Technology of Precise Orbit Determination

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Since 1971, most domestic orbit determination systems have been developed by Fujitsu and its technology is highly evaluated by people involved in the field. In the mid-1990s, with the increased precision and sophistication of satellite Earth observations there was a need for greater accuracy in determining orbits that could not be provided by conventional systems. Thus, the Japan Aerospace Exploration Agency (JAXA; formerly known as the National Space Development Agency of Japan) has planned the development of a Global and high accUracy Trajectory determination System (GUTS), which uses GPS and satellite laser ranging (SLR) technology. Fujitsu developed the core technology for this and operated the system. Furthermore, Fujitsu has been engaged in the operation of GUTS and is committed to maintaining and improving the precision of orbit determination technology through continuous improvement of this system.

This paper introduces the overview of the GUTS, core technologies related to orbit determination developed by Fujitsu and the current situation with regards to derived precision of orbit determination. It also describes the overview of a precise positioning experiment system based on our experience of using the core technology of GUTS.

1. Introduction

The satellites launched by domestic space development agencies are being operated within the framework of the task known as "tracking and control". Tracking and control means identifying the operational status of the onboard equipment in a satellite in orbit, appropriately controlling the satellite and maintaining it in the specified orbit. To achieve these things, it is essential to precisely determine the satellite's location and establish a link between a terrestrial antenna and the satellite.

The orbit determination described in this paper refers to the technology to precisely identify the movement of a satellite (its position and velocity). Since 1971, Fujitsu has been engaged in the field of orbit determination systems at the main domestic space development agencies. Until the beginning of the 1990s, the position accuracy requirements for satellites at an altitude lower than 1000 km had been in the order of several 100 m to 1 km. The systems supplied by Fujitsu satisfied such requirements.

In the mid-1990s, a higher level of sophistication and precision was required for the Earth observation missions of satellites. The optical observation and remote sensing of the Earth's surface using multi-spectrum observation as well as precise observation on a 24-hour basis using radio waves were implemented by the Advanced Earth Observing Satellite-II (ADEOS-II) and Advanced Land Observing Satellite (ALOS). The position determination accuracy requirements for orbit determination systems was less than 10 m for ADEOS-II and less than 1 m for ALOS, which could not be achieved by conventional technologies. To satisfy these requirements, the Japan Aerospace Exploration Agency (JAXA; formerly known as the National Space Development Agency of Japan) has planned the development of a Global and high accUracy Trajectory determination System (GUTS),[1),2)] which was a precise orbit determination system using Global Positioning System (GPS) data whose benefits had been demonstrated in the United States. Upon starting the conceptual design, Fujitsu participated in discussions and accumulated precise orbit determination technology through establishing GUTS.

The following sections of this paper outline the current status with regards to the GUTS system, core technologies of GUTS and the derived precision of orbit determination, and give an overview of the ongoing project for a precise positioning experiment system.

2. Overview of precise orbit determination technologies

In this section, one of the most familiar examples of precise orbit determination technology (a car navigation system) is introduced at first, followed by an explanation of a sophisticated version of such technology and the method of verifying the accuracy of a precise orbit.

2.1 Positioning using GPS satellites

A car navigation system is the most familiar example of positioning that uses GPS satellites. In a car navigation system, radio waves (the positioning signal) sent from GPS satellites are received by a GPS antenna in the vehicle and the vehicle's position is calculated based on that data. The observation data used for this calculation is called "pseudo range" and the calculation is carried out by multiplying the difference between the time of the satellite which is included in the GPS wave and the time of the GPS receiver in the vehicle by the speed of light. Because there is a difference between the GPS satellite's clock and the GPS receiver's clock in general, the range calculated in this process is called a "pseudo" range, and does not correspond to the actual range. Since the GPS satellite's position and the clock offset are broadcast from GPS satellites, four unknown variables (the three-dimensional position of the vehicle and the clock offset) are calculated in the positioning of the car navigation system, resulting in the need to receive positioning signals from at least four satellites simultaneously.

