

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. The weight and power consumption of the GPS receiver are 35 g and 1 W, respectively. We expanded the frequency sweep range in order to cover large Doppler shift in orbit. We tested the performance in low earth orbits by means of a GPS simulator. The GPS receiver succeeded in cold start acquisition in less than 60 minutes. The GPS receiver for automobile- navigation generates position data with time tag which is not accurate enough to space application. The GPS receiver was modified to output pseudorange data with accurate time tag. The range error caused by the receiver is measured to be 1 meter. The position accuracy is estimated to be less than 20 meters in the low earth orbits. The GPS receiver can be operated with 20 krad (Co60) radiation and is SEL-free for 200MeV proton radiation. SEU may occur in low earth orbits once a several days. This GPS receiver will be on-boarded on INDEX satellite, which will be launched in 2005.

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.¹⁻³ Several advanced positioning technologies such as double frequency differential GPS and differential carrier phase GPS are available in the consumer market. The key technologies for their miniaturization are highly integrated circuits for receiver functions, based upon mass productions.¹

On the other hand, space-borne GPS receivers are as heavy as several kg and power consumption is as much as 10 W.⁴⁻⁶ In general, the space-borne GPS receivers are manufactured with use of radiation-hardened 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 and the performance of the modified receiver in orbit.

ISSUES ON GPS RECEIVER FOR SPACE APPLICATION

Large Doppler Shift in Orbit

The most serious issue on GPS receivers for space application is the large Doppler shift in orbit. GPS receivers can not acquire the radio signal from the NAVSTAR satellites due to the large Doppler shift. The orbits of the NAVSTAR satellites are circular orbits with altitude of 20,000 km, the orbit velocity of which is about 3.9 km/sec. The self-rotating velocity of the earth is about 0.4 km/sec at the equator. Velocity of automobile is as high as 0.04 km/sec. Range rate between NAVSTAR satellite and a user in automobile is as high as 1.3 km/sec, which gives Doppler shift of ± 6.8 kHz.

On the other hand, orbit velocity of low earth satellite is as large as 7.5 km/sec. Range rate between NAVSTAR satellite and a user satellite in low earth orbit is determined mainly by the orbit motion of the user satellite. It is calculated to be as high as 8.6 km/sec, which gives the large Doppler shift of ± 45 kHz. When an automobile-navigation GPS receiver is on a satellite, it can not acquire the radio signal from NAVSTAR satellite due to the large Doppler shift.

Short Visible Time

Orbiting period of NAVSTAR satellite is about 12 hours, and the earth rotates about its axis with period of 24 hours. A GPS user on the earth can track a specified NAVSTAR satellite for several hours on an average. Time to first fix (TTFF), which is the time between power-on and first positioning, of common automobile-navigation GPS receivers are less than several minutes. Therefore, in most cases, a combination of visible NAVSTAR satellites does not change during the search and acquisition process of automobile-navigation.

On the other hand, a visible time of NAVSTAR satellite from a user satellite is mainly determined by the orbit motion of a user satellite, since the orbiting period of a low earth satellite is about 100 minutes. NAVSTAR satellites above local horizon of the user satellite should be utilized for positioning in order to avoid ionospheric delay. Visible time of a NAVSTAR satellite above local horizon of a user satellite in the low earth orbit is no longer than 50 minutes.

Time to first fix (TTFF) of GPS receiver on a user satellite is expected to be much longer than one of automobile-navigation on earth due to the large Doppler shift in the orbit. In such conditions, a combination of visible NAVSTAR satellites may change during the search and acquisition process in the user satellite. This situation may make acquisition process in the orbit difficult.

Time Synchronization

A GPS receiver determines its position and clock error simultaneously with use of pseudorange data. However, some GPS receivers for automobile-navigation pay less attention to accuracy of time tag than to position accuracy with respect to earth-fixed coordinate. This is because automobile move much slower than earth rotation about its axis. Even if a GPS receiver on a car driving with 40 m/sec (about 94 mile/hour) has time tag error of 0.2 seconds, the position error in the earth-fixed coordinate is as large as 8 meters. This amount of position error is acceptable for automobile- navigation.

On the other hand, a user satellite orbiting with

velocity of 7.5 km/sec yields a position error of 1.5 km with respect to the inertial coordinate, if time tag error is 0.2 seconds. Surely this amount of time tag error is not acceptable for space-borne GPS receivers. Time tag accuracy for a space-borne GPS receiver is required to be less than order of 0.1 msec.

PERFORMANCE OF GPS RECEIVER FOR AUTOMOBILE-NAVIGATION

Specification of GPS Receiver for Automobile-Navigation

Model CCA-370HJ of Japan Radio Cooperation 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 36.3 x 11.0 mm³. 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, which is described in Appendix.

Table 1. Specification of the GPS Receiver for Automobile-Navigation

Receiving system		Multichannel (8 Channels)
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 \pm 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
Operative temperature		-30°C to +70°C



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

Figure 2 shows the functional block diagram of the GPS receiver.¹ Radio signal amplified at the pre-amplifier is input to the receiver. Radio signal is down-converted to several MHz intermediate frequency (IF signal), which is then input to the base-band block. There are eight channels for search and track and one channel dedicated for search in the base-band block.

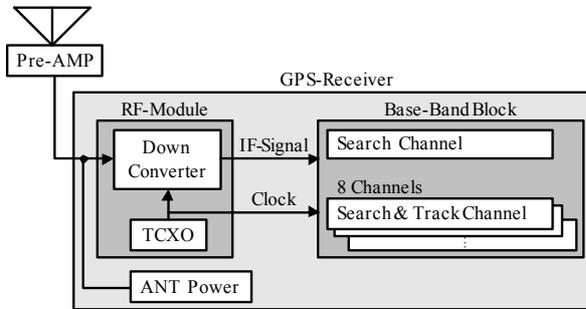


Figure 2. Functional Block Diagram of Automobile-Navigation GPS Receiver

Evaluation by Means of GPS Simulator

We evaluate the performances of CCA-370HJ on earth surface by means of GPS simulator (SPIRENT STR2760), which is a GPS simulator with 10 channels. STR2760 can simulate radio signal received by a GPS receiver on a user satellite.

Figure 3 shows the setup of the test with the GPS simulator.

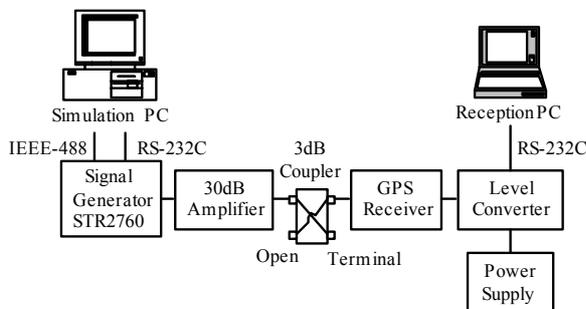


Figure 3. GPS Simulation Configuration

Search and Acquisition Process

In order to evaluate search and acquisition process of CCA-370HJ, the simulation tests of search and acquisition at a fix position on the earth surface have been performed under condition of cold start, where no information on the position of the user is given to the GPS receiver. The position of the user is fixed at the latitude of 35°39', the longitude of 139°38', the altitude of 42.730 m. The start time is 0:00:00 UTC, the first of July 1999. Then the 44 cases of simulations are repeated at every 35 hours. Output

data from CCA-370HJ include the status data that indicate which NAVSTAR satellite the search and track channel searches or tracks. Outline of search and acquisition process can be estimated based upon these information. Figure 4 shows the flow chart of the search and acquisition process of CCA-370HJ.

