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GPS Receiver and Orbit Determination System On-Board VSOP Satellite

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Abstract

In 1995 the VSOP satellite, which is called MUSES-B in Japan, will be launched under the VLBI Space Observatory Programme(VSOP) promoted by ISAS(Institute of Space and Astronautical Science) of Japan. We are now developing the GPS Receiver(GPSR) and On-board Orbit Determination System. This paper describes the GPS(Global Positioning System), VSOP, GPSR(GPS Receiver system) configuration and the results of the GPS system analysis.

The GPSR consists of three GPS antennas and 5 channel receiver package. In the receiver package, there are two 16bits microprocessing units. The power consumption is 25 Watts in average and the weight is 8.5kg. Three GPS antennas on board enable GPSR to receive GPS signals from any NAVSTARs(GPS satellites) which are visible.

NAVSATR's visibility is described as follows. The VSOP satellite flies from 1,000km to 20,000km in height on the elliptical orbit around the earth. On the other hand, the orbit of NAVSTARs are nearly circular and about 20,000km in height. GPSR can't receive the GPS signals near the apogee, because NAVSTARs transmit the GPS signals through the NAVSTAR's narrow beam antennas directed toward the earth. However near the perigee, GPSR can receive from 12 to 15 GPS signals. More than 4 GPS signals can be received for 40 minutes, which are related to GDOP(Geometric Dillusion Of Precision of selected NAVSTARs). Because there are a lot of visible NAVSTARs, GDOP is small near the perigee. This is a favorqble condition for GPSR.

Orbit determination system onboard VSOP satellite consists of a Kalman filter and a precise orbit propagator. Near the perigee, the Kalman filter can eliminate the orbit propagation error using the observed data by GPSR. Except a perigee, precise onboard orbit propagator propagates the orbit , taking into account accelerations such as gravities of the earth, the sun, the moon, and other acceleration caused by the solar pressure. But there remain some amount of calculation and integration errors. When VSOP satellite returns to the perigee, the Kalman filter eliminates the error of the orbit determined by the propagator. After the error is eliminated, VSOP satellite flies out towards an apogee again.

The analysis of the orbit determination is performed by the covariance analysis method. Number of the states of the onboard filter is 8. As for a true model, we assume that it is based on the actual error dynamics that include the Selective Availability of GPS called 'SA', having 17 states. Analytical results for position and velocity are tabulated and illustrated, in the sequel. These show that the position and the velocity error are about 40m and 0.008m/sec at the perigee, and are about 110m and 0.012m/sec at the apogee, respectively.

1. GPS

The Global Positioning System is an all weather, world-wide, 3-dimensional, real time radio navigation system.

GPS consists of three segments : space segment, ground segment and user segment. Space segment consists of 24 satellites which are called NAVSTAR cruising on 12-hour orbits at an altitude of 20,183km The constellation for the NAVSTAR consists of 6 orbital planes uniformly separated 60 degrees apart(see fig.1).

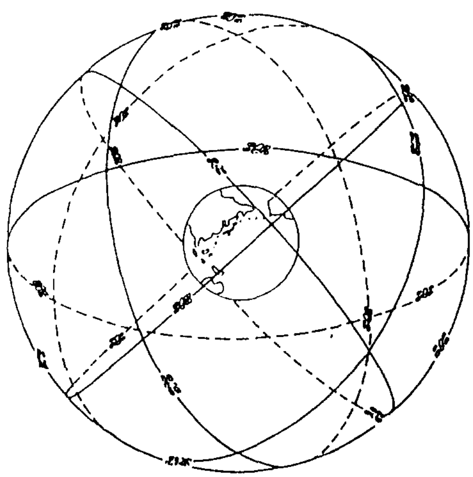

fig.1 GPS constellation

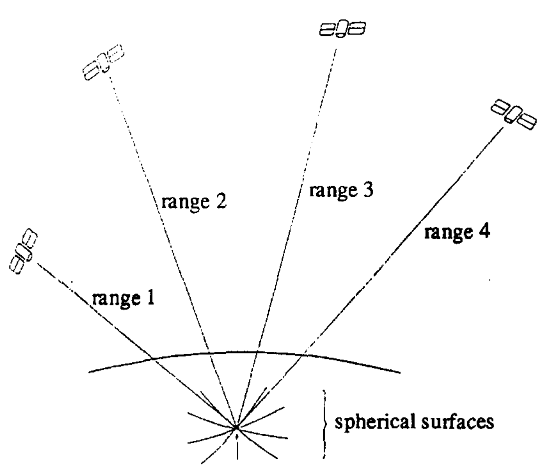

fig.2 principles of GPS navigation system

3 NAVSTARs are on each orbital plane, and the remaining 6 NAVSATRs are active spare satellites in space. There are now 17 NAVSTARs in the orbits including BLOCK II satellites launched under Phase II of the GPS program. The number of 24 satellites ensures visibility of 6 to 11 satellites, that are located at 5degrees or more above the horizon to users located anywhere in the world, at any time.

Ground segments operate NAVSTARs so as to keep station, transmit updated GPS message, and so on. User segment means a GPS receiver(GPSR). A GPSR has to track GPS signals, decodes GPS message and finally obtains the GPS navigation solution.

Signals are transmitted at two L-band frequencies(1227 and 1575 MHz). They are modulated by two codes which are called P-code and C/A-code. These are pseudo randam noise. The NAVSTAR carries a shaped-narrow-beam antenna toward the earth that radiates near uniform power of at least -160dBW for C/A code to users.

Four satellites are normally required for navigation, and those four offering the best geometry should be selected manually or automatically by the receiver system, using ephemeris information transmitted by NAVSTARs. A set of four measured data relative to selected NAVSTARs and four sets of absolute positions and velocitites of NAVSTARs are used to calculate the position and velocity of GPSR, as in fig.2. Ranges to the four satellites are determined by the signal transmission time. The messages from GPS contain ephemeris parameters that enable the user to calculate the absolute position of each satellite at the time of signal transmission. The other data are delta ranges, that are . integrated doppler frequencies. With this data, the velocity of the GPSR can be calculated.

2. VSOP Satellite

In VSOP(VLBI Space Observatory Programme), ISAS of Japan launches the VSOP satellite which has a deployable large scale antenna in order to observe important space objectives. By this VSOP satellite, we can get clear patterns of space objectives such as quasars, and can calculate precise inclination of the earth's rotat-

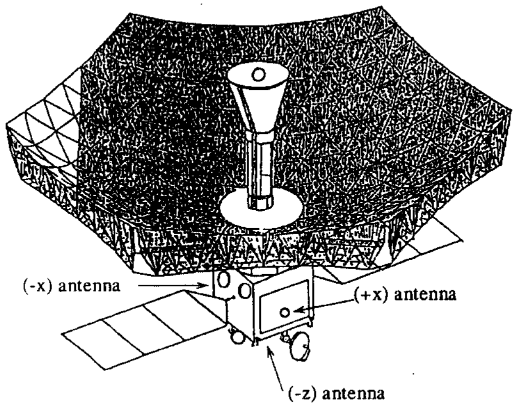

fig.3 Outlook of the VSOP satellite

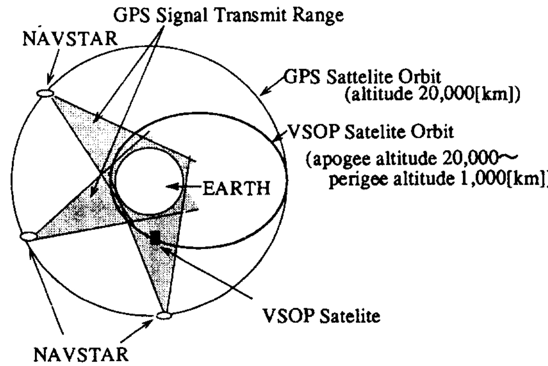

fig.4 Orbit of the NAVSTAR and the VSOP satellite

ing axis and so on. In order to accomplish these mission objectives, requirements to the satellite technologies are very strict. Among them, the requirement on OD(Orbit Determination) of the VSOP satellite is 300[m] in position error and 1.0[cm/sec] in velocity, for the purpose of correlating the observed data acquired by the large scale antenna of the VSOP satellite, with those observed on the ground antenna array. The VSOP satellite will be launched by the M-V rocket, in its first flight, into an earth orbit in the winter of 1995.

The orbit is eliptical ranging from 1,000 km to 20,000 km and the inclination is 46.4 degrees.

In fig.3, the outlook of the VSOP satellite is shown. This satellite has a box-shaped body, with two solar array paddles and a large scale deployable 10[m] antenna. The signals gathered by this large antenna are fed to a low noise amplifier, which is completely cooled by an

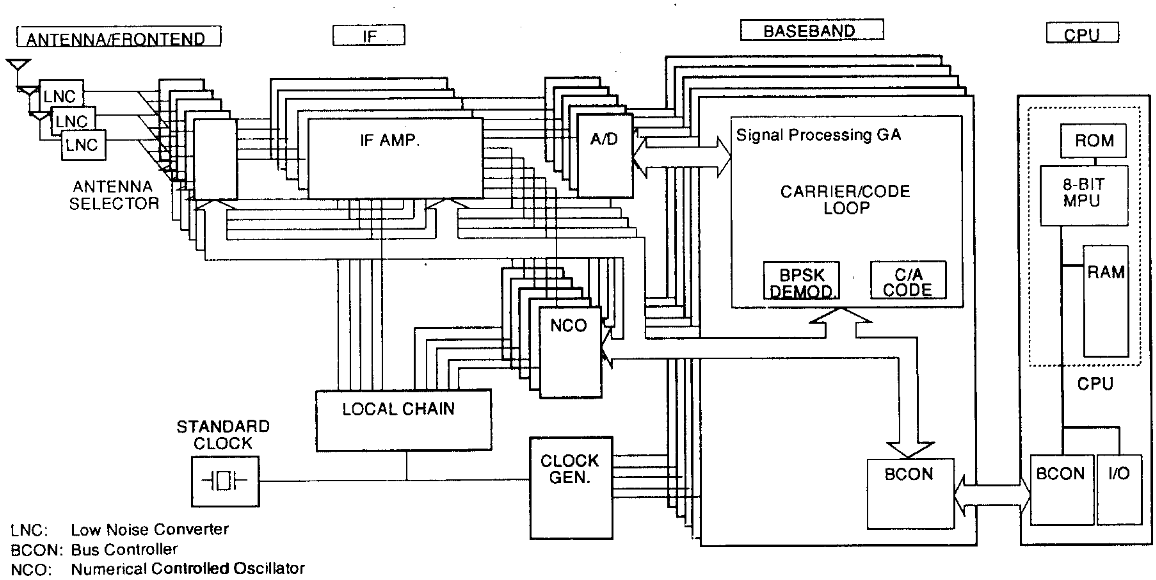

fig.5 Block diagram of GPS receiver

onboard cooler, and clock signals of hydrogen maser from the earth station are recieved.

Orbits of the NAVSTARs are circular with 20,000km in height. On the other hand, the orbit of VSOP satellite is elliptical, and its apogee height is as high as that of NAVSTARs. The GPS signals are transmitted from a GPS narrow beam antenna towards the earth. Thus the GPS receiver onboard the VSOP satellite can't receive GPS signals in the neiborhood of the apogee, as shown in fig.4. However GPS receiver can receive the signals when the VSOP satellite is near the perigee. Then the orbit determination system onboard can navigate the satellite using GPS data near by perigees.

3. GPS Receiver (GPSR)

The GPS receiver consists of three GPS antennas and one GPS receiver package. GPSR has 5 GPS signal processing channels and 2 CPU receiver control units, as shown in fig.5. They use radiation hardened silicon gate arrays which are endurable against the radiation of 100K total dose. The average power consumption is 25[watt] and the weight is 8.5[kg]. GPS antennas are installed on the box-shaped body that are showed in fig.3. The GPS antenna is an omni beam antenna in order to receive GPS signals from anywhere in the hemisphere.

The software package of GPSR of the size of 64K bytes consists of three modules. The first one is the orbit determination system software. It calculates the position and velocity of the VSOP satellite at every 8 seconds. The second module is a receiver control software. It selects and assigns the optimal NAVSTARs to the GPS signal processing channels in order to obtain good navigation results, then decodes the GPS messages and calculate the positions and velocities of NAVSTARs using ephemeris data contained in the message. The third one is the GPS signal tracking software, acting every 4 milli seconds in order to make up the code and carrier tracking loops in the GPS signal processor on each channel. On the other words, the phase and carrier lock loops of the GPS signals are realized by the software.

4. Analysis of GPS System

4.1 Visibility

Since NAVSTARs transmit the signals toward the earth, the GPSR can receive more signals near the earth.

First the coverage of GPS antennas is considered. Near the earth, the antenna coverage may be shaded by the earth, because the field of view of the earth is more than 60 degrees. Hence the VSOP satellite has to change its attitude to look at space objects, antennas are installed on -z, +x, -x planes of the VSOP satellite's body(fig.3), and the total coverage is close to that of a hemisphere. However in this paper we assume that the antenna coverage is close to a sphere in order to simplify the GPS system analysis.

Fig.6 shows the number of the visible NAVSTARs from the VSOP orbit under the above condition of the GPS antenna coverage. At the perigee, from 12 to 15 NAVSTARs are visible. We observe a decrease of the visible NAVSTARs at the perigee because of the earth's shading effect. However more than 4 NAVSTARs are visible during 40 minuites. But at the apogee, NAVSTARs are not visible, and such pattern will be repeated every 6 hours.

The C/N_0, meaning the ratio of the strength of the

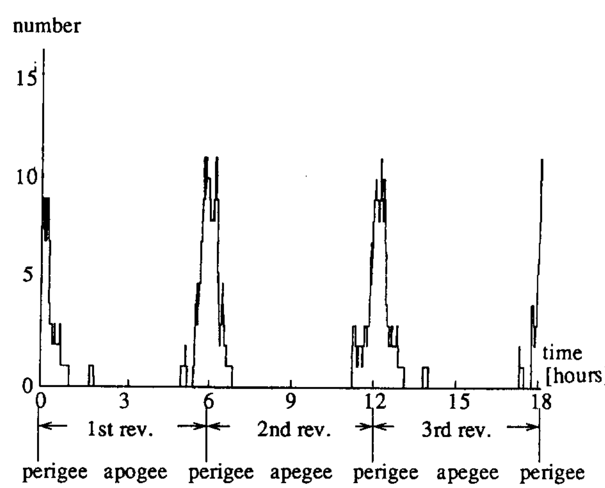

fig.6 number of visible NAVSTARs in VSOP orbit

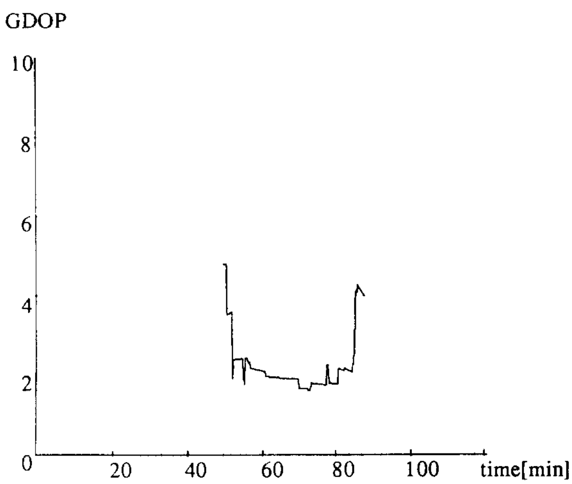

fig.7 Typical GDOP near perigees

GPS signal and the heat noise, is an index indicating the quality of received GPS signals, as well as the quality of GPSR observation. From the analytical point of view, we have to select signals having C/N_0 more than 33 [dBHz].