If seen from the altitude of GPS satellites (20 000 km), even satellites that move in an orbit with an altitude lower than 1000 km such as Earth observation satellites have a geometrical condition not much different from the terrestrial condition. Accordingly, the position and clock offset can be calculated using the same principle as that mentioned above.

2.2 Precise orbit determination

Because GUTS requires more precise position calculations than in the case of a car navigation system, it receives radio waves of two frequency bands that are sent from a GPS satellite and, for each of them, the calculation is carried out using more precise data called "carrier phase" in addition to the pseudo range. Further, because the accuracy of the GPS satellite's position and the clock offset broadcasted from the GPS satellite is insufficient, the GPS satellite's position and the clock offset are calculated more accurately by using observation data from ground GPS stations in various areas of the world.

Besides observation data, an extremely precise satellite dynamical model and observation model are necessary. In the case of GUTS, the dynamical model and observation model that comply with the latest version of the Technical Note at that time (IERS Conventions 1996) issued by International Earth Rotation and Reference Systems Service (IERS) were introduced. Some of the values used for these models may change on a daily basis, and so they need to be updated every day by acquiring the latest data from overseas servers.

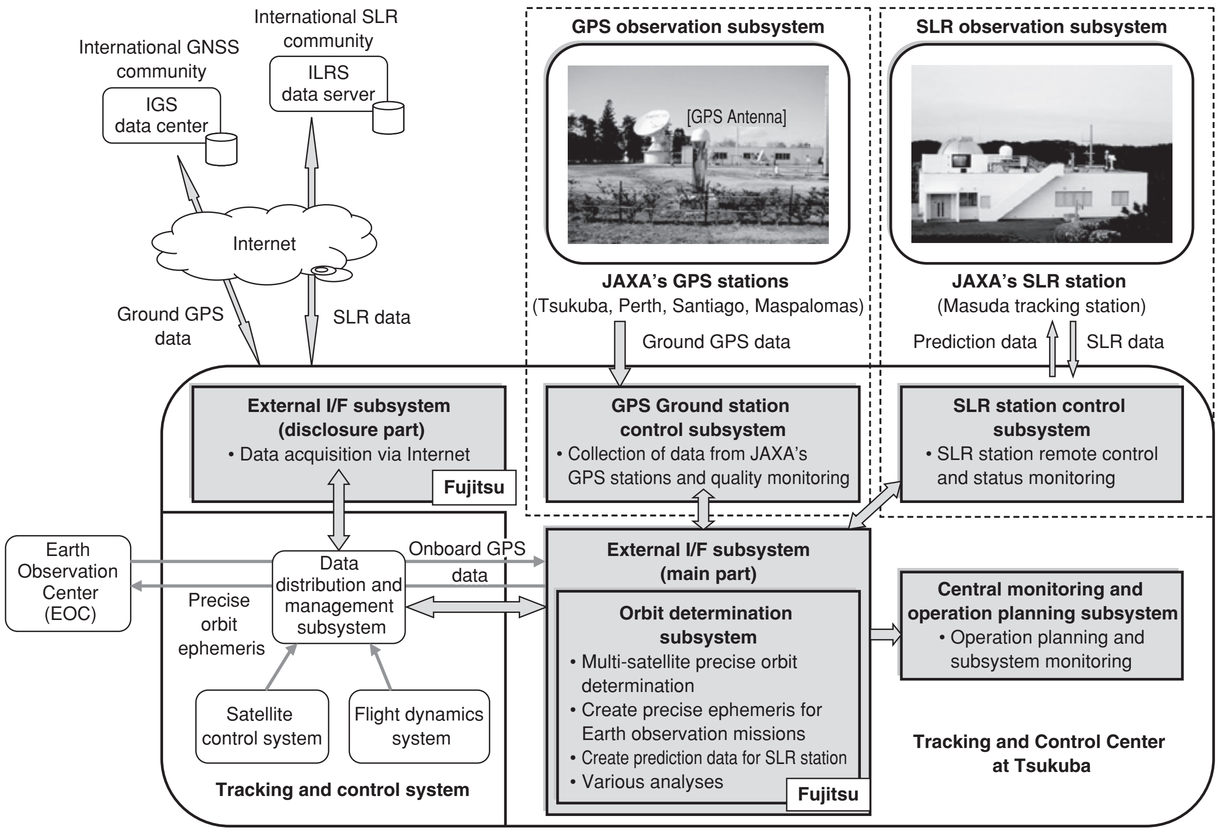

Figure 1
GUTS configuration.

2.3 Method for precision validation

While precise determination of a satellite's orbit is possible using GPS data, another means of observation with the equivalent precision is necessary to verify it. Satellite Laser Ranging (SLR) is often used for this purpose. SLR sends a laser of a short pulse width to a satellite and measures the time until the pulse returns to it after being reflected by a reflector on the satellite with a precision of less than ten picoseconds. In the case of low orbital satellites such as Earth observation satellites, the measurement precision is less than 1 cm.

3. Global and high accUracy Trajectory determination System (GUTS)

As mentioned in the previous section, the elements necessary for GUTS are a satellite with an onboard GPS receiver (user satellite), ground GPS stations, server computers for orbit determination and acquiring Internet data, SLR station, and various pieces of software for processing and operating precise orbit determination. In addition, because GUTS is planned to be configured as a highly automated system, there should be features to plan, execute and monitor observations on an unmanned basis. The system overview indicated in **Figure 1** was designed based on these concepts. The range of functions covered by GUTS in this figure is the five subsystems described below:

1) Central monitoring and operation planning subsystem, which plans operation schedule for orbit determination and SLR of GUTS and monitors status of each subsystem.
2) GPS observation subsystem, which is comprised of the JAXA GPS stations

in the Tsukuba Space Center (Japan), Perth (Australia), Santiago (Chile) and Maspalomas (Canary Islands); and a GPS station control subsystem for collecting data from these stations.

3) SLR observation subsystem, which is comprised of a JAXA SLR station in Tanegashima (Japan) and an SLR station control subsystem for remote-controlling this station.
4) Orbit determination subsystem, which precisely determines and evaluates a satellite's orbit by using GPS and SLR data.
5) External interface subsystem, which distributes precise orbit information of satellites for users besides receiving various data necessary for orbit determination from the Internet and other systems in the Tsukuba Space Center.

3.1 Acquisition of technologies at conceptual design phase

Fujitsu has been involved with GUTS since the beginning of its conceptual design phase in 1994. During the conceptual design phase, Fujitsu accumulated precise orbit determination technologies for research of the basic technologies mentioned in the previous sections through activities such as conducting research based on the latest literature[3] and visiting the Jet Propulsion Laboratory (JPL) in the United States. Further, since 1996, Fujitsu has accumulated orbit determination technologies using SLR by improving the existing orbit determination systems (NOCS2) and conducting orbit determination experiments based on SLR data to verify various SLR-related models.

3.2 Subsystems developed by Fujitsu

Upon completing the conceptual design phase as mentioned in the previous paragraph, Fujitsu started development of the orbit determination subsystem and the external interface subsystem from 1997 and announced the results in 2000.

The orbit determination subsystem had a client-server configuration comprised of Windows PC clients, UNIX computation servers and a data accumulation server.

Clients are equipped with a user interface application.

Precisely determining orbits requires large matrix processing so the computation server performs parallel processing with multiple CPUs.

The file management function of the data accumulation server has a portability focusing on the analysis application, allowing optional configuration by the analyzing party as required without any administrator authority.

The external interface subsystem obtains various data necessary for orbit determination from various servers on the Internet. A series of security countermeasures are being implemented based on Fujitsu's know-how, