual-frequency GPS receiver has been done for a joint project by CSA and JAXA. This paper reports the results of performance assessment of the NovAtel OEM4-G2L dual frequency receiver with modified firmware. The signal simulator tests for LEO mission are performed, and the initial tracking/acquisition performance, single point navigation accuracy and the effect of the deterioration of the L2 (Pseudo-Y) signal on the navigation accuracy are evaluated in this study. Furthermore the comparison of a navigation performance between the NovAtel OEM4-G2L and the JAXA micro GPS receiver developed based on a single frequency terrestrial GPS receiver is discussed.

INTRODUCTION

The JC2Sat-FF is a nanosatellite mission consisting of two nanosatellites demonstrating the feasibility of maintaining spacecraft formation using aerodynamic drag. This mission will be the first project developed in the scheme of international collaboration between Canadian Space Agency (CSA) and Japan Aerospace Exploration Agency (JAXA).

The primary objective of this project is to demonstrate spacecraft formation keeping technology powered by aerodynamic drag control and GPS-based relative navigation. The principle advantage of this concept is that no propulsion system is required. A literature survey of all proposed or planned FF missions indicates that a propulsion system is imperative which inherently increases the complexity and cost of the spacecraft design. There is no mission, for any class of satellite, which attempts to demonstrate the FF concept utilizing aerodynamic drag only.

One of the challenges of this project is to demonstrate

that the nanosatellite which has capability to carry out several advanced experiments, can be built at low cost, with a small team and in a short time frame.

Low cost and high performance GPS navigation system is key to this mission. Compared with a system with single-frequency GPS sensors. GPS dual-frequency carrier-phase observations enable one to provide higher accuracy, to adapt on larger baseline applications up to few hundreds of kilometers, and also to improve the identification of systematic Despite measurement errors. the significant advantages of the GPS dual-frequency sensor system, only few space missions have adopted this system due to the practical limitation on the available selection of space-capable dual-frequency receivers. Space qualified dual-frequency GPS receivers are extremely expensive, especially for a small satellite project.

An attractive approach for a mission with limited cost is to adopt a commercial GPS receiver.

In some previous studies, it has been confirmed that

the NovAtel's commercial dual frequency GPS receiver has the capability to track GPS signals under an on-orbit situation with higher velocity, acceleration and jerk^{1,2}.

This paper reports the results of a performance assessment of the NovAtel OEM4-G2L dual frequency receiver with special firmware. Signal simulator tests for a LEO orbit are performed, and the initial tracking/acquisition performance, navigation accuracy and the effect of the deterioration of the L2 (Pseudo-Y) signal on the navigation accuracy are evaluated. Furthermore a comparison of the navigation performance between the NovAtel OEM4-G2L and the JAXA micro GPS receiver developed based on a single frequency terrestrial GPS receiver is discussed. This micro GPS receiver has been adopted as navigation sensor in several small satellite projects in JAXA as well as in an experimental instrument attached to the Japanese Experiment Module (JEM) on the International Space Station (ISS).



Figure 1 JC2Sat-FF mission concept

DUAL FREQUENCY GPS RECEIVER

It is well known that the most significant error source for absolute spacecraft navigation is the ionospheric delay. The ionospheric delay is significant for altitudes up to ~1000km³. If uncorrected for, this can lead to errors of several tens of meters. Many of the receivers currently in use onboard spacecraft are single frequency receivers. In previous studies, several methods by which the effect of this error may be reduced have been proposed. A paper introduces an ionospheric correction method for a single frequency receiver based on the model of the ionospheric error for LEO altitude⁴. A 90% reduction in the ionospheric error is achieved for the test case presented in the study. Alternatively, by making use of the fact that the group and phase delays have the opposite signs, by taking the average of the pseudorange and carrier phase measurements, a range measurement free of the ionospheric delay is obtained. On the other hand, this measurement now has a bias due to the carrier phase ambiguity. This bias must be estimated, which can take time. This is one of the areas of benefit of a dual frequency receiver. The dispersive nature of the ionosphere is frequency dependent, and as such, with pseudorange measurements at two different frequencies, they may be combined to give an ionosphere free pseudorange measurement.

