Korean Journal of Remote Sensing, Vol.19, No.3, 2003, pp.181~190

A Simulation Based Assessment for Evaluating the Effectiveness of Quasi-Zenith Satellite System

Yong-Cheol Suh and Ryosuke Shibasaki

Department of Civil Engineering, Tokyo University

Abstract : Since the operation of the first satellite-based navigation service, satellite positioning has played an increasing role in both surveying and geodesy, and has become an indispensable tool for precise relative positioning. However, in some situations, e.g. at a low angle of elevation, the use of satellites for navigation is seriously restricted because obstacles like buildings and mountains can block signals. As a mean to resolve this problem, the quasi-zenith satellite system has been proposed as a next-generation satellite navigation system. Quasi-zenith satellite is a system which simultaneously deploys several satellites in a quasi-zenith geostationary orbit so that one of the satellites always stay close to the zenith if viewed from a specific point on the ground of East Asia. Thus, if a position measurement function compatible with GPS is installed in the quasi-zenith and stationary satellites, and these satellites are utilized together with the GPS, four satellites can be accessed simultaneously nearly all day long and a substantial improvement in position measurement, especially in metropolitan areas, can be achieved. The purpose of this paper is to evaluate the effectiveness of quasi-zenith satellite system on positioning accuracy improvement through simulation by using precise orbital information of the satellites and a three-dimensional digital map. Through this developed simulation system, it is possible to calculate the number of simultaneously visible satellites and available area for positioning without the need of actual observation. Furthermore, this system can calculate the Dilution Of Precision (DOP) and the error distribution.

Key Words : Quasi-Zenith Satellite System, GPS, Simulation System, Orbital Information, 3-D Digital Map.

1. Introduction

In recent years, satellite-based navigation has been widely used in positioning. On the other hand, the demand for higher accuracy and wider applicability has been continuously increasing. It is well known that the accuracy, availability and reliability of the positioning results are heavily dependent on the number and geometric distribution of tracked satellites. As for the recent positioning services like GIS (Geographic Information System), ITS (Intelligent Transportation System) and LBS (Location Based Service), seamless and more accurate information is actually needed. Over the past several years, leading public and private organizations in Japan have been investigating proposals for developing an advanced space-based augmentation system for GPS. Last year, the Japanese government authorized continued work on a concept for a Quasi-

Received 28 February 2003; Accepted 20 April 2003.

Zenith Satellite System (QZSS), developed by the Advanced Space Business Corporation team. If all proceeds as planned, by 2008 the quasi-zenith satellite system would provide a new integrated service for mobile applications in Japan based on communications and positioning. QZSS's positioning capabilities would, in effect, represent a new-generation GPS space augmentation system, with limited navigation capabilities, In other words, although the quasi-zenith satellite system is seen primarily as an augmentation to GPS, without requirements or plans for it to work in standalone mode, quasi-zenith satellite system can provide limited accuracy positioning on its own. The service also can be augmented with geostationary satellites in Japan's MTSAT (Multi-functional Transport Satellite) Satellite-based Augmentation System (MSAS) currently under development, which features a geostationary satellite-based design similar to the U.S. Federal Aviation Administration's Wide Area Augmentation System (Petrovski *et al.*, 2003). Consequently, it is anticipated that the quasi-zenith satellite system will contribute to more accurate and reliable positioning services by providing users better line-of-sights to the satellites. However, in order to adopt this quasi-zenith satellite system as a national undertaking on a larger scale, it is necessary to evaluate how this system may complement the existing satellite-based positioning and improve the positioning accuracy. The purpose of this paper is to evaluate the effectiveness of the quasi-zenith satellite system on positioning accuracy using precise orbital information of the satellite and a three-dimensional digital map through simulation.

2. Characteristics of Quasi-zenith Satellite System

The quasi-zenith satellite system is a satellite constellation consisting of three or more satellites placed in inclined geo-synchronous circular orbits with an inclination of around 45 degrees. The satellite is also called the figure-8 satellite because the locus of the sub-satellite point of this satellite traces a figure "8" from the north to the south centering a place at the equator. The quasi-zenith satellite system has not been formally defined yet, but it is a satellite constellation with at least three satellites. The satellites work in three shifts of eight hours; at least one of three satellites can be seen near the zenith.

