QZSS – Japan's New Integrated Communication and Positioning Service for Mobile Users

Ivan G. Petrovski, Makoto Ishii, Hideyuki Torimoto, Hitoshi Kishimoto, Toshio Furukawa, Masayuki Saito, Toshiyuki Tanaka, and Hiroaki Maeda

Japan is planning to create a regional augmentation — the Quasi-Zenith Satellite System, or QZSS — that will provide additional GPS-like signals aimed at improving position-ing capability for mobile users, along with new communications services. In this article, members of the private consortium developing QZSS describe the proposed system design and its anticipated benefits.

Dr. Ivan G. Petrovski is in charge of R&D at GNSS Technologies Inc. and the head of the Institute of Advanced GNSS Technologies in the Mercantile Marine University.

Makoto Ishii is director for sales and marketing at GNSS Technologies Inc.

Hideyuki Torimoto is president and CEO of GNSS Technologies Inc.

Hitoshi Kishimoto is vice-president and general manager for system development of ASBC (Advanced Space Business Corporation).

Toshio Furukawa and Masayuki Saito work in the Space Solution Systems Development Division of MELCO (Mitsubishi Electric Corporation).

Toshiyuki Tanaka is a senior engineer in the Space IT Project Center, Hitachi Ltd.

Hiroaki Maeda works in the CS Solutions Division of NTS (NEC TOSHIBA Space Systems, Ltd.)

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-Zenith Satellite System (QZSS), or Jun-Ten-Cho in Japanese, developed by the Advanced Space Business Corporation (ASBC) team, including Mitsubishi Electric Corp., Hitachi Ltd., and GNSS Technologies Inc. (See the sidebar, "The Evolution of the QZSS Project.")

If all proceeds as planned, by 2008 the QZSS would provide a new integrated service for mobile applications in Japan based on communications — video, audio, and data broadcasts — 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 QZSS is seen primarily as an augmentation to GPS, without requirements or plans for it to work in standalone mode, QZSS can provide limited accuracy positioning on its own. The service also can be augmented with geostationary satellites in Japan's MTSAT 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 (WAAS).

This article describes the current overall QZSS concept, design considerations and alternatives including the satellite constellation, ground tracking network, and system timing, as well as plans for a differential corrections service.

Market Drivers

To understand demands for new augmentation systems such as QZSS, one should look at the GPS market in Japan. Today, Japan leads the world in many applications of GPS equipment and services for civil use. The necessity for the new advanced augmentation system came from the spread of civil use of GPS service in such areas as car navigation, aviation, maritime, mapping, land surveying, telecommunications, and so forth.

Approximately two million GPS-equipped car navigation units are sold annually in Japan with a cumulative total of 9,620,000 units sold from 1993 until 2002. According to market forecasts, annual sales will increase to as many as 2.7 million units per year within the next few years. Currently, about 3.8 million GPS-equipped cellular phones are in use in Japan today. The total installed base of cell phone users in Japan is 70 million units, equal to about 60 percent of the entire population. This represents the potential size for GPS in Japan's cellular phone market. The annual sale of cellular phone units is about 45 million units per year.

The number of GPS reference stations for synchronizing the CDMA telecommunications infrastructure is 9,000 today and is expected to grow up to 17,000 by 2005. The Japanese surveying market is relatively small — an estimated 1,500 receivers with very low turnover. GPS receivers used in construction number about 3,000, and the maritime market does not exceed 10,000 units. Potentially, railway cars can be equipped with GPS, which could add another 30,000 units.

As one can see, car navigation is the second-largest market in terms of unit volume after cellular phones. The turnover rate for cellular phones in Japan much higher than for car navigation: the average unit's lifespan doesn't exceed one or two years. But the cellular phone market will not necessarily coincide with the GPS market. On the contrary, Japanese car manufacturers have expressed an intention to provide new-generation cars with an integrated multimedia system, which will function as

an office on wheels and include GPS as standard equipment. We can estimate the potential car navigation market on the size of annual domestic car sales, which is between 4 and 4.5 million. Today only about a half of these cars are equipped with GPS.