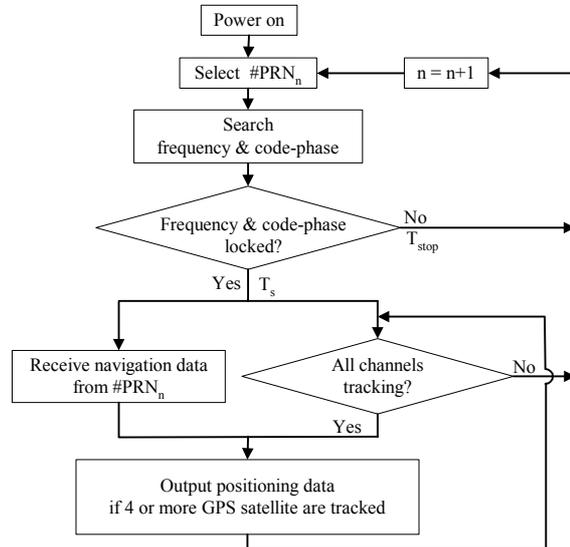


Figure 4. Flow Chart of Search and Acquisition Process

When the receiver is powered on, the order of the pseudo random noise code number (#PRN₁, #PRN₂, - - -) of NAVSTAR satellite that the receiver searches is determined by the receiver itself. Then the receiver searches the NAVSTAR satellite of #PRN₁ that is expected to search at first. In the search process, the correlation calculation between the pseudo random noise code #PRN₁ and the received signal is executed with respect to direction of code phase, when the frequency is assumed to be a certain value. If the assumed frequency is not close to the real frequency of the received signal, the correlations for any code phase do not have a sharp peak. Then the assumed frequency is shifted by a small amount of resolution, and the same correlation calculation is repeated. When the correlation function shows a sharp peak for the certain value of frequency and code phase, the receiver locks on the NAVSTAR satellite of #PRN₁. The time T_s of this search process distributes for 1~10 seconds, depending on the cases of simulation. If the search process does not succeed for 12~26 seconds, the receiver judges that the NAVSTAR satellite of #PRN₁ is not visible from the receiver position. Then the receiver moves to the search process for the next NAVSTAR satellite of #PRN₂. The average time that the receiver gives up and stops the search is about 16 seconds and is denoted by T_{stop}.

When the search of the NAVSTAR satellite of #PRN₁

succeeds, the receiver performs the following two procedures in parallel. The one is that the receiver searches the NAVSTAR satellite of #PRN₂ along the directions of frequency and code phase. Another is that the tracking of #PRN₁ is shifted to one of the eight track channels. Then the navigation data is received and decoded from NAVSTAR satellite of #PRN₁ at the channel. It takes 30 seconds to receive the ephemeris data of #PRN₁. Then it takes 12.5 minutes to receive almanac data for all NAVSTAR satellite.

Sequentially, in this manner, the NAVSTAR satellite #PRN_n is searched by the channel dedicated for search channel. If #PRN_n is locked on, then it is shifted to a search and track channel. When four NAVSTAR satellites are locked on and tracked, the position data is output. Time to first fix (TTFF) is defined as the time between the power-on and this stage. When there are vacancies in the search and track channels, the next NAVSTAR satellite #PRN_{n+1} is searched and tracked. The same procedure is repeated until there is no vacancy in the search and track channels.

Time to first fix (TTFF) for cold start is estimated as

$$\text{TTFF} = 4 T_s + (N-4) T_{\text{stop}} + 30 \quad [\text{sec}] \quad (1)$$

Here the receiver tries to search N satellites of NAVSTAR in total until 4 NAVSTAR satellites are locked on. The time T_s in the first term of the right-hand side is the average time of search where the search successfully finishes. In cases of automobile-navigation, $T_s=5$ seconds. The second term is the total time of searches where the searches do not succeed well. In the case of automobile-navigation, $T_{\text{stop}}=16$ seconds. The third term is the receiving time of the ephemeris data from the fourth NAVSTAR satellite that is locked on. The minimum TTFF is calculated to be 50 seconds for $N=4$, and the maximum TTFF is 8 minutes 18 seconds for $N=32$. Forty-four cases of cold start simulation at the fixed position on earth surface indicate that the minimum TTFF is 49 seconds ($N=4$) and the maximum TTFF is 4 minutes 19 seconds ($N=17$). These results agree well with equation (1).

Next we discuss on the search time T_s , which is important for the TTFF in space-borne GPS receivers. The search times of the code phase are the same both for receivers for automobile-navigation and for space-borne receivers since the search in the code phase direction is performed in a batch by the correlator circuit. On the other hand, 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

$$\Delta f_s = \Delta f_d + \Delta f_o \quad (2)$$

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 ± 12 kHz. Thus the scanning range Δf_s of frequency is about ± 17 kHz for CCA-370HJ for automobile-navigation application.

On the other hand, space-borne receivers require a wide range of frequency scanning due to the large Doppler shift. The scanning time T_s and T_{stop} may increase, compared to the case of automobile-navigation. Furthermore, the visible time of a NAVSTAR satellite above the local horizon of the user satellite is no longer than 50 minutes. Increase in the search time may degrade the search performance in the orbit.