1) Arrangement of Quasi-Zenith Satellite Orbits

The quasi-zenith satellite is, to be precise, a satellite that has an inclined geo-synchronous orbit. This orbit has the same orbital altitude (35,786km) as a geostationary orbit and has an inclination such as that shown in Fig. 1. The satellite revolves once a day synchronously as the earth rotates. When the quasi-zenith satellite system is used for East Asia, three satellite are located on the figure "8". The three satellites are not orbiting the same inclined orbit, but are deployed in three different orbits at the same inclination and at ascending node intervals of 120 degrees. Each satellite moves on the locus at a phase difference of eight hours from each other. The service is provided by switching

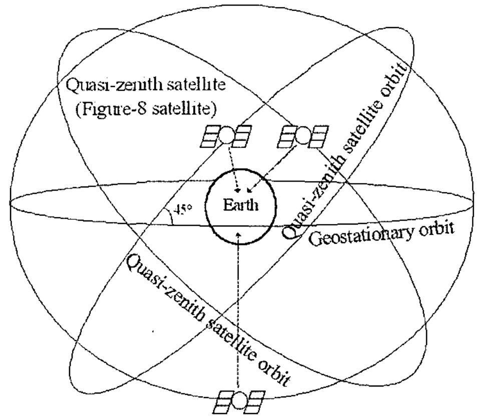


Fig. 1. Arrangement of three satellite orbits.

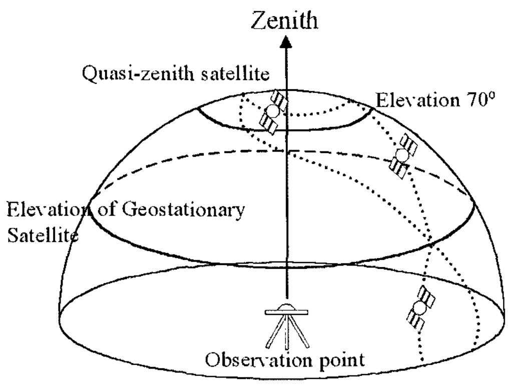


Fig. 2. Satellite locus on the celestial sphere in East Asia.

the satellites every eight hours to keep the maximum angle of elevation.

2) Satellite Locus on the Celestial Sphere in East Asia

When the satellites cross over the equator on the celestial sphere, the elevation is about 45 degrees. For the 8 hours when the satellite moves at the northern tip of the figure-8 locus, the elevation is over 70 degrees.

Quasi-zenith satellite is a system which simultaneously deploys several satellites in a quasi-zenith geostationary orbit so that one of the satellites always stay close to the zenith if viewed from a specific point on the ground of East Asia. The satellites are placed into three different orbits separated by 120 degrees and always have an angle of elevation to East Asia of 70 degrees or more, thus enabling synchronization of the ground locus. Since in addition to having features equivalent to those of conventional satellites, the orbit of the quasi-zenith satellite is such that it remains nearly stationary above East Asia region. Fig. 2 shows Satellite locus on the celestial sphere in East Asia.

3. Satellite Orbital Estimation

As is well-known, Kepler's Second Law of Motion states that a line joining a satellite and the Earth sweeps out equal areas in equal intervals of time. Therefore, due to the highly elliptical shape of the quasi-zenith satellite orbit, a satellite will linger in the part of the orbit with high altitude, as its velocity decreases when it goes far form Earth. This will allow the quasi-zenith satellites to spend most of their time over the desirable region. To estimate the number and geometric distribution of tracked GPS satellites and quasi-zenith satellite at a particular time, the satellite orbit must be simulated. The GPS satellite orbit can be estimated with Keplerian model and satellite orbital elements which can be acquired from CelesTrack WWW web site (http://celestrak.com).

1) Keplerian model

Keplerian orbital dynamics problem is defined by the differential equation.

$$\ddot{\mathbf{r}} = -\mu \frac{\mathbf{r}}{r^3} \tag{1}$$

where $\mathbf{r}$ is the position vector of the satellite and r is the magnitude of the position vector. The gravitational parameter, μ, is a physical constant dependent upon the mass of the central body.