For JC2Sat, the GPS receivers will be used for relative positioning. The use of dual-frequency measurements allows for larger satellite separations (due to ionospheric error removal), and faster integer ambiguity resolution, as is needed for double difference carrier phase differential GPS⁵.

NOVATEL OEM4-G2L RECEVER

Receiver Description

The baseline GPS receiver for the JC2Sat-FF mission is the NovAtel OEM4-G2L with raw data output (Figure 2). The OEM4-G2L is a small, high performance dual frequency (L1/L2) commercial receiver designed for terrestrial and aircraft applications. The attractive physical features of the receiver are small footprint (100mm \times 60mm \times 16mm), low power consumption (1.6W) and mass (56g). These features make the receiver of particular interest for small satellite mission with tight onboard resources. The OEM4-G2L provides a total of 24 tracking channels. Twelve channels are allocated for L1 C/A-code tracking and another twelve channels are in charge of L2 P-code tracking. The maximum rate of measurement and navigation solution update is 20Hz.

This receiver is planned for use on several nanosatellite missions by the University of Toronto Institute for Aerospace Studies (UTIAS) as well as the Canadian CASSIOPE mission. Radiation testing and performance analysis have been performed for this receiver⁶. And also a favorable qualification study of the OEM4-G2, which is a sister product of the OEM4-G2L, has been done by DLR². The results of these works show the viability of using COTS GPS receiver for LEO application.



Figure 2: NovAtel OEM4-G2L

Firmware Modification

In this study, only a few simple modifications on the firmware such as the removal of altitude limit, velocity limit and tropospheric delay correction are attempted to obtain adequate navigation solution for a LEO mission. Since the GPS signals at LEO are completely unaffected by the tropospheric delay, this correction causes large positioning error mainly in radial direction as found in the DLR test².

PERFORMANCE ASSESSMENT OF NOVATEL OEM4-G2L

As pointed out in many previous studies, the characteristics of GPS signals received in LEO are quite different from on the ground. Spaceborne receiver used in LEO encounter higher speed (roughly 7.5 km/s), larger Doppler shifts (up to 40 kHz) as well as higher line-of-sight acceleration (roughly 1G).

A GPS simulator test is the only way to realistically assess the tracking performance of GPS receiver under such high-signal dynamics as seen in LEO. Tests with a ground based antenna using real GPS signals do not suffice for this purpose. All tests were conducted at NovAtel Inc. in Calgary, Canada. The Spirent STR4760 dual-frequency GPS signal simulator supplying 8 and 12 channels was used.

Simulation Scenario

The simulations were configured for the nominal JC2sat-FF orbit, which is a sun-synchronous orbit at 650 km altitude with time of descending node 13:00. The epoch is taken to be 4 February 2007 at midnight. This is start of GPS week 1413.

The tropospheric delay is disabled. The spacecraft ionosphere model is used with a constant total electron content (TEC) value, except in the error free simulation.

The GPS constellation orbital parameter are obtained from the broadcast ephemeris data provided by IGS in RINEX form for the same day with the epoch described above.

The satellite selection method was chosen to be based upon the range, i.e. the closest satellites are used. Note that this means that satellites that could potentially provide a better dilution of precision (DOP) are not used. In particular, in the tests using the 8 channels simulator, DOP was sometimes very large and the navigation solution showed less-accurate results at the time.

Receiver Settings

As found by the tests at DLR, carrier smoothing should be ideally disabled for the receiver used on orbit. The carrier smoothing time constants for L1 and L2 were set to their minimum value by a command. In addition, the elevation mask angle was also expanded by a command because it is possible to see GPS satellite below zero degree elevation for LEO altitude.

