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Miniature Space GPS Receiver by means of Automobile-Navigation Technology

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ABSTRACT

Miniature space GPS receivers have been developed by means of automobile-navigation technology. We expanded the frequency sweep range in order to cover large Doppler shift on orbit. The GPS receiver was modified to output pseudorange data with accurate time tag. We tested the performance in low earth orbits by means of a GPS simulator. The range error caused by the receiver is measured to be 0.9 meter in RMS. Receiver was on-boarded on INDEX ("REIMEI") satellite, which was launched in 2005. Cold start positioning was confirmed repeatedly to finish within 30 minutes on orbit. The orbit determination was performed to evaluate the random position error of GPS receiver by means of the residual error. The random error of GPS position is as large as 2 meter for PDDP=2.5 on orbit. The RMS value of range error is evaluated to be 0.6m from the flight data. These results on orbit are consistent with the simulation results in use of a GPS simulator. This miniature space GPS receiver is at present in commercial market.

INTRODUCTION

Recently miniature GPS (Global Positioning System) receivers have been utilized for automobile- navigation equipments as well as cellular phones. Their weight is several tens grams and their power consumption is less than 1 watt. The key technologies for their miniaturization are highly integrated circuits for receiver functions, based upon mass productions.[1,2]

On the other hand, space-borne GPS receivers are as heavy as several kg and power consumption is as much as 10 W.[3-5] In general, the space-borne GPS receivers are manufactured with use of space-qualified parts dedicated for space application, separately from commercial GPS receiver manufacturing. This leads to expensive development cost and large size of instruments.

In this research, we modified a model of GPS receiver for automobile-navigation to space application successfully. This paper describes the issues of such modification[6] and the performance of the modified receiver on orbit.

The next chapter describes the performance of the commercial GPS receiver for automobile-navigation. Then we explain the modification for space application. Evaluation with a GPS simulator was performed to predict the performance on orbit. The following chapter describes the results of the simulation. The flight results are qualitatively described in the last chapter. The conclusion is finally presented.

PERFORMANCE OF GPS RECEIVER FOR AUTOMOBILE — NAVIGATION

Specification of GPS Receiver for Automobile-Navigation

Model CCA-370HJ of Japan Radio Corporation is selected to be modified for space application in this research. Specification of CCA-370HJ is shown in Table 1.[2] Its weight is 35 grams and its size is 58.7 x

Table 1: Specification of the GPS Receiver CCA-370HJ for Automobile-Navigation

Receiving system		8 Channels (Tracking)
		1 Channel(Acquisition)
RF input	Frequency	1575.42MHz (L1) C/A code
	Sensitivity	-126dBm
Geodetic system		WGS-84
Positioning accuracy		30 m 2DRMS
Maximum velocity for tracking		200km/h (56m/sec)
Output data rate		1Hz
TTFF	Hot start	8.5sec to 52sec
	Warm start	25sec to 88sec
	Cold start (Spec)	95sec to 11min
	Cold start (Actual)	50sec to 5min
Power supply	Main voltage	DC +5.0V±0.25V
	Current	180mA typ. 270mA max
Preamplifier power supply		DC +4 to 5V 10mA to 30mA
Weight		35g
Size		$58.7 \times 36.3 \times 11.0$ mm^3

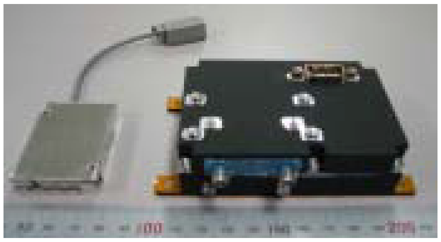


Fig.1: Left : Automobile-Navigation GPS Receiver CCA-370HJ,
Right : Flight Model with RF Hybrid for INDEX Satellite

36.3 x 11.0 mm^3. The receiver has 8 channels for NAVSTAR satellite tracking, one of which is utilized for search and acquisition. This model is applied to many instruments for automobile-navigation. The left side of Figure 1 is the photograph of CCA-370HJ. The right side of Figure 1 is the flight model receiver for INDEX satellite. The flight model contains a RF hybrid for all-sky GPS antenna.