From equation (1), the orbital equation and the Kepler's equation can be formulated. Equation (2) shows the orbital equation, and equation (3) shows the Kepler's equation.

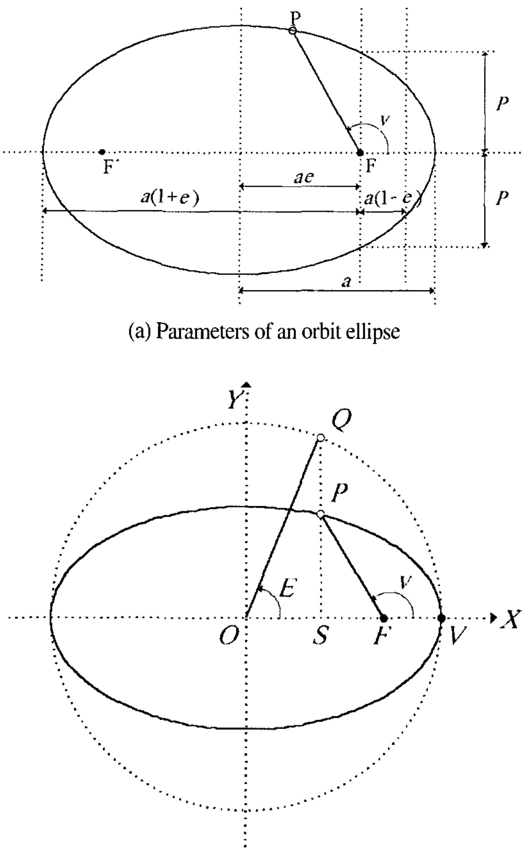
$$\begin{aligned} r &= \frac{p}{1+e\cos v} \\ p &= a(1-e^2) \end{aligned} \tag{2}$$

$$M = n(t-T) = E - e\sin E \tag{3}$$

$$n \equiv \sqrt{\frac{\mu}{a^3}}$$

$$\cos E = \frac{e+\cos v}{1+e\cos v}$$

Where p is semi-latus rectum, a is semi-major axis, e is eccentricity, v is true anomaly, M and E are mean anomaly and eccentric anomaly, n is mean motion, T is



(a) Parameters of an orbit ellipse

(b) Relationship between an orbit ellipse and the auxiliary circle

Fig. 3. Orbital parameters.

time of periapsis passage, t is a particular time, and the orbital parameters are illustrated in Fig. 3. With Newton's law, eccentric anomaly E can be computed from known value, which is mean anomaly M, and then v also can be computed. Consequently, with some conversions of coordinates, the satellite orbit and satellite position at a particular time can be computed.

2) Keplerian Orbital Elements

Seven elements are required to define a satellite orbit. This set of seven numbers is called satellite orbital elements, or sometimes Keplerian orbital elements. These numbers define an ellipse, orient it about the earth, and place the satellite on the ellipse at a particular time. In the Keplerian model, satellite orbit in an ellipse has a constant shape and orientation. The Earth is at one focus of the ellipse, not the center; unless the orbit ellipse is actually a perfect circle (Y. Konishi *et al.*, 2001). The basic orbital elements are explained in detail as shown in Appendix

4. Estimation of Available Area for Positioning

This simulation system consists of a three-dimensional digital map, a model of GPS satellite orbits and a model of quasi-zenith satellite orbits information. This system was developed with JAVA, and each GPS satellites, quasi-zenith satellites and map data are all implemented as individual class.

The study area is divided into the grid cells and by using the three-dimensional coordinates of the buildings of digital map, this simulation system estimate whether the line-of-sight from the center of each grid cell to each GPS satellite or quasi-zenith satellite intersects any objects or not. Then the number of visible GPS or quasi-zenith satellite is computed for each grid cell. If the numbers of tracked satellites are four or more over at a particular grid cell, this simulation system recognizes that the cell is available for positioning. Fig. 4 shows the concept of developed simulation system for estimating available area of positioning by GPS and quasi-zenith satellites.