Initial Acquisition Performance

The initial acquisition performance was assessed in a series of simulator tests. The purpose of this test is to determine the time to first fix (TTFF) from a cold start for different points in the orbit. The TTFF is defined to be the time at which both a position and velocity solution are obtained.

Table 1 shows the results for the TTFF measurement. The TTFF varies between just under 2 minutes to over 8 minutes. The average of TTFF is 232.2 seconds (c.a. 4min). This result is consistent with the result of TTFF assessment for OEM4-G2 (2-12min) reported by DLR².

In this test, 12 channels GPS signal simulator was used.

Table 1: Initial Acquisition Performance Test

Case	TTFF [sec]	Latitude at receiver activation [deg]
1	315	-0.03314
2	118	75.76264
3	497	26.62787
4	115	-47.9419
5	111	-55.8707

Error Free scenario

All error sources are set to zero in this scenario, so that the only error source is the receiver clock error and measurement noise. The purpose of this test is to provide a reference against which all other tests can be compared. Another aim of this simulation is to verify the effect of the removal tropospheric delay correction on the firmware.

The navigation accuracy and the GDOP are illustrated in Figure 3 and Figure 4, based on the comparison between receiver navigation solution and simulation output. The results are presented in a reference frame aligned with the radial, along-track and cross-track direction. The results are summarized in Table 2.

The position errors are almost zero mean white noise. It is clear that the accuracy on radial direction is dramatically improved compared to the simulation result in the DLR study². Only a small modification on the firmware, invalidation of the tropospheric correction, can derive good positioning accuracy. On the other hand, the radial velocity error has a similar systematic offset, which can most probably be attributed to a slight timing error in the sampling of the Doppler. This error could be avoided by using carrier phase range rate in the offline processing.

The large spike found in the all graphs is due to lack of a computed GPS solution from receiver. The GDOP value is very large at the time. Note that only an 8 channel simulator was used in this test. It shows that the navigation accuracy could be extremely poor when the satellite tracks only few GPS satellites. The antenna layout should be considered very carefully in the satellite system design. Also the filter implemented in the on-board navigation software should be designed with the serious consideration of this fact.

Table 2: Summary of the result of the simulationwith error free scenario (OEM4-G2L)

	Radial	Cross-track	Along-track
Mean Position Error	0.0258 [m]	-0.0127 [m]	-0.00919 [m]
Position Error S.D.	0.571 [m]	0.186 [m]	0.252[m]
Mean velocity Error	0.0579 [m/s]	0.00264[m/s]	0.00498[m/s]
Velocity Error S.D.	0.0766[m/s]	0.0282[m/s]	0.0322[m/s]

* S.D.: Standard Deviation









Figure 5: GDOP (error free)

Ionospheric Error scenario

The ionospheric delay with TEC value of 10^{17} is introduced in this simulation test. The purpose of this test is to evaluate the effectiveness of the receiver in using dual frequency measurements to remove the ionospheric delay.

The navigation accuracy and the GDOP are illustrated in Figure 6 and Figure 7, and the results are summarized in Table 3.

Comparing this results with the results in the error free simulation, with the exception of slightly larger mean error in the radial direction of the both position and velocity, the navigation accuracy are not much different. It implies that the receiver makes good use of the dual frequency measurements to remove ionophseric delay.

Table 3: Summary of the result of the simulationwith ionospheric error scenario (OEM4-G2L)

	Radial	Cross-track	Along-track
Mean Position Error	0.0624 [m]	-0.00982[m]	-0.0292 [m]
Position Error S.D.	0.584 [m]	0.186 [m]	0.247[m]
Mean velocity Error	0.0604 [m/s]	0.00039[m/s]	-0.0091[m/s]
Velocity Error S.D.	0.0744[m/s]	0.0229[m/s]	0.0256[m/s]

* S.D.: Standard Deviation

Ionospheric Error with High TEC scenario

In this test, the ionopheric delay is set with 10 times larger TEC value $(10^{18} \text{ electrons/m}^2)$. The purpose of this test is to see the effect of large ionosopheric delay on the receiver performance.