Cold Start Acquisition on Ground

We performed simulation tests of the commercial GPS receiver for automobile navigation. The GPS simulator Spilent 476 with 12 channels was used for the test. Forty-four cases of cold start simulation at the fixed position on earth surface indicate that the minimum time to first fix (TTFF) is 49 seconds (N=4) and the maximum TTFF is 4 minutes 19 seconds (N=17), where the receiver tries to search N satellites of NAVSTAR in total until 4 NAVSTAR satellites are locked on.

The CCA-370HJ receiver has 8 channels for tracking, one of which is utilized for search and acquisition. Therefore the search and the acquisition operation is a sequential operation in CCA-370HJ receiver. Time to first fix (TTFF) for cold start is modeled as

$$\mathrm{TTFF} = 4\,T_{acq} + (N-4)\,T_{fail} + 30\ [\mathrm{sec}]. \qquad (1)$$

The first term is the total time of the acquisition for four NAVSTRAR satellites. The time T_{acq} is the average time of the acquisition for one NAVSTAR satellite when the acquisition successfully finishes. The second term is the total time of searches when the searches do not succeed well. The time T_{fail} is the time of search for one NAVSTAR satellite, when the acquisition fails. In the case of automobile-navigation, approximately T_{acq}=5 seconds and T_{fail}=16 seconds. The third term is the receiving time of the ephemeris data from the fourth NAVSTAR satellite that is locked on.

The search of the frequency direction is performed repeatedly by scanning the frequency input to the correlator. The search time of the frequency direction increases proportionally to the scanning range of frequency.[1] The frequency range Δf_s of the scanning for the frequency search is supposed to be determined such that Δf_s envelops the maximum frequency range Δf_d of the Doppler shift and the frequency drift Δf_o of the local oscillator (temperature compensated crystal oscillator, TCXO). Thus

$$\Delta f_s = \Delta f_d + \Delta f_o\,. \qquad (2)$$

The maximum Doppler shift Δf_d in automobile-navigation is calculated to be about ±5 kHz. The frequency drift Δf_o of the TCXO in CCA-370HJ is estimated to be ±12kHz. Thus the scanning range Δf_s of frequency is about ±17kHz for CCA-370HJ for automobile-navigation application.

Radiation Test

We performed total doze radiation tests of the GPS receiver with Co60. In the radiation test, GPS radio signal received outside of the radiation facility is guided by a coaxial cable and irradiates the GPS receiver under radiation test. The receiver survives for 20 krad during GPS positioning.

Also radiation tests with proton of 30 MeV and 200 MeV have been carried out. No single event latch-ups are observed for 30 MeV and 200 MeV proton. Protons of 200 MeV induce single event upsets at the GPS receivers. It is estimated that single event upset may occur once per several days at sun-synchronized orbit of 1200 km altitude.

MODIFICATION FOR SPACE APPLICATION

Expansion of Frequency Scanning Range

We calculate distribution of the Doppler shift that is received by a GPS receiver on the low earth satellite. The user satellite is assumed to be amateur radio satellite JAS2, where the altitude of about 690 km, the inclination of 98.6°, the right ascension of 102.3°, the eccentricity of 0.035, argument of perigee of 154.7°, the mean anomaly of 107.2°, and the epoch time of 0:00:00 UTC, the first of July, 1999. The duration of simulation is two months from the epoch time. Figure 2 shows the cumulative time as a function of the Doppler shift. The maximum Doppler shift is calculated about ±45 kHz.

In order to modify the automobile GPS receiver CCA-370HJ for space application, the frequency range Δf_s of the scanning is required to be expanded up to ±57 kHz by substituting Δf_d=±45kHz and Δf_o=±12kHz into Eq. (2). Since the original automobile receiver has the scanning range of ± 17 kHz, the scanning range for space application is 3.3 times as wide as one of automobile receivers. The manufacturer of CCA-370HJ modified the scanning range of frequency in their embedded ROM program based upon our analysis for space application.

Time Synchronization

We perform simulation tests by means of Spilent 476 simulator, where the GPS receiver is on a satellite in a low earth orbit. The simulation shows that the automobile GPS receiver outputs inaccurate time tag with a fluctuation of less than 0.3 second. The manufacturer of CCA-370HJ explains that accurate determination of the position and the receiver clock bias is performed in CCA-370HJ. However, only the accurate position data are output with inaccurate time tag. The position data are output in terms of earth-fixed coordinate WGS-84 and velocity of automobile is less than 56m/sec (200km/h).The fluctuation of time tag is within tolerance for automobile navigation.

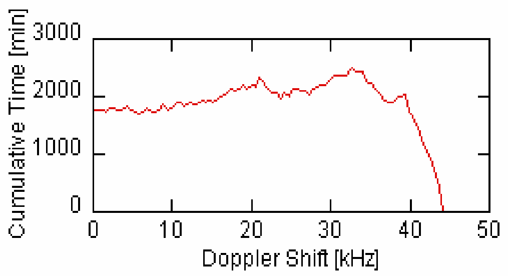


Fig.2: Cumulative Time of Doppler Shift of GPS Signal Received by Low-Earth-Orbit Satellite

However, it is not the case for space application. The GPS receiver for automobile-navigation generates position data with time tag which is not accurate enough to space application. Therefore, as a minimum amount of modification, the GPS receiver was modifies to output pseudorange data with an accurate (less than a micro second) time tag[6]. The pseudorange data is transmitted to a ground station through satellite telemetry system. The accurate position is calculated on ground with a conventional GPS algorithm. This version of GPS receiver modified for space application is evaluated in this paper and was on-board on INDEX satellite.

As the second version, we have already developed the further improved version of the space GPS receiver, which can output accurate position data with accurate time tag. The improved version is scheduled to be tested on orbit in 2008.

PERFORMANCE EVALUATION WITH GPS SIMULATOR

Cold Start Acquisition on Orbit

We perform simulation tests by means of Spilant 476 simulator with 12 channel signals, where the GPS receiver is on a satellite in a low earth orbit.

The satellite orbit assumed to be one of INDEX (a=7009.939km, e=0.0039, i=97.829 deg, Ω=165.908 deg, ω=196.661 deg, epoch time=2005 Aug 23rd 21:09:58.8UTC). The number of the NAVSTAR satellites that geometrically visible from INDEX satellite is temporarily distributed between 8-13. The average number of the visible NAVSTAR satellites is 10.7. The visible satellite number is equal to or less than 12 for 93% of time. The antenna is assumed to cover all the sky, which is an appropriate model for INDEX satellite. We tested 44 simulation cases where

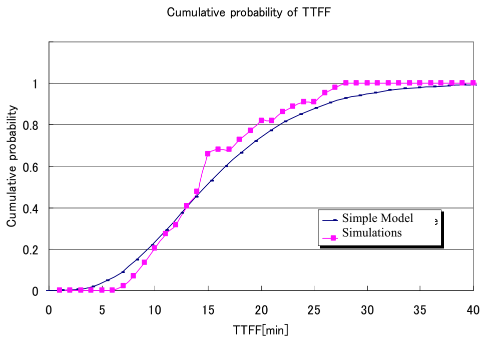
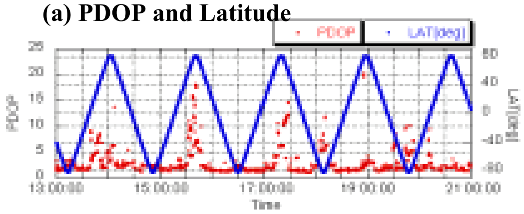


Fig.3: Cumulative Probability of TTFF Based on GPS Simulation

(a) PDOP and Latitude



(b) Position Error

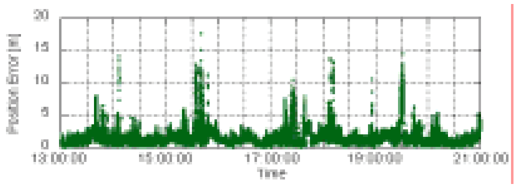


Fig. 4: Position Error on Orbit Based on GPS Simulation # 1
(a)PDOP and Latitude, (b)Position Error

the GPS receiver powers on every 20 minutes from the epoch time with a cold start mode. Figure 3 indicates the cumulative probability of time to first fix (TTFF). The minimum TTFF is 8 minutes and the maximum TTFF is 28 minutes. These TTFF values are 7-10 times longer than the original GPS receiver for automobile-navigation on ground. For the receiver modified for space, approximately T_{acq}=32sec and T_{stop}=84sec (see Eq.(1)). The reason is that the frequency scanning range is expanded to cover large Doppler frequency on orbit. Note it is confirmed that a GPS receiver for automobile navigation can not start positioning in the case of satellite orbiting condition.