Fig. 5 shows the simplified three-dimensional digital map (DiaMap by Mitsubishi Corporation) of Shinjuku district used in this simulation. This map combines high-quality digital color satellite images down-linked directly from the 1m resolution IKONOS low-orbit satellite and elevation data gathered from 30 cm vertical accuracy airborne laser sensors with sophisticated information technology such as virtual reality systems, databases, and network technology.

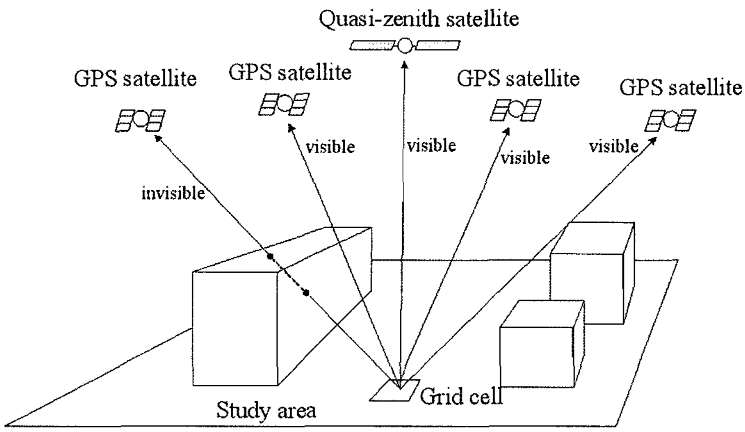


Fig. 4. Concept of available area estimation.

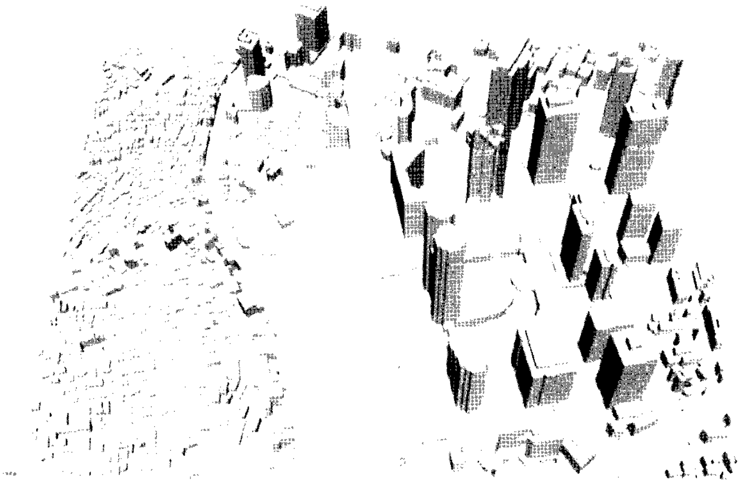


Fig. 5. Three-dimension digital map which used in this simulation.
(DiaMap by Mitsubishi Corporation)

The conditions under which this simulation was carried out are listed as follows.

- Estimate process at every ten minutes from 0 O'clock, Nov 15, 2002 to 0 O'clock, Nov 16, 2002, that is, a total of 145 steps.
- Estimate 24 GPS satellite and 3 quasi-zenith satellite orbits by using the actual satellite orbital elements on Nov 14, 2002.
- Use simplified three-dimensional digital map of the Shinjuku district (1 sq km) of Tokyo in Japan as the study area. This area lies on the fringe of a region of poor observability.
- The study area is divided into grid cells of a regular tetragon of 2 meter on each side.

Furthermore, the Dilution Of Precision (DOP) and the error distribution have been calculated using precise orbital information of the satellite and the 3-Dimensional digital map.