MODIFICATION TO SPACE APPLICATION

Expansion of Frequency Scanning Range

In order to modify the GPS receivers for automobile-navigation to space application, the range of frequency scanning has to be expanded such that the scanning range covers the large Doppler shift in the orbit. However, the wide range of frequency scanning increases in the scanning time of frequency, furthermore, the search and acquisition time. If the improperly large range of the frequency scanning were selected, search and acquisition process would never finish until the NAVSTAR satellite remains visible.

We calculate distribution of the Doppler shift that is received by a GPS receiver on the low earth satellite⁷. The user satellite is assumed to be amateur radio satellite JAS2, where the altitude of 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 period of simulation is two months from the epoch time. Figure 5 shows the cumulative time as a function of the Doppler shift. The maximum Doppler shift is calculated to be about ± 45 kHz.

In order to modify the automobile GPS receiver CCA-370HJ to space application, the frequency range Δf_s of the scanning is required to be expanded up to ± 57 kHz by substituting $\Delta f_d = \pm 45$ kHz and

$\Delta f_0 = \pm 12 \text{ kHz}$ into eq.(2). Since the original automobile receiver has the scanning range of $\pm 17 \text{ kHz}$, the scanning range for space application is 3.3 times as wide as one of automobile receivers. The manufacturer modified the scanning range of frequency in their embedded ROM program under our analysis for space application

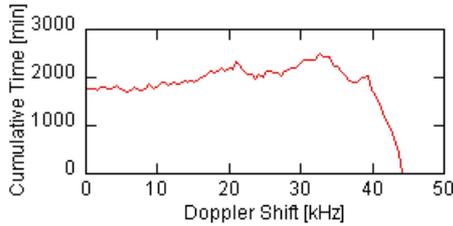


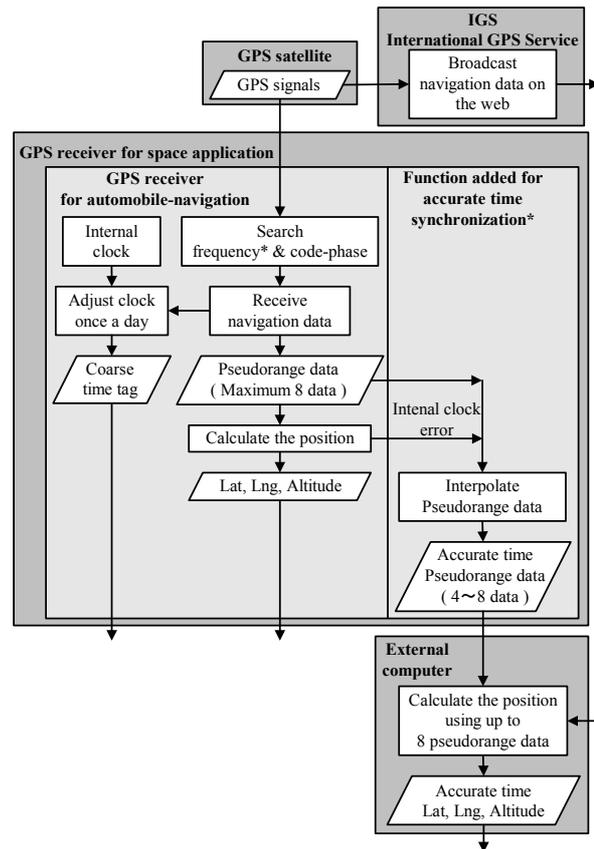
Figure 5. Cumulative Time for Two Months of Doppler Shift of GPS Signal Received by Low-Earth-Orbit Satellite

Improvement of Time Synchronization

A GPS receiver determines its position and clock error simultaneously with use of pseudorange data. However, some GPS receivers for automobile-navigation pay less attention to accuracy of time tag than to position accuracy with respect to the earth-fixed coordinate. This is because automobiles move much slower than earth rotation about its axis.

A model CCA-370HJ outputs the position data and the time tag based upon its free-running clock without time correction by position determination. This simplified algorithm of CCA-370HJ is supposed to be due to cost-performance optimization by the manufacturer. When the first NAVSTAR satellite is locked on in the search and acquisition process after power-on, the internal clock of CCA-370HJ is roughly synchronized with the TOW from the NAVSTAR satellite. Then this time correction is performed once a day to keep the clock error within one second. The left part of Figure 6 shows the flow chart of the positioning algorithm of CCA-370HJ.