The orbits of NAVSTAR satellites are circular orbits with altitude of about 20,000km and period of about 12 hours. The orbit of INDEX is the circular orbit with altitude of 640km and period of 97 minutes. Approximately speaking, the combination of the NAVSTAR satellites visible from INDEX satellite remains almost the same during a relatively short time (let say 25min) compared with the orbit period (97 min). We propose the following simple model on the GPS cold start TTFF in a short time region. The GPS receiver searches the Mth NAVSTAR satellite at a certain time. The probability p that the Mth NAVSTAR satellite is visible is given as

$$p = \frac{\text{average number of visible NAVSTAR}}{\text{total number of NAVSTAR}}$$

$$= 10.7 / 32 = 0.33. \qquad (3)$$

The probability P_N that receiver searches totally N NAVSTAR satellites and then locks on four NAVSTAR satellites for positioning is given by a binominal distribution as

(a) Satellite (b) Fixed Position on Earth

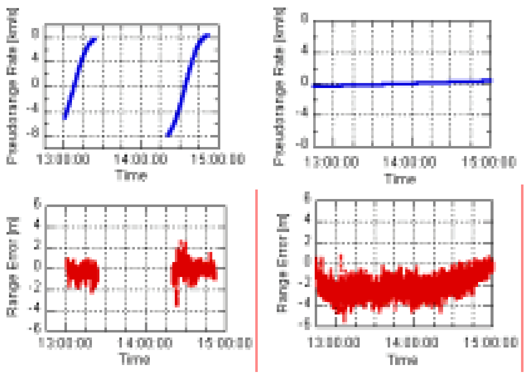


Fig. 5: Pseudorange Rate and Range Error Based on GPS Simulation #1
(a) Satellite in 690km Sun Sync. Orbit
(b) Fixed Position on Earth

$$P_N = {}_N C_4 p^4 (1-p)^{N-4}. \qquad (4)$$

Then we obtain the probability that the receiver acquires four NAVSTAR satellites at time t, combining Eqs.(1) and (4). The result of this simple model is also shown in Figure 3 and is qualitatively consistent with the simulation result in Figure 3.

Position Accuracy

In order to predict the accuracy of GPS positioning on orbit we perform simulation tests with a GPS simulator. The position data are calculated based on the pseudorange data from the receiver by an external computer. The orbit is assumed to be a sun-synchronous orbit with altitude of 690km (a=7068.137km, e=0.0, i=98.19°, Ω=0, ω=0). Figure 4 shows the result of the simulation #1 without ionospheric effect.

Figure 4(a) is the time history of the position dilution of precision (PDOP) and the latitude of the user satellite. PDOP value, namely, visibility of NAVSTAR satellite changes due to the orbit motion of the user satellite. On average 6~8 NAVSTAR satellites are tracked by the receiver and the average value of PDOP is 2.7. At a certain moment when the user satellite is at high latitude, the number of visible NAVSTAR satellites decreases to 4~5, and PDOP value degrades to higher than 10. Figure 4(b) shows time history of the position error. When the PDOP value degrades to higher than 10, the position error becomes more than 10 m. However, RMS value of position error for eight hours is 2.0 m.

Range Accuracy

Performance of GPS receiver is essentially determined by range accuracy. Combining with PDOP values,

Table 2: Estimated Error on Orbit (RMS, [m])

Error source	Estimated error in orbit
Ephemeris data	2.1
GPS satellite clock	2.1
Ionosphere	5.4
Receiver measurement	0.9
Total range error	6.2
Position error (PDOP = 2.7)	16.7

range accuracy results in position accuracy. We obtain the range error on orbit with a GPS simulator in the following way. Based upon the pseudorange data from the GPS receiver, we calculate the time error of the receiver clock with an external computer. The range between the user and the NAVSTAR satellite is calculated from the pseudorange data and the clock error. This range is compared with the true range data from the GPS simulator to evaluate the range accuracy of the receiver.

Attention is mainly paid to the large pseudorange rate in the orbit. If pseudorange rate is too large compared with the loop frequency response, tracking loop for the pseudorange could not follow the rapid change of the pseudorange. The orbit parameters are the same as ones in the section of Position Accuracy. Figure 5(a) shows time history of the pseudorange rate and the range error of NAVSTAR satellite of PRN=28 for the 690km sun-synchronous orbit. The ionospheric delay is not included in this simulation (simulation #1). The pseudorange rate changes rapidly from +8 km/sec to –8 km/sec during the visible time of 30 minutes due to the orbit motion of the user satellite. However, the range error remains almost constant as much as 0.9m in RMS.

Figure 5(b) shows the data obtained from the same receiver for the fix position on earth surface. The NAVSTAR satellite of PRN=24 remains visible for several hours on the earth surface and the pseudorange rate is very small. The range error has drifting bias error of about 2 m and random error of about 2 m.

These results indicate that CCA-370HJ with the modification for space application keeps almost the same range accuracy in orbit as on the ground. No degradation due to the large pseudorange rate is observed. The RMS value of the range error of receiver measurement is 0.9 m in orbit without the ionospheric effect.

Next, the simulation #2 where ionospheric effect is included is performed. The ionospheric model of NATO, STANAG is applied to the simulation.[7,8] This model provides with the ionospheric delay Di as Eq.(5)

$$D_i = \frac{82.1 \times TEC}{F_c^2 \times \left(\sqrt{\sin^2 E + 0.076} + \sin E\right)} \text{ [m]} . \qquad (5)$$

The quantity TEC denotes the total electron content [m^{-2}]. The typical value of TEC=1.0 x10 ^{7}[m^{-2}] is assumed in the simulation#2. There, F_c and E denote the carrier frequency of GPS signal [Hz] and the elevation angle of the NAVSTAR satellite with respect to the local horizon of the user satellite, respectively. This model provides with the ionospheric delay of 1.6~12 m according to the elevation angle of 90º ~ 0º.

In the simulation #2, we add the ionosperic effect to the simulation #1. The simulation #2 gives the range error of 5.5m in RMS. Based upon the simulation #1 without the ionopheric effect and the simulation #2 with the ionospheric effect, the RMS value of range error due to the ionosheric effect for the above-mentioned model and the parameter is estimated to be 5.4m.

Prediction of Position Accuracy on Orbit

The purpose of the simulation in this research is to evaluate the range error from the receiver itself. Therefore these simulations #1,#2 do not include the ephemeris data error and the clock error of the NAVSTAR satellites. Total position errors on orbit including the ephemeris data and the clock error of the NAVSTAR satellites are estimated. Table 2 shows the total range error and the error budget as well as the position error on orbit. The receiver range error is 0.9 m from the simulation #1 in the previous section. The error due to the ionospheric delay is 5.4 m in RMS from the previous section. The typical values of the ephemeris error and the clock error of the NAVSTAR satellites are obtained from ref 8. The PDOP value is 2.7 in average which is observed in the simulation #1. The total position error is estimated to be 16.7 m (RMS) by multiplying the range error by PDOP.

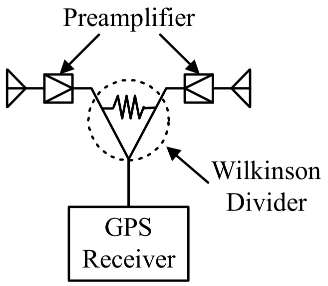


Figure 6: Configuration of All-Sky Antenna

FLIGHT TEST OF MINIATURE SPACE GPS RECEIVERS IN INDEX SATELLITE

The GPS receiver modified for space application was onboard in INDEX satellite. INDEX has mass of 72 kg and three axial attitude control function with accuracy of 0.05° .

We developed a new type of all-sky GPS antenna combined with two GPS antennas. Most of GPS receivers for automobile-navigation equip their preamplifier inside the antenna. Their RF coaxial cable between the antenna and the receiver works also as a power feeder for the preamplifier circuit. A RF hybrid has to work not only as RF combiner for two antennas, but also as dc power feeder for two preamplifiers without resistance. A Wilkinson divider meets this requirement for RF performance and dc performance. Figure 6 shows the configuration of the all-sky antenna. Figure 7 shows the two GPS antennas in the INDEX satellite and the measurement result of the antenna pattern with INDEX satellite body. For coverage of 95 %, the antenna gain is measured to be higher than –5 dBi, which is the requirement for the GPS receivers.

INDEX satellite was launched by Dnpre rocket from Baikonuar base on Aug. 24th 2005. The GPS receiver powered on in cold start mode on Aug. 27 16:02 (UTC) above Japan. It started positioning successfully 7 minutes later.