5. Results of Simulation

The typical graphical output is given in Figs. 6, 7 and Figs. 8, 9, which estimate the availability of positioning using the only GPS satellite system, and the integrated GPS and quasi-zenith satellite system through simulation using the concept shown in Fig. 4. Especially, Fig. 6 shows the available area of positioning which is defined as the set of the grid cells where four or more GPS or quasi-zenith satellites are visible at every six hour over a period of 24 hours from 0 O'clock on Nov 15, 2002, the output of four steps was sampled from all estimated 145 steps representatively. The upper figure shows the case of using the only GPS, and the lower figure shows the case of using integrated GPS and quasi-zenith satellites. Blue represents areas with signals from four or more satellites available, white areas have signals from fewer than 4 satellites, and black areas are buildings. As shown in the these results, since the availability ratio of tracked GPS satellites may not be sufficient for accurate and reliable positioning, it is very hard to navigate in urban environments. Accordingly, through integration of GPS and quasi-zenith satellite, it is possible to obtain a drastic improvement of available area compared with the GPS-only case and this might be sufficient to fulfill the user requirements. The more satellites we deploy, the higher accuracy we have. Fig. 7 shows the number of visible satellite transmitters. Upper four figures show the number of visible GPS satellite, and lower four figures show the number of visible GPS and quasi-zenith satellite. The color legend indicates the number of satellites, which is received along a line-of-sight to the satellites without any obstruction at a particular grid cell. As shown in the cases of using integrated GPS and quasi-zenith satellite transmitters, the number of visible satellites increased by one compared with the cases of using the only GPS satellite transmitters because the quasi-zenith satellites work in three shifts of eight hours; at least one of three satellites can be seen near the zenith.

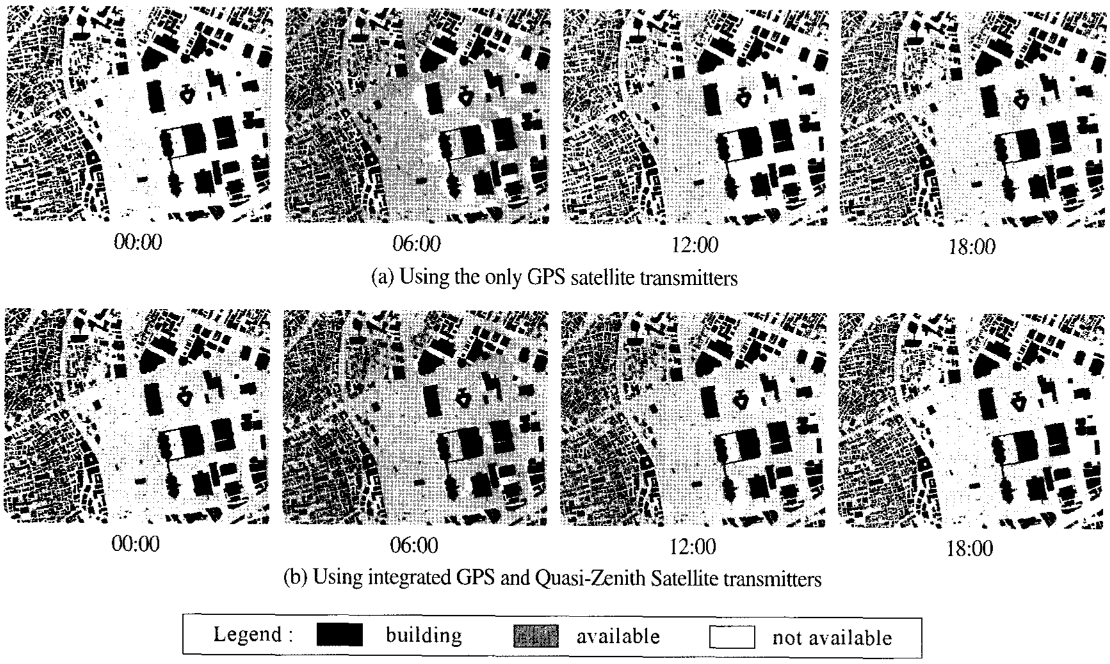


Fig. 6. Available area of the positioning.