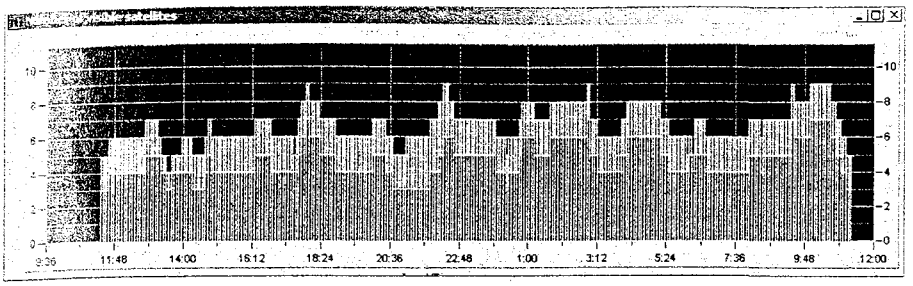


FIGURE 1 Simulation of anticipated number of GPS satellites (blue) and QZSS asymmetrical 8-shaped orbit satellites (green) over Tokyo during a 24-hour period at an elevation of at least 30 degrees

FIGURE 2 Snapshots of ranging signal availability analysis for Shinjuku district (downtown Tokyo). At left, the map of the area covers approximately 1×1 kilometer. In the center image (GPS only) and right image (GPS + QZSS 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.

This calls for reliability and availability of positioning service, which at present has some limitations due to the limited satellite visibility typical in Japan urban canyons and mountainous regions. QZSS will augment GPS to meet these requirements.

Although QZSS is expected to primarily benefit car navigation users, it will undoubtedly also benefit all user segments in Japan — and to a certain extent, Asia as well — through the improved visibility, availability, constellation geometry, and corrections services. **Figure 1** demonstrates the improved satellite visibility in Tokyo area above 30-degree elevation mask (blue is GPS only, green GPS and QZSS). **Figure 2** presents a snapshot signal-availability analysis for the Shinjuku (Tokyo downtown) district, with the white areas representing obstructed areas in which signals from fewer than four satellites are available for a 3D position fix. The depicted area is approximately one square kilometer. In the case of GPS-only (the middle panel), positioning is possible on only 24 percent of the total area; for GPS and QZSS (right panel), on 70 percent.

We are also investigating possibilities for improving assisted GPS service for cellular phones by providing assistance data

The Evolution of the QZSS Project

QZSS is a new concept developed by the private sector, with the government sector assuming responsibility for the associated technology development, especially the portion of the project involved with the positioning service (in contrast with data broadcast and communication). This effort has taken place in the context of Japan–U.S. cooperation on GPS, formalized by the GPS Joint Statement signed November 22, 1998, by the heads of state at that time, President Bill Clinton and Prime Minister Keizou Obuchi. The 1998 policy statement established a cooperative mechanism that provided for annual plenary meetings and working groups. Japan's stated policy objective was "to secure and enhance user interest," and the QZSS initiative is the logical continuation of this policy.

At the GPS–QZSS Technical Working Group meeting in early December 2002, Japanese and U.S. governmental representatives discussed the creation of QZSS. The representatives from the two nations deliberated the technical requirements for QZSS signal structure, codes, and power. To date,the positioning service of QZSS is seen as an advanced space augmentation system for GPS that will reside in the GPS L1, L2, and L5 frequencies. QZSS will use the same signal structure as GPS and employ pseudorandom noise (PRN) code designations above those of the GPS constellation and WAAS. Other types of signal modulation, such as binary offset carrier (BOC) and binary phase shift keying (BPSK), are also under consideration now. Currently, involved governmental institutions continue to work toward definition of the signal structure. The latest meeting was held in May.

The Advanced Space Business Corporation (ASBC) was founded in November 2002, to facilitate public participation in the QZSS project and provide a vehicle for public investment. More than 50 major Japanese companies are now participating in ASBC, including Mitsubishi Electric Corp., Hitachi Ltd., NEC Toshiba Space Systems, Ltd. and GNSS Technologies Inc. ASBC will manage the QZSS infrastructure and provide a revenue stream through fee-for-use service, although part of the QZSS service will be free. One proposal under consideration for the fee-based service calls for incorporating a decoding device into user equipment.

The Japanese government's participation in the QZSS project includes the formation of the QZSS Development and Utilization Council comprised of the Japan Federation of Economic Organizations as well as four Japanese ministries: the Ministry of Education, Culture, Sports, Science and Technology (MECSST); the Ministry of Economy, Trade, and Industry; the Ministry of Public Management, Home Affairs, Posts and Telecommunications; and the Ministry of Land, Infrastructure, and Transport. The governmental sector also includes the National Space Development Agency of Japan, which is the leading enterprise under the MECSST and is in charge of the overall design of the QZSS space segment and monitoring network. The other principal institutions involved include the Electronic Navigation Research Institute, which is working on differential correction services; the Communications Research Laboratory, which is in charge of system time; and the Advanced Institute of Science and Technology, which is working on various components such as correction service and time keeping.