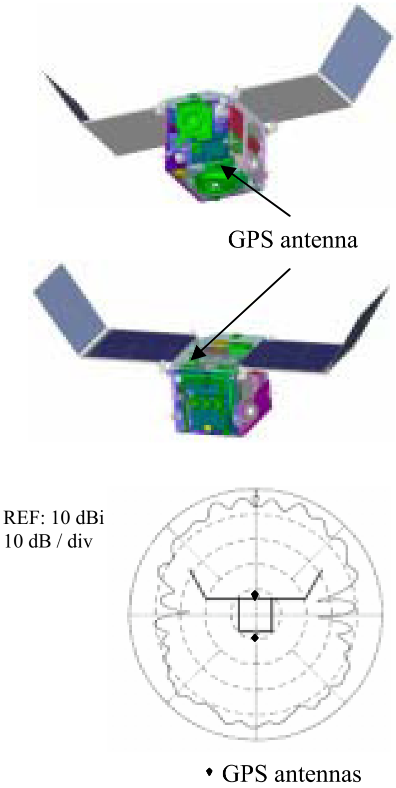


Figure 7: All-Sky Antenna Configuration and Pattern of INDEX Satellite

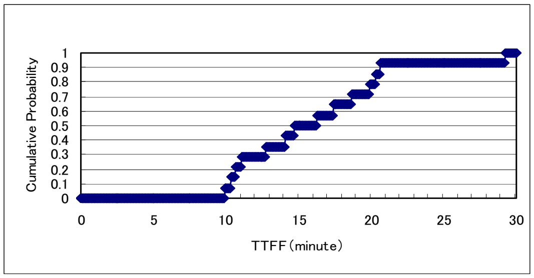


Fig.8: Cumulative Probability of Cold Start TTFF of Flight Results in INDEX

We measured the TTFF on orbit by cold-starting every 12hours 40 minutes from July 25th 2006. Figure 8 indicates the cumulative probability of TTFF for cold start mode. Cold start positioning succeeded within 30 minutes, which is consistent with the GPS simulations shown in Figure 3.

We evaluated the position accuracy of the GPS receiver on orbit. Based upon the GPS simulation, the position accuracy on orbit is estimated to be 16.7m in Table 2. Unfortunately we do not have any other positioning data which is more accurate than the GPS data. Therefore, orbit determination is performed in use of GPS position measurement. Then the residual error, which is defined as a difference between the GPS measurement and the orbit determination, is considered a random error of GPS receiver if orbit determination duration is short enough. The pseudorange data which the onboard GPS receiver measures every second is transmitted to ground. The position of INDEX satellite is calculated on ground in use of the pseudorange. Then the orbit determination is performed with a gravity model (WGS-84 gravity model with 12 harmonics in this research). Finally the residual errors are calculated as a difference between the GPS position data and the orbit determination data. Figure 9 is the residual errors, the PDOP values, and the number of visible GPS satellites as functions of time. The orbit determination is performed in use of GPS data for 60 seconds. The behavior of these values are very consistent with the GPS simulation shown in Figure 4. The number of visible GPS satellites is seven in average. The number of visible NAVSTAR satellites is more than six for 97% of time. PDOP value is less than 4.0 for 90% time. The average value of PDOP is 2.5.

Table 3 shows the average and the standard deviation of the residual error in the along-track direction, the radial direction, the out-of-plane direction and the total position error. The residual error follows to be a random distribution without bias. The standard deviation of the total position error is 1.46 m in RMS, which is consistent with the result of the GPS simulation #1 (2.0m in RMS). The standard deviation of the position error in the radial direction is almost twice as large as the ones of along-track and the out-of-plane components. This is because the NAVSTAR satellites distribute in the outward direction and the "vertical" DOP is larger than the "horizontal" DOP.

In Figure 10, the values of PDOP are divided into several bins and the RMS values are calculated in each bin. The RMS value of the residual error in each bin is almost proportional to the PDOP value as shown by circles in Fig.10. In general,

$$\text{RMS position error} = \sigma_{\text{range}} \times \text{PDOP}, \qquad (6)$$

where σ_{range} is the RMS value of range error. The slop of the fitted line of the RMS value in Figure 10 corresponds to σ_{range}, which is about 0.6 m. The RMS value of range error observed in the orbit is consistent with the RMS value of range error in the GPS simulation #1 in Figure 5 (0.9m).

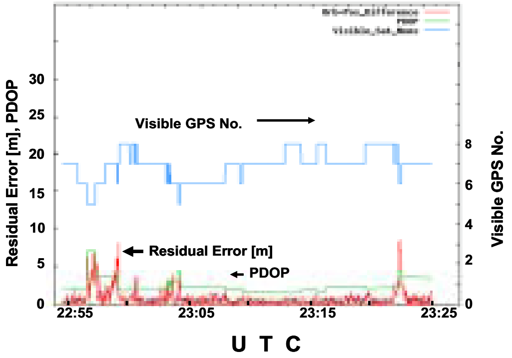


Fig.9: Residual Position Error (Random Position Error), PDOP and Number of Locked Satellite in INDEX GPS Flight Data. Interval of Orbit Determination is 60 second.

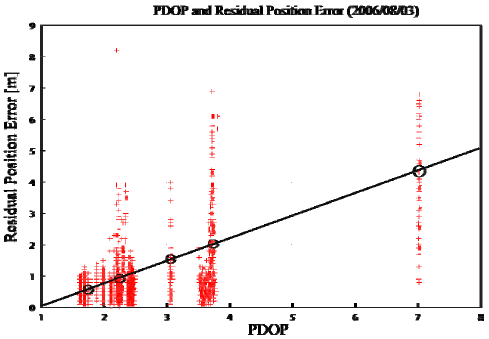


Fig.10: Relation between Residual Position Errors (Random Position Error) and PDOP in INDEX GPS Flight Data. Open Circles show RMS Values Residual Position Errors in Each Bin of PDOP.

Table 3: Residual Error of GPS Positioning on Orbit

Component	Average[m]	Standard Deviation[m]
Radial	0.09	1.23
Along-Track	0.03	0.42
Out-of-Plane	-0.08	0.67
Total	-	1.46

CONCLUSION

Miniature space GPS receivers have been developed by means of automobile-navigation technology. We expanded the frequency sweep range in order to cover large Doppler shift on orbit. The GPS receiver was modified to output pseudorange data with a accurate time tag. First the performance in low earth orbits by means of a GPS simulator. The range error caused by the receiver is measured to be 0.9 meter in RMS. The position accuracy is estimated to as much as 16.7 meters (RMS) in the low earth orbits. Mainly the ionospheric effect degrades the accuracy of GPS positioning.

This GPS receiver was on-boarded on INDEX satellite, which was launched in 2005 into a circular orbit with 640km altitude. Cold start positioning was confirmed repeatedly to finish within 30 minutes on orbit. The orbit determination was performed to evaluate the random position error of GPS receiver by means of the residual error. The random error of GPS position is as much as 2m (RMS) for PDOP=2.5 on orbit. The RMS value of range error is evaluated to be 0.6 m from the flight data. These results on orbit are consistent with the simulation results in use of a GPS simulator.

This miniature Space GPS receiver is at present in commercial market[9].

References

1. Hata, M., Ogasawara, Y., Shoji, M., Itoh, W.,Kume, A., Mino, A., Kojima, S., Okada, Y.and Ohga, T., "GPS-SOC for Automobile- Navigation," Proceedings of GPS Symposium 2002, in Japanese,

Japanese Institute of Navigation, pp.113-122, Nov. 2002.

2. Japan Radio Corporation, “Speceification of GPS Receiver CCA-370HJ,” in Japanese, 1998.

3. Unwin, M.J, Oldfield, M.K., Purivigraipong, S. and Kitching, I., “Preliminary Orbital Results from the SGR Space GPS receiver,” Proc. of ION GPS-1999, pp.849-855, 1999.

4. Mehlen, C. and Laurichese, D., “Real-Time GEO Orbit Determination Using TOPSTAR 3000 GPS Receiver,” Proc. of ION GPS-2000, 2000.

5. Kawano, I., Mokuno, M. and Kasai, T., “Relative GPS Navigation for an Automated Rendezvous Docking Test Satellite ETS-VII,” Proc. of ION GPS-97, Kansas City, Mo, USA, Sep. 1997.

6 H. Saito Y. Hamada, K. Shinkai, H. Sasaki, and S. Kuroki, “Tiny GPS Receiver for Space Application” The IEICE Transactions on Communications (Japanese Edition), vol. J88-B, no.1, pp.79-89.Jan. 2005.

7. NATO Standard Agreement STANAG 4294 Issue 1.

8. Parkinson, B.W., “GPS Error Analysis” Global Positioning System: Theory and Applications Volume I, pp.469-483, AIAA, 1995

9. http://spacelink.biz/