The navigation accuracy and the GDOP are illustrated in Figure 9 and Figure 10, and the results are summarized in Table 4.

The large spike and non zero-mean error in the plots are mainly due to poor GDOP. However there are also several exceptions which have large positioning error despite relatively good GDOP. These phenomena are attributed to the incorrect ionospheric delay correction due to the loss of L2 signal. When both L1 and L2 measurements are available, the ionospheric-free measurement is used to obtain better ionospheric correction. It is well known that the L2 signals are more difficult to track. In case that an L1 measurement is available whereas the L2 signal of same GPS



Figure 6 Position Error (ionospheric error)



Figure 7 Velocity Error (ionospheric error)



Figure 8 GDOP (ionospheric error)







Figure 10 Velocity Error (high TEC)



Figure11 GDOP (high TEC)

satellite is not tracked, the OEM4-G2L switches to the model-based ionospheric delay correction. In fact, the model used (Klobuchar model) was developed for terrestrial application, thus it obviously does not give the proper correction in a space application. In other words, for effective removal of the ionospheric delay, both L1 and L2 measurements must be used for each GPS satellite. If the number of L1 measurement used exceeds the number of L2 measurements available, then it is clear that there are at least some measurements used that are corrected for the ionospheric delay with inappropriate way.

Figure 12 shows the plot of the total position error, i.e. the root-mean-square (RMS) of the position error, and Figure 13 shows the difference between the number of L1 measurement and L2 measurement. It is found in the plots that the times at which the error is non-zero mean are the times at which more L1 measurements are used than L2. This is a characteristic behavior of the OEM4-G2L in a space application.

Table 4: Summary of the result of the simulationwith high TEC scenario (OEM4-G2L)

	Radial	Cross-track	Along-track
Mean Position Error	0.00479 [m]	-0.00753[m]	-0.141[m]
Position Error S.D.	1.06 [m]	0.294 [m]	0.549[m]
Mean velocity Error	0.124 [m/s]	0.0129[m/s]	-0.0800[m/s]
Velocity Error S.D.	0.179[m/s]	0.0581[m/s]	0.109[m/s]

* S.D.: Standard Deviation



Figure 12 Total position Error (high TEC)



Figure 13 Difference between the number of L1 and L2 measurements (high TEC)

SINGLE FREQUENCY MICRO GPS RECEIVER

Receiver Description

The Micro GPS Receiver (MGPSR) has been developed based on the automobile-navigation technology by JAXA (Figure 14). The MGPSR is the single frequency receiver with 8 tracking channels for L1 signal.

In order to convert the terrestrial receiver to a spaceborne receiver, several modifications were implemented in its firmware. Some of the modifications are introduced below.

The frequency sweep range was expanded to cover a larger Doppler shift on orbit. The altitude limit and the tropospheric delay correction were removed. The ionospheric delay correction was also removed because the original correction method is designed for terrestrial application and is not adequate in space application. Since the receiver is a single frequency receiver, it means that the receiver does not have any means to compensate the ionospheric delay. The capability of raw data output including pseudo-range and carrier-phase measurement was added. It can be used for various application fields such as precise orbit determination and GPS-based attitude determination.

The case and, the signal and power interface board are adopted to endure launch and the space environment, and to comply with the EMC/EMI requirements in space systems. The radiation hardness of the commercial parts used in MGPSR have been evaluated in the Gamma ray irradiation tests and the Cf-252 radiation tests.

Table 5 shows the basic specification of the MGPSR.