It is technically possible to modify the algorithm such that the receiver outputs the position data with the corrected time tag. In this time, however, this modification of the algorithm was not performed because of its cost and complexity. Instead, the algorithm was modified such that only the pseudorange data is output with the time tag that is compensated with use of time correction by position determination. The pseudorange is time-tagged at every right second of UTC. This pseudorange data at every right second is calculated by linear interpolation assuming that pseudorange rate remains constant during these a second.



* denote modified parts for space application
Figure 6. Flow Chart of Positioning Calculation

PERFORMANCE OF MINIATURER SPACE-BORNE GPS RECEIVERS

Outline of GPS Simulation for Space-Borne Receiver

We perform the simulation tests for the modified version of CCA-370HJ for space-borne receivers by means of GPS simulator SPIRENT STR2760. The orbit elements of the user satellite and the ephemeris of the NAVSTAR satellites are provided to the GPS simulator. At this simulation the clock error and the position error of the NAVSTAR satellites are ignored since the purpose of this simulation is evaluation of the receiver itself.

The antenna pattern is assumed to be uniform above the elevation of 1° with respect to the local horizon. The ionospheric model of NATO, STANAG is applied to the simulation.^{9,10} This model provides with the ionospheric delay D_i as eq.(3)

$$D_i = \frac{82.1 \times TEC}{F_c^2 \times (\sqrt{\sin^2 E + 0.076} + \sin E)} \quad [\text{m}] \quad (3)$$

The quantity TEC denotes the total electron content [m^{-2}]. The typical value of $TEC = 1.0 \times 10^7 [\text{m}^{-2}]$ is

assumed in these simulations. 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 $90^\circ \sim 0^\circ$.

Performance of Search and Acquisition

We perform the simulation tests of search and acquisition for the two low earth orbits shown in Table 2. No information on the user position is provided with the receiver (cold start condition). For the sun-synchronous orbit of 690 km altitude, the start time of the first simulation is 0:00:00 UTC, the first of July 1999. Forty-four trials of the cold start are repeated at every 35 hours. The epoch time is assigned as the start time of each simulation. For the sun-synchronous orbit of 1200 km altitude, the epoch time is 15:25:52 UTC, the first of October, 2003. Twelve trials of cold start are repeated at every 70 minutes after this epoch time. Figure 7 shows the time to first fix (TTFF), which is defined as the time between the cold start time and the first positioning. The horizontal axis is TTFF, and the vertical axis is the cumulative probability of the cases where TTFF is shorter than the value of the horizontal axis. Figure 7 shows that for all cases the search and acquisition for cold start succeeds within 60 minutes. On the other hand, commercial version of CCA-370HJ without the modification for space application is found to remain unlocked for several orbit periods.

Table 2. Orbital Elements of GPS Simulation

	690km	1200km
	Sun synchronous orbit	Sun synchronous orbit
Semi major axis	7068.137 km	7578.142 km
Inclination angle	98.19°	100.41°
Right ascension	0°	97.38°
Eccentricity	0	0.002
Mean anomaly	0°	160.11°
Argument of perigee	0°	65.49°
Epoch time (UTC)	Cold start time	Oct/01/2003 15:25:52

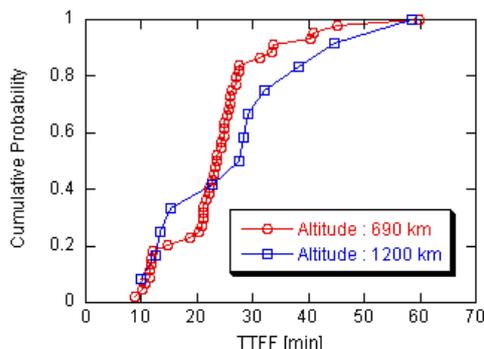


Figure 7. Cumulative Probability of TTFF in Simulations for Orbits

The search and acquisition process is carefully observed for forty-four cases by means of the receiver status. The search time T_s , which is defined as the average time of search where the search successfully finishes, is $T_s = 1 \sim 64$ seconds. The time T_{stop} that the receiver gives up and stops the search for the NAVSTAR satellite is $T_{stop} = 68 \sim 100$ seconds. These T_s and T_{stop} of the space-borne receiver are about five times as large as those of automobile receivers.

Positioning Calculation with External Computer

A model CCA-370HJ with the modification for space application can perform cold start acquisition for low earth orbits as shown in the previous section. However, the position data from CCA-370HJ are not accurate enough for space application due to its poor time synchronization. The receiver was modified such that the pseudorange data is output with the time tag which is compensated with use of time correction for the free-running clock.

Based upon the pseudorange data with the accurate time tag from CCA-370HJ, we calculate the user position with an external computer. All available sets of the pseudorange from NAVSTAR satellites are utilized by least-square-error method with equal weight. The navigation data such as ephemeris data are obtained from open data source of the International GPS Service. The right part of Figure 6 shows the flow chart of the positioning algorithm with the external computer. In order to evaluate the accuracy of this algorithm with the external computer, the pseudorange data from the GPS simulator is input to this external computer. It is confirmed that the position error of this algorithm is less than 3 cm.

Accuracy of Range Data

Based upon the pseudorange data from the GPS receiver, we calculate the time error of the receiver clock with the 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 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. Figure 8(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 about 1meter.

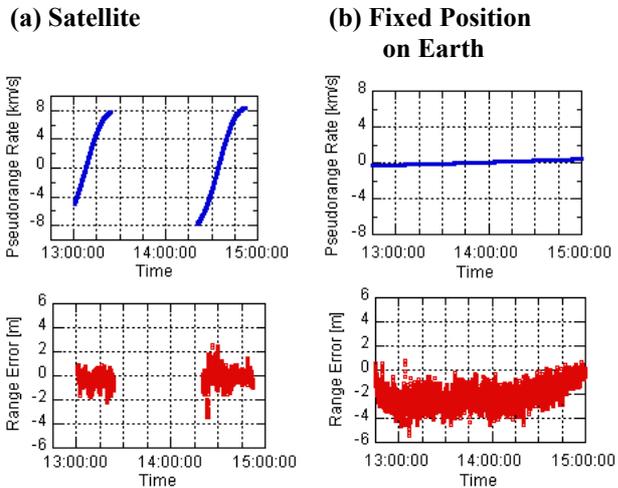


Figure 8. Pseudorange Rate and Range Error
(a) Satellite in 690km Sun Sync. Orbit
(b) Fixed Position on Earth

Figure 8(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 root-mean-square (RMS) value of the range error of receiver measurement is 0.9 m in orbit without the ionospheric effect. When the ionospheric effect is included based upon eq.(3), the similar simulation #2 gives the range error of 5.5 m in RMS.

Position Accuracy

In order to confirm accuracy of the pseudorange data from CCA-370HJ with modification, the position data are calculated by the external computer. Figure 9 shows the result of the simulation #1 without ionospheric effect.

Figure 9(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. At 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 9(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 about 2 m.

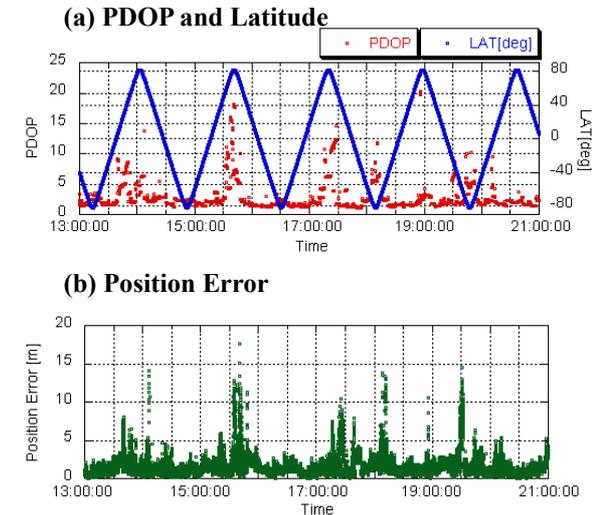


Figure 9. Position Error in Orbit
(a) PDOP and Latitude
(b) Position Error

Next, the simulation #2 where ionospheric effect is included is performed for similar condition for eight hours. The external computer does not execute any correction for the ionospheric effect. The RMS value of the range error for the eight hours is 10.6 m.

Prediction of Position Accuracy in Orbit

The purpose of the simulation in this research is to evaluate the range error from the receiver itself. Therefore these simulations do not include the ephemeris data error and the clock error of the NAVSTAR satellites. Total position errors in orbit including the ephemeris data and the clock error of the NAVSTAR satellites are estimated. Table 3 shows the total range error and the error budget as well as the position error in orbit. The receiver error is 0.9 m from the simulation #1. The ionospheric delay error combined with the receiver range error is 5.5 m in RMS from the simulation #2. The error of the ionospheric delay is calculated to be 5.4 m in RMS. The typical values of the ephemeris error and the clock error of the NAVSTAR satellites are obtained from ref 11. The PDOP value is 2.7 which is observed in the simulation #1. The total position error is estimated to be 16.7 m by multiplying the range error by PDOP.

Table 3. Estimated Error in 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

Radiation Test

We performed total dose 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.

CONCLUSION

We have developed the miniature GPS receivers that output pseudorange in orbit, based upon the commercial GPS receivers with several tens grams for automobile-navigation. The first of modifications is that the scanning range of frequency for search and acquisition is expanded such that it covers the large Doppler shift in orbit. The second issue is that in general GPS receivers for automobile-navigation do not require time tag with high accuracy. We modify the GPS receiver such that pseudorange data is output with time tag with accuracy enough for fast motion of satellite. A series of simulations with a GPS simulator have been performed in order to evaluate the GPS receiver modified for space application. It is confirmed that cold start acquisitions successfully finish within 60 minutes and the range error of the receiver itself is as large as 1 meter. The external factors such as PDOP, the ionospheric delay, the ephemeris error, and the GPS clock error may degrade the position accuracy to about 20 meters.

This GPS receiver will be onboard on INDEX satellite scheduled in launch in 2005. The GPS antenna of INDEX is a new type of all-sky antenna, which is described in the Appendix.

Acknowledgements

Mitsubishi Electric Corporation financially supported us to modify the GPS receiver and Japan Radio Corporation kindly modified their receiver to space application. Prof. T.Hayashi at Chiba Institute of Technology introduced us to Japan Radio Corporation. AmTech Corporation, Institute of Space Technology and Aeronautics / Japan Aerospace Exploration Agency, and NT Space let us use the GPS simulators. Mr. H Tomita provided us with useful technical discussions and warm encouragement. We deeply thank all of them.

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APPENDIX ALL-SKY GPS ANTENNA

Most of GPS receiver systems for automobile-navigation use a patch antenna since the GPS signals come from the sky. On the other hand, for satellites with attitude control in inertial coordinate system or without attitude control, the GPS signals arrive from any direction with respect to satellite body. One solution for this issue is that several antennas are switched one after another according to the satellite motion. Another solution is that all-sky antenna is used to receive the GPS signals from any direction.

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 A1 shows the configuration of the all-sky antenna. Figure A2 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.

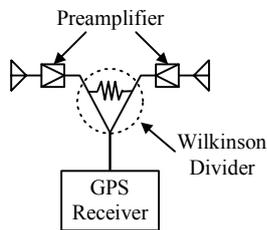


Figure A1. Configuration of All-Sky Antenna

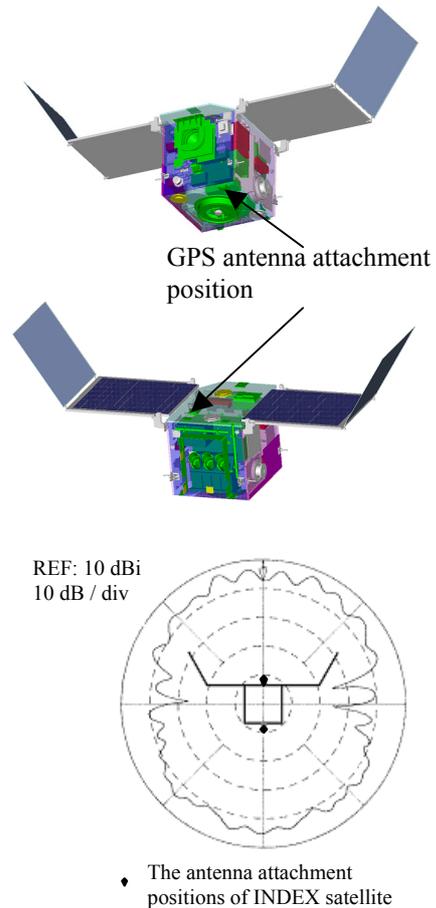


Figure A2. All-Sky Antenna Pattern with INDEX Satellite