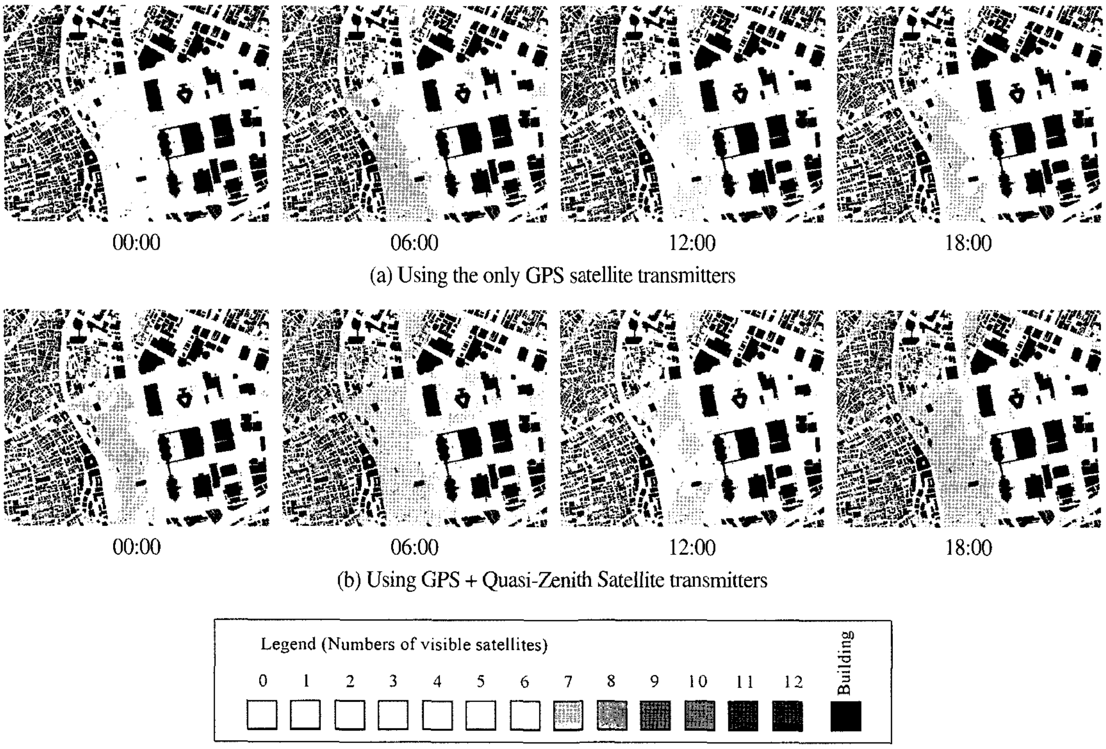


Fig. 7. Number of visible satellites transmitters.