The GDOP(Geometric Dilution Of Precision) is an index of the navigation performance. We can calculate the GDOP when we can expect that 4 or more NAVSTARs are visible. In the VSOP orbit, 4 NAVSTARs are visible for 40 minuites near the perigee, and the GDOP is smaller than 2.0 which is a good condition for navigation.

4.2 Navigation Error Analysis

When the GPSR receives the range and delta range data near the perigee, a Kalman filter will be activated by the onboard orbit determination system. On the other hand, when the VSOP satellite is away from the perigee, the GPSR have to propagate the orbit taking into account accelerations that affect hte VSOP satellite without GPS data.

In such case, there are several accelerations to be considered. They are classified in two groups. One is the gravity anomaly and the others are solar pressure, air drag and acceleration caused by the relativity effect. The usual orbit determination system on the ground considers all accelerations. However because of the restriction of the computer capacity, the onboard system must select the most effective accelerations. The GPSR takes into accountcs the gravity of the earth, the moon, the sun and solar pressure. Because the other accelerations are so small that integration of them is not carried out. The requirement to the navigation system is 300[m] in position error. Considering this restriction, we have to estimate the accelerations in the order of 8.0×10^{-7}[m/sec^2] to meet the system requirement. We also have to consider the numerical error in integration. We employ 8-degree Runge-Kutta integration method, and the integration error is smaller than 3[m] after one revolution of the VSOP satellite around the earth(fig.8), and satisfying the requirement.

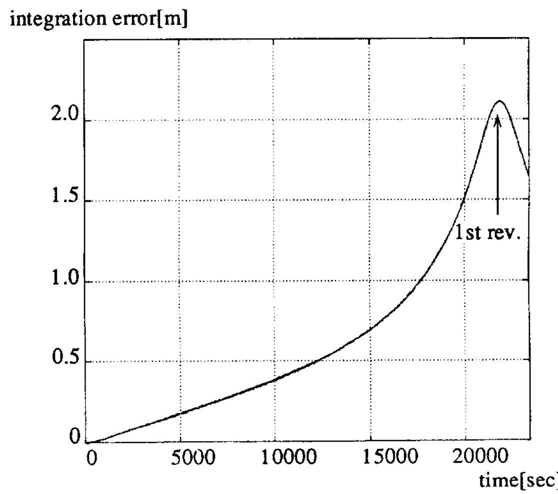

fig.8 integration error by the OD

When the VSOP satellite is near the perigee, GPS error sources affect the GPS range and delta range, and consequently the navigation result. First, we have to survey the GPS error sources. We can divide GPS error sources into 3 groups : GPS system error, GPS signal transmission error and GPS receiver's error. Most of these errors can be compensated by the GPS system information and model equations. But it's difficult to eliminate SA(selective availability) error and ionospheric delay error. SA is an error intentionally inserted in order to degrade the accuracy of the OD by the GPS. Ionospheric error is modeled by the GPS system and compensation parameters are transmitted by GPS signals. But they are only for ground users, and there are no effective method for space users to compensate them. Total GPS error is from 20[m] to 40[m] on range data and about 0.32[m/sec] on delta range data.

Table 1 shows the results of the navigation analysis. At the perigee, the position error is about 5[m] (40[m] when SA is inserted) and the velocity error is less than 1.0[cm/sec]. At the apogee, the position error is about 64[m](109[m] with SA) and the velocity error is about 1.0[cm/sec]. This analytical result is obtained by the method of covariance analysis for Kalman filters. When the VSOP satellite is near the perigee, the onboard navigation is carried out by means of 8-state Kalman filter, including position x,y,z, velocity x,y,z, clock bias and clock drift. Fig.9 and fig.10 are navigation error profiles. Because of the visibility problem of NAVSTARs, it is clear that the navigation error is smaller at the perigee than at the apogee. These figures clearly illustrate that the navigation error increases become larger as the VSOP satellite moves away from the perigee.

table.1 Navigation error

	perigee	apogee
without SA effect		
position error	4.8 m	63.2 m
velocity error	0.46 cm/sec	0.98 cm/sec
with SA effect		
position error	40 m	108.6 m
velocity error	0.76 cm/sec	1.22 cm/sec

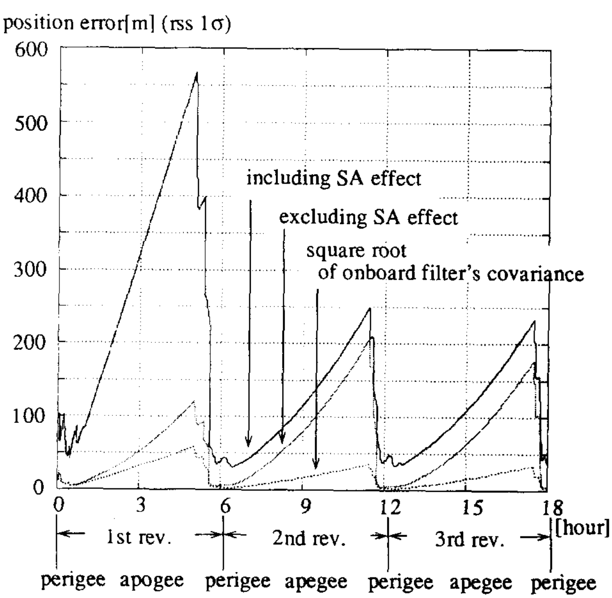

fig.9 Position error profile in VSOP orbit

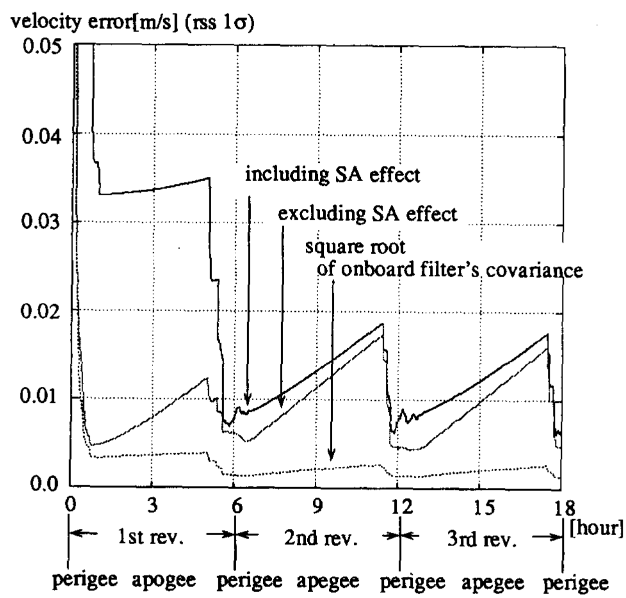

fig.10 Velocity error profile in VSOP orbit

5. Conclusion

This paper describes the VSOP satellite and the role of the GPS receiver system onboard .

The complete GPS will be build in 1995. And it's useful for the low earth orbits satellites to use the GPS receiver system as well as the onboard orbit determination system. And we describe the GPS receiver system as well as the orbit determination system for the VSOP satellite, that will be launched in 1955, and its feasibility is demonstrated in this paper.

Refernces

[1] *Navstar Global Positioning System(GPS) System Characteristics*, STANAG 4294, 1989

[2] Nishimura,T., et al, *High Precision Orbit Estimation by the GPS Receiver onboard the VSOP satellite,* in Proceedings of the 7th Guidance and Control of Aerospace System Symposium in Japan,1990