According to current plans, a QZSS software-based simulation system should be introduced by the end of this year. Involved institutions (including ASBC, GNSS Technologies, NASDA and others) will conduct a system feasibility study until March 2004. Next, the main development of all system components will take place from March 2004 to March 2007, including tests using the Engineering Test Satellite VIII. Starting in 2007, we will conduct a one-year test phase for the system. QZSS should become operational in the third quarter of 2008.

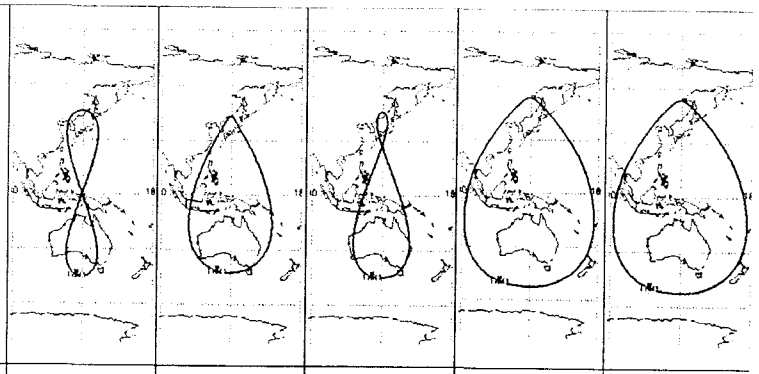
Satellite ground track					
Inclination	45°	42.5°	45°	52.6°	52.6°
Eccentricity	0	0.21	0.099	0.36	0.36
Number of satellites	3	3	3	3	4

FIGURE 3 Characteristics of options for QZSS orbit configurations

through the QZSS, including GPS orbital data, and time.

Satellite Constellation

The QZSS constellation will consist of three satellites moving in periodical highly elliptical orbits (HEOs) over the Asia region. The image on the opening page of this article depicts an artist's rendering of the QZSS satellite. The big antenna on the top is for S-band communication. The QZSS satellites will be launched with Japan's H-IIA launch vehicle or a similar type of launcher. Satellites will have L-, S-, and Ku-band capabilities (S-band for broadcasts and low-speed communications, Ku-band for high-speed communications and TT&C).

Five types of constellations, which are being considered for QZSS, were registered with the International Telecommunications Union in November 2002. **Figure 3** presents the main characteristics for these orbits. We have analyzed mainly two types of orbit with different Keplerian parameters. These are a 45-degree inclination with eccentricity of 0.1 (asymmetric 8-shape) and an inclination of 52.6 degrees with eccentricity of 0.36 (tear drop shape), corresponding to Type 3 and Type 4/5, respectively, in Figure 3.

Figure 4 demonstrates a satellite distribution for these constellations (types 3 and 4) in the orbital plane. A symmetrical 8-shape orbit has been dropped from consideration due to the frequent satellite maneuvers that would be required to avoid collisions as a satellite passes through the highly populated geostationary belt. Also this constellation would provide less favorable visibility over the northern hemisphere in comparison with HEO.

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 QZSS orbit, a satellite will linger in the part of the orbit with high altitude, as its velocity decreases when it goes far from Earth. This will allow the QZSS satellites to spend most of their time over the desirable region. As can be seen from the elevation graph in Figure 6 (for the asymmetrical figure-8 orbit), a QZSS satellite typically operates more than 12 hours a day with an elevation above 70 degrees, a performance characteristic from which the term "quasi-zenith" derives.

To help choose among possible orbits, we looked at the advantages and disadvantages of each orbit from the positioning and communication service point of view. For positioning, we used a newly developed simulation tool to analyze the satellite availability, observability, and their potential for accuracy and ambiguity resolution assistance, taking into account the number of visible satellites, their geometry, and relative speed. (See the sidebar, "A QZSS Simulation Tool.") The simulation tool estimates potential user accuracy based on user-to-satellite geometry, satellite-to-network geometry, visibility, and coverage. We also looked at the possible design for tracking networks to find an optimal design, considering visibility and coverage as criteria. We estimate achievable accuracy of ephemeris estimation for given location of tracking stations.