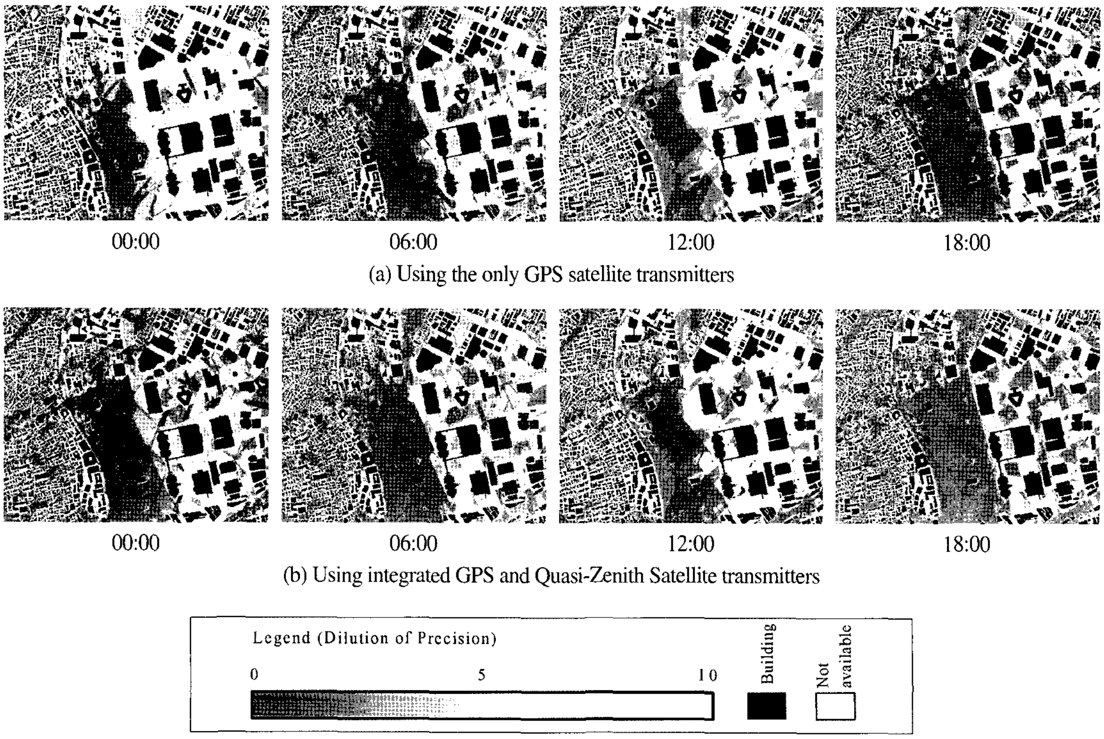


Fig. 8. Horizontal dilution of precision.

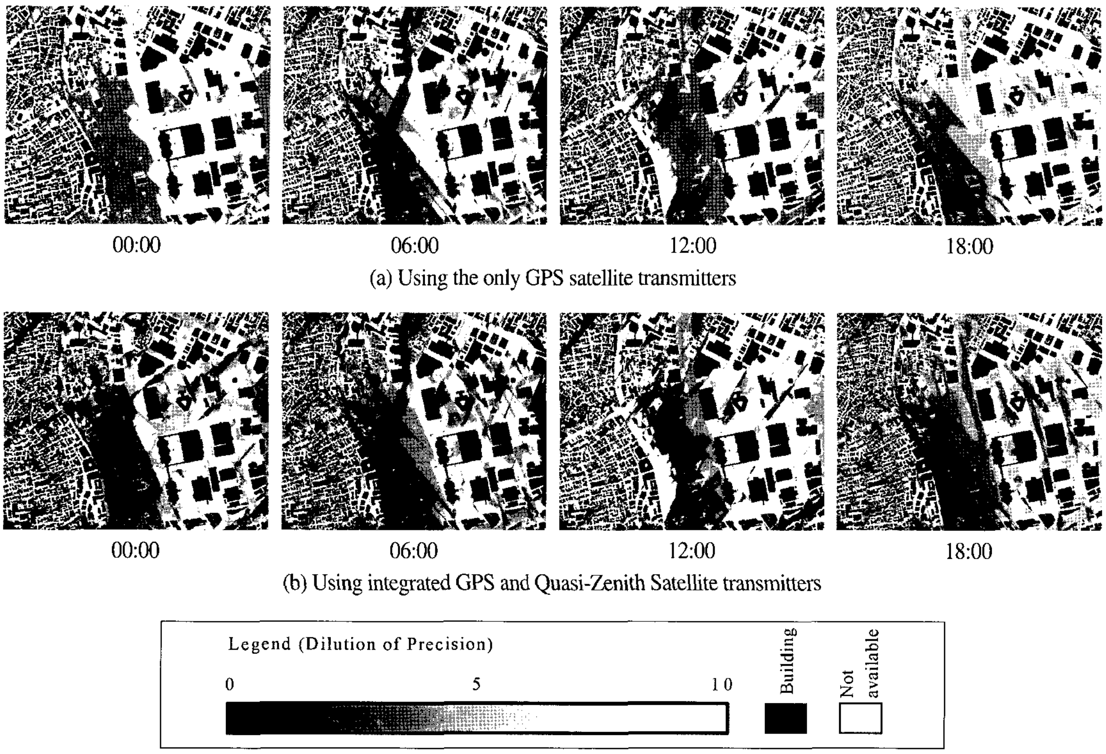


Fig. 9. Vertical dilution of precision.

This simulation system also can estimate the distribution of Dilution of Precision (DOP) factor including HDOP (Horizontal Dilution of Precision), VDOP (Vertical Dilution of Precision), TDOP (Time Dilution of Precision) and PDOP (Position Dilution of Precision). The approach used in preparing the results that follow was to calculate the DOP values at each point in time using all combinations of available satellites taken 24 hours all day long. The geometry of the visible satellites is an important factor in achieving high quality results especially for point positioning and kinematic surveying. The geometry changes with time due to the relative motion of the satellites. A measure of the geometry is the Dilution of Precision (DOP) factor. A result of HDOP and VDOP versus time at the test area is shown in Fig. 8 and Fig. 9. As can be seen from the results, the DOP values improved drastically by integration of GPS and quasi-zenith satellite. Moreover it is clear that the value of VDOP at each time frame is worse than that of HDOP in the urban areas. These results match the actual circumstances because the quasi-zenith satellite system has a feature that any one of the satellites can be seen near the zenith.

6. Conclusions

The goal of this study was to evaluate how quasi-zenith satellite system might complement the existing satellite-based positioning and improve the positioning accuracy. Using this developed simulation system, it is possible to estimate how the availability of positioning will be changed by the number and geometric distribution of tracked GPS and quasi-zenith satellites without the need of actual observation. Consequently, the results from a simulation system have been presented, which demonstrate the efficiency of integrated GPS and quasi-zenith satellite system in improving the performance of precise positioning system. Furthermore, this developed simulation system may also be applicable when evaluating or planning to install new positioning satellite system.

Acknowledgements

Authors would like to acknowledge the efforts of Mr. Yusuke Konishi and Mr. Tomihiro Hakamata of the University of Tokyo for their support and assistance in preparing the paper.

References

Hofmann-Wellenhof, B., H. Lichtenegger, and J. Collins, 2001. *GPS - Theory and Practice*, Fifth, revised edition, SpringerWienNewYork.

Konishi, Y., and R. Shibasaki, 2001. Development of A Simulation System to Estimate Available Area of GPS and Pseudolite, *Proceeding of the 22nd Asian Conference on Remote Sensing*, 5-9 November, Singapore, pp. 1506-1511.

Petrovski, I., M. Ishii, H. Torimoto, H. Kishimoto, T. Furukawa, M. Saito, T. Tanaka, and H. Maeda, 2003. *GPS World magazine;* QZSS - Japan's New Integrated Communication and Positioning Service for Mobile Users, June, pp. 24-29.

Suh, Y. C., Y. Konishi, T. Hakamata, and R. Shibasaki, 2002. Development of simulation system for assessing the layout of pseudolite in urban environment, *Proceeding of the 23rd Asian Conference on Remote Sensing,* 25-29 November, kathmandu, Nepal : CD-rom.

Tanaka, M., 2000. Concept of Quasi-zenith Communications System, *Journal of IEICE*, 83(3): 232-234.

Tanaka, M., K. Kimura, S. Kawase, H. Wakana, and Iida, T., 2000. Applications of the figure-8 satellite, *18th AIAA International Communications Satellite Systems Conference*, Oakland, U.S.A. AIAA-2000-1116.

URL, Communication Research Laboratory, *Quasi-zenith Satellite Communications System Using Figure-8 Orbit*, http://www2.crl.go.jp/ka/control/efsat_old/index-j.html.

URL, CelesTrack WWW, *Navigation satellites, GPS Operational Data*, http://celestrak.com.

Appendix

***t* : epoch** A set of the orbital elements is a snapshot of the satellite orbit at a particular time. Epoch is simply a number which specifies the time when the snapshot was taken.

***i* : inclination** The orbit ellipse lies in a plane known as orbital plane. The orbital plane always goes through the center of the earth, but may be inclined any angle relative to the equator. Inclination is the angle between the orbital plane and the equatorial plane.

Ω : right ascension of ascending node (RAAN) The above inclination and this RAAN can orient the orbital plane in space. After the inclination could be specified, there are still an infinite number of possible orbital planes. If we specify where along the equator the line of nodes pokes out, we will have the orbital plane fully specified.

The line of nodes pokes out two places, but we only need to specify one of them. One is called the ascending node (where the satellite crosses the equator going from south to north), and the other is called the descending node (where the satellite crosses the equator going from north to south).

ω **: argument of periapsis** The major axis passes through the center of the earth, and another line passing through the center of the earth, the line of nodes, was already identified. The angle between these two lines is called argument of periapsis.

e **: eccentricity** In the Keplerian model, the satellite orbit is an ellipse. Eccentricity tells us the shape of the ellipse.

n **: mean motion &** ***M*** **: mean anomaly** Refer to the previous Keplerian Orbital Elements.