Figure 14 MGPSR and the original commercial

GPS receiver Table 5: Basic specification of MGPSR

Item	Specifications	
Size	72 x 50 x 40 mm (GPSR)	
	45 x 54 x 15 mm (Antenna)	
Mass	215g (GPSR)	
	60g (Antenna)	
Power	1.5W (typical)	
Frequency	1575.42 MHz (L1)	
No. of channels	8 ch	
Output data	PPS signal	
	Navigation data	
	Raw data	
	Ephemeris data	
Interface	RS-422, +5VDC	

PERFORMANCE ANALYSIS OF MICRO GPS RECEIVER

In order to compare the single point navigation performance of MGPSR with the NovAtel OEM4-G2L, a series of simulation tests with same simulation parameters were conducted in JAXA. The Spirent GSS7700 GPS signal simulator supplying 12 channels was used in this test.

Note that the 8 channels simulator was used to assess the performance of OEM4-G2L. This difference on the simulation condition should be taken into account in the comparison of both simulation results.

Error Free scenario

The navigation accuracy and the value of PDOP are illustrated in Figure 15 and 16, and the results are summarized in Table 6.

Comparison with the result of the error free simulation for OEM4-G2L shows that the navigation errors are more noisy in the radial direction, and non zero-mean error is found in the along-track direction. The bias in the along-track direction is attributed to the measurement timing error of the receiver.

Table 6: Summary of the result of the simulationwith error free scenario (MGPSR)

	Radial	Cross-track	Along-track
Mean Position Error	1.62 [m]	0.844 [m]	3.41[m]
Position Error S.D.	3.22 [m]	0.997 [m]	1.42[m]

* S.D.: Standard Deviation





Figure 16: GDOP (error free)

Ionospheric Error scenario

The ionospheric delay is introduced in this simulation. The navigation accuracy and the value of PDOP are illustrated in Figure 17 and 18, and the results are summarized in Table 7.

It is clear from the figures that an additional bias error appears only in the radial direction. The navigation accuracy of the MGPSR is directly affected by the existence of ionospheric delay because any means of the ionospheric delay correction is not implemented. The average radial bias found in this test is approximately 4.6 m.

Table 7: Summary of the result of the simulationwith ionospheric error scenario (MGPSR)

	Radial	Cross-track	Along-track
Mean Position Error	-2.95[m]	0.542[m]	3.41[m]
Position Error S.D.	3.75[m]	0.956[m]	1.39[m]



Figure 17: Position Error (ionospheric error)



Figure 18: GDOP (ionospheric error)

Ionospheric Error with High TEC scenario

In this test, the ionopheric delay is set with 10 times larger TEC value $(10^{18} \text{ electrons/m}^2)$.

The navigation accuracy and the value of PDOP are illustrated in Figure 19 and 20, and the results are summarized in Table 8.

The result shows the single point navigation accuracy of the MGPSR is affected significantly by ionospheric delay in a different manner from the OEM4-G2L.

As remarked above, the navigation accuracy of OEM4-G2L deteriorates only in case the receiver does not use ionospheric-free measurement based on L1 and L2 signals. However the TEC value used in this test is not realistic number in typical satellite orbit.

	Radial	Cross-track	Along-track
Mean Position Error	-46.8 [m]	-2.98[m]	1.84[m]
Position Error S.D.	11.3 [m]	3.57[m]	2.89[m]

Table 8: Summary of the result of the simulationwith high TEC scenario (MGPSR).



Figure 19: Position Error (high TEC)



Figure 20: PDOP (high TEC)

SUMMARY

Several tests and qualification of a commercial dual-frequency GPS receiver, NovAtel OEM4-G2L, have been conducted in the scheme of the international collaboration between the CSA and JAXA. On the basis of the results of the signal simulator test, basic characteristics and performance of the receiver were evaluated. The results show that the OEM4-G2L is suitable for use in a LEO application.

The comparison of the navigation performance between the NovAtel OEM4-G2L and the JAXA MGPSR developed based on the single frequency terrestrial GPS receiver was also performed. Some advantages of the dual-frequency receiver were confirmed in this study.

A more detailed study such as the assessment of raw measurement accuracy will be performed in the future work.

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