Figure 3 depicts the ground tracks for the constellations under consideration and **Figure 5** shows five stations of a tracking network configuration that is being used

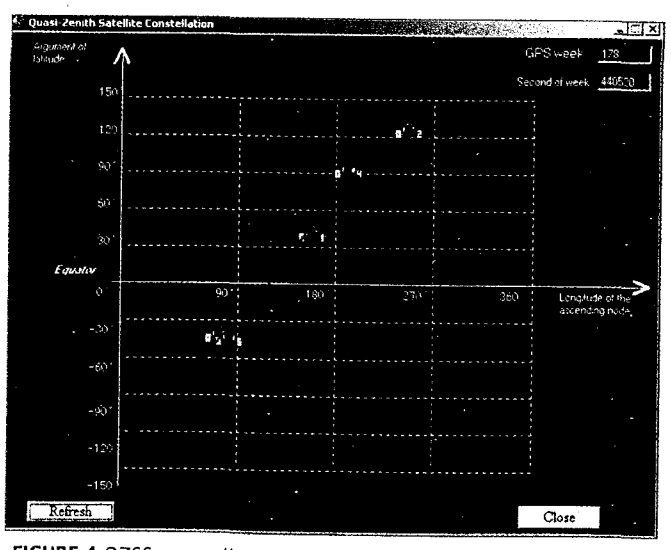


FIGURE 4 QZSS constellation deployment of satellites in orbital planes for Type 3 and Type 4 (as described in Figure 3)

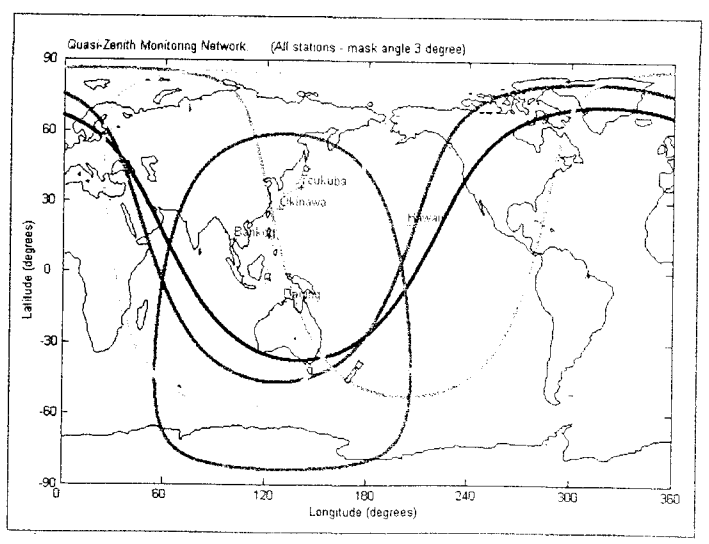


FIGURE 5 Preliminary location of tracking stations used for QZSS simulation

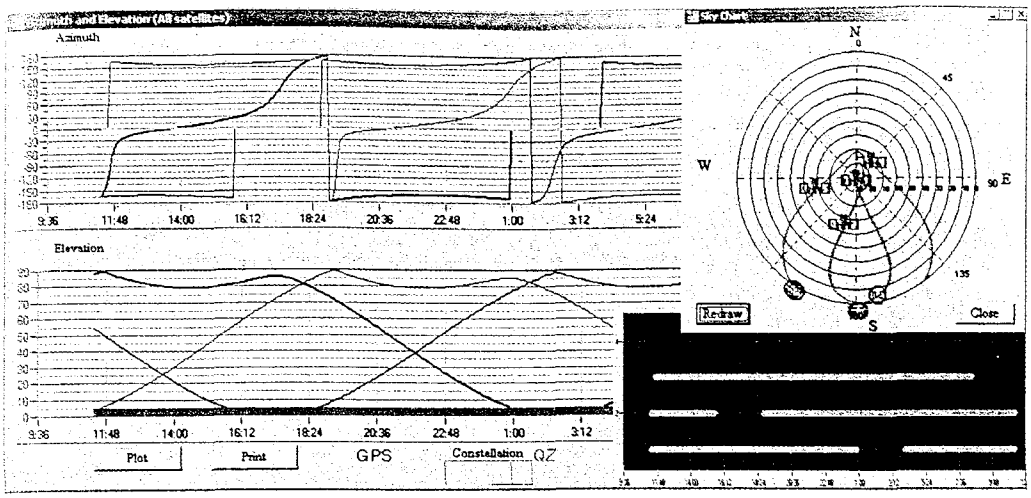


FIGURE 6 Azimuth, elevation, visibility, and sky chart for various QZSS orbits.

for purposes of simulations. (Because this configuration is not optimal, it will almost certainly not be the final tracking network design.) At the moment the *asymmetrical* 8-shape orbit appears to be a more probable candidate. This orbit goes about 400 kilometers below the geostationary satellites belt and therefore requires less frequent collision avoidance maneuvers in comparison with a *symmetrical* 8-shape orbit. However, satellites should be monitored for a collision risk at orbit intersections, which is not the case for tear-drop shape orbits.

The asymmetrical 8-shape orbit also gives better characteristics for positioning service due to superior geometry. It also has better performance for purposes of ambiguity resolution due to improved satellite visibility, geometry, and azimuth-elevation dynamics, that is, quicker satellite movement relative to a user. **Figure 6** shows azimuth, elevation and visibility graphs for this constellation and sky chart for number 3 and 4 types (from Figure 3) in Tokyo. It also can provide potentially better ephemeris estimation, because of better satellite to monitoring network geometry.

A QZSS Simulation Tool

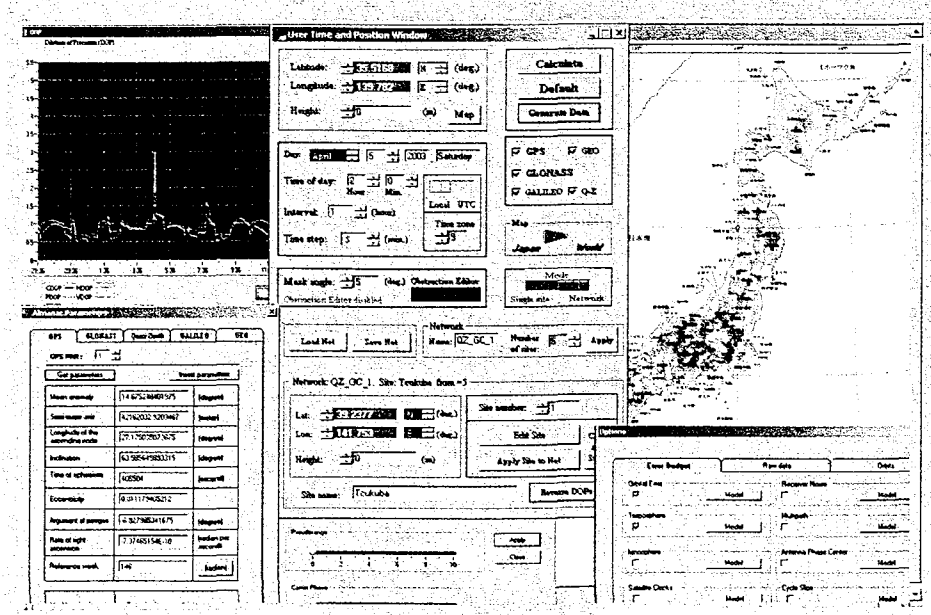
GNSS Technologies Inc. is developing a QZSS software simulation tool to evaluate various options for all QZSS components during the feasibility study stage. The software will provide a shell graphical user interface with source code to the organizations that are engaged in QZSS development. It also incorporates several libraries that allow users to generate QZSS data in the form of pseudoranges, Doppler, and carrier-phase observations for single users or networks. The libraries allow users to simulate orbital errors, satellite clock errors, signal propagation errors, receiver-specific errors, and multipath.

Among the software's distinctive features is its ability to simulate QZSS together with GPS satellites, providing users with the opportunity to incorporate real GPS data. System developers must get around a significant problem, however: Part of the error budget in the QZSS signal is strongly correlated with that of the GPS. These errors should be the same in QZSS error model and GPS real data. For example, atmospheric error, multipath, and receiver specific error will be correlated for QZSS and GPS. Therefore, if GPS data came from the measurements and QZSS data have been simulated, we should provide that these errors are correlated for both data.

The software optionally may use simulated ionospheric and tropospheric data, or these errors can be generated from the real data from the GeoNet reference station network. A user can modify atmospheric errors according to the specific task. When the user simulates several reference stations, the software also simulates correlated area errors for the network rather than limiting the user to separate station models with modified parameters.

The program allows users to substitute the software's models with their own models. First they input coordinates for the network, specify time, interval of simulation, and sampling interval. Then users can choose relevant errors and error models. The accompanying screen capture images give examples of software input and visualization panels. The software outputs data in RINEX (Receiver Independent Exchange) format, which then is processed using the Bernese GPS software package.

Users can estimate the accuracy of orbit determination, where the calculated ephemerides are compared with true ones. Users also can analyze the effect of various QZSS components designs on the achievable accuracy. GPS observations can be generated by the software or received from a GPS receiver connected to a GPS simulator with the same input parameters as the simulation software, including an ionospheric model.



Input panel of the QZSS simulation tool developed for the project

Tracking Network

The accuracy of the system will directly depend upon the accuracy with which one can determine QZSS satellites' orbits. To provide real-time ephemerides for QZSS, a network has to be constructed. The task is complicated, because the satellite-to-groundstation geometry for a regional network is much worse than for global networks as in the case of GPS and GLONASS.

The QZSS design calls for three types of tracking networks. The first is a part of the control segment and responsible for collecting data used to provide the system with broadcast ephemerides, QZSS satellite clock models, and clock differences to GPS system time. These data will be uploaded to QZSS satellites for incorporation into the navigation message. This network has to have very high integrity. For its geodetic coordinate system, the QZSS will use the International Terrestrial Reference Frame (ITRF) or the Japanese Geodetic Datum (JGD-2000), which is linked to ITRF. Apart from this, the system should provide an overlay system functionality for GPS, including GPS satellite clock corrections. As the next step QZSS also can provide the same functions for GALILEO and GLONASS, including time shifts to GALILEO and GLONASS system time.

The second network serves to provide enhanced functionality with precise ephemerides. The proposal for this network would establish a regional component with about eight stations to track the QZSS satellites and a global component with 25 stations to monitor the GPS constellation. The QZSS will use the third network to collect atmospheric data. It consists of 20 reference stations in Japan during the first stage and 10 reference stations outside Japan in Asia. The current plan calls for use of Japan's Geographical Survey Institute (GSI) GeoNet network with more than 1,200 GPS reference stations to generate carrier phase corrections. Three or four laser ranging systems will also be used for test and initial QZSS calibration.

The development of this ground network includes selection of the optimal design for tracking station locations. To do this, we need to estimate available user accuracy based on the tracking station locations. We also have to analyze the proposed network based on the inverse visibility study (satellite to reference stations) in terms of possible accuracy of ephemeris estimation (based on geometry), and visibility and availability of reference stations for QZSS and for GPS.

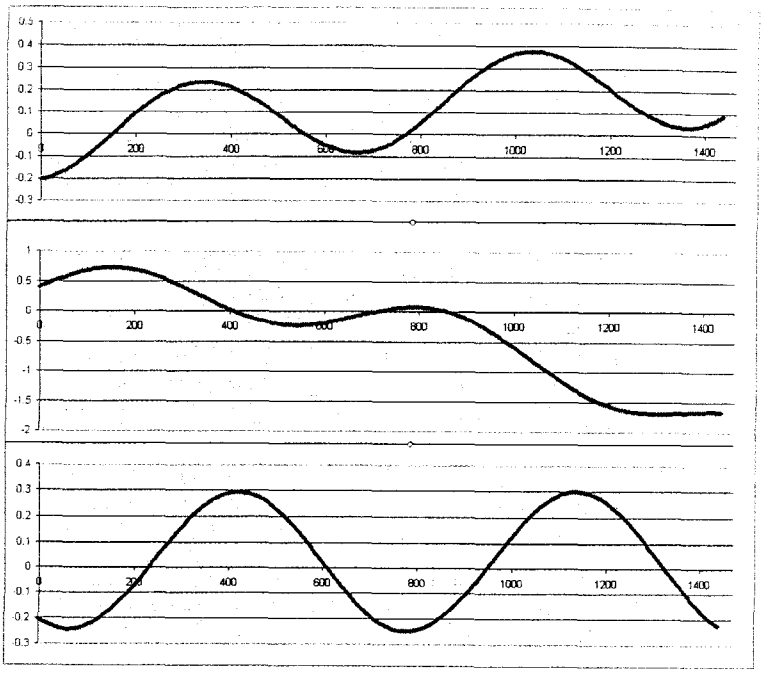


FIGURE 7 Error components (from top: cross-track, along-track, radial) of estimated QZSS satellite position for 12-hour data arc. (Vertical scale in meters.)

For example, we used our simulation software and Bernese GPS postprocessing software to analyze whether the tracking-station network can estimate a QZSS ephemeris and, if so, with what accuracy. We simulated the asymmetrical figure-8 QZSS orbits. Using a disturbed orbit as an initial guess for orbit estimation with the Bernese software, we estimated a QZSS ephemeris on the basis of simulated measurements from the given network of reference stations (as shown in Figure 2) with decimeter-level accuracy.

The simulation verified the QZSS orbit's observability from the given tracking network. GPS ephemerides had been fixed to International GPS Service (IGS)–precise orbits. We concluded that an attempt to improve GPS orbits using the QZSS regional network gives less-accurate results in comparison with IGS orbits. Figure 7 shows the estimated position errors (from top: cross-track, along-track, radial) for QZSS satellites over a 12-hour period.

The QZSS project will require international cooperation in order to provide places to locate tracking stations. The development of the algorithm for differential service and precise ephemeris estimation is expected to be done in cooperation with NASA's Jet Propulsion Laboratory (JPL).

A Matter of Time

The quality of QZSS differential corrections depends partly on the type of time synchronization, the quality of onboard clocks, and the frequency of uploads from the ground control segment. QZSS System Time will be aligned to the Japan UTC (CRL). QZSS navigation messages will provide time correction to GPS system time, either directly or through UTC (USNO). Depending on the eventual QZSS implementation, the navigation message can transmit an explicit clock model or an overall error correction can be broadcast. Clock accuracy and the data processing burden will vary as a function of the frequency of uploads.

As part of the overall QZSS test program, QZSS time comparison equipment, developed by the Communication Research Laboratory (CRL), will be placed onboard ETS-VIII and evaluated. This equipment will provide time comparison, using two-way time transfer (TWTT) over S-band, with accuracy better than 1 nanosecond. This equipment will be used in QZSS to assist time synchronization.

Different options for satellite clocks under consideration now. Use of high-accuracy atomic clocks would allow the system to operate for some time without ground support in case of emergencies, such as earthquakes, in which uploads from ground control were unavailable. It will also provide the capability to improve estimation of orbits through better clock error modeling. A system based on low-accuracy clocks has no prototypes but basically could work in a similar fashion to pseudolites, for example, providing users with co-transmitted clock corrections. The satellite clocks also will be a factor in the determination of QZSS satellite lifespan, the requirement for which is 12 years.

Differential Correction Service

In considering the QZSS differential correction service, we should highlight the differences from the WAAS-like MTSAT (multi-functional transport satellite) Satellite-

Based Augmentation System (MSAS). In terms of ranging service, QZSS will provide better geometry and more frequencies, which will allow direct estimation of ionospheric errors. Moreover, QZSS plans to follow GPS signal modernization, in which case civil codes with higher chip rates than the L1 C/A-code will be available on L2 and L5 in the near future. Apart from this, QZSS will have its own system time and therefore provide potentially better service.

Differences also exist between QZSS and MSAS in the way corrections are generated. The QZSS will have dissimilar content and format in the corrections messages. Ionospheric grids for QZSS will be generated differently, partly because many more reference points will be available in Japan. MSAS ionospheric corrections are based on global modeling, which demands less density of reference stations.

As with ionospheric corrections, QZSS will use a dense local grid for the tropospheric correction, rather than the global model used by MSAS. QZSS will use Japan's GeoNet network and generate more accurate atmospheric corrections by giving more weight to actual observations instead of modeling. These corrections are on satellite-by-satellite and epoch-by-epoch basis. QZSS will use the same grid data for all frequencies and for code and carrier phase corrections. In the Asian region outside Japan, however, QZSS will use global ionospheric modeling.

On the other hand, QZSS will not need the same high integrity level as MSAS, which has design requirements for safety-of-life applications. In any case, achieving this integrity level with QZSS would be difficult, taking into account the different infrastructure, onboard satellite clocks, constellation dynamics relative to monitoring network, and so on. Therefore, QZSS cannot substitute MSAS for safety-critical missions, but instead can provide more high-accuracy and diverse services.

Using the unique advantage of a very dense GeoNet reference station network in Japan, we are conducting a feasibility study to provide RTK corrections through QZSS, using area corrections grids. Apart from the grid data, the RTK corrections will incorporate one or several data streams from artificially created reference stations (ARS). Although operated at the same position as a real reference station, an ARS can provide data for a satellite which is not visible from the receiver location. To remove orbital errors from data, the precise ephemeris is estimated and transmitted to the user. The QZSS corrections from two sub-streams (one includes ionospheric corrections, another – orbital) applied to the ARS data are intended to bound the overall errors sufficiently to allow users to implement conventional RTK approaches.

Conclusion

An Advanced Space Business Corporation team including MELCO, Hitachi, NTS and GNSS Technologies, is currently working on a clarification and definition of requirements for the QZSS, which then will be submitted to related governmental institutions. A definition study will continue approximately until June of 2004 when basic business models and system design will be specified.

Acknowledgements

The availability analysis over 3D map was performed using software developed by the laboratory of Prof. R. Shibasaki. The authors would like to acknowledge Dr. Yoaz Bar-Sever for helpful discussions and the preparation of cooperation with JPL. We would also like to acknowledge Mr. Bryan Townsend for participation in network error modeling for G-Sim and Dr. Urs Hugentobler of Astronomical Institute of Bern University for practical discussions on precise orbit estimation. ⊕

Manufacturers

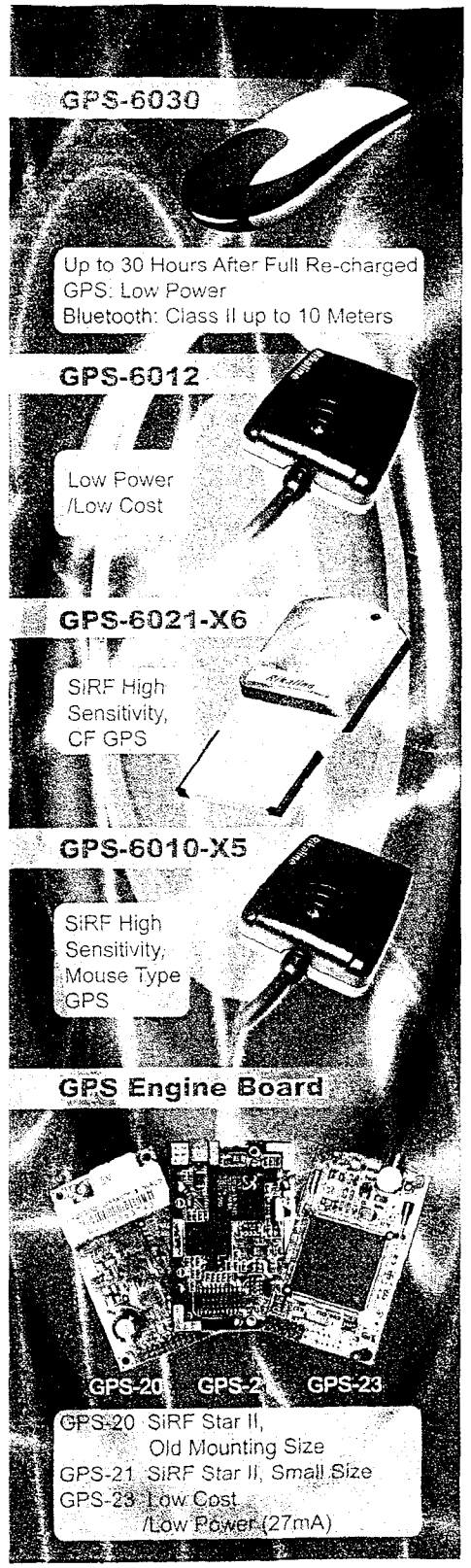
The signal-availability analysis in Figure 2 was done using 3D *DiaMap* by **Mitsubishi Corporation.** Figures 1, 3, 4, 6, and 7 were produced using *G-Sim*, a QZSS simulation tool from **GNSS Technologies Inc.**, Tokyo, Japan, developed by the first author.

Some network RTK software modules and libraries for ionospheric and tropospheric corrections for G-Sim and the QZSS-RTK ARS feasibility study were developed by **Forgis Technologies Inc.**, Calgary, Alberta, Canada.

We also used an *STR 4760* GPS simulator from **Spirent Communications,** Paignton, UK.

Further reading

Isao Kawano, "Satellite Positioning System using Quasi-Zenith and Geostationary Satellites" (Japanese language). *Transactions of the Institute of Electronics, Information and Communication Engineers, Vol.J84-B* December 2001.



Rikaline

Rikaline International Corp.
Web: www.rikaline.com.tw
E-Mail: info@rikaline.com.tw

Tel: ++886 2 2370 4688
Fax: ++886 2 2370 4686
Add: 10F, No.64, Kang-Ding Road, Taipei, Taiwan 108, R.O.C.

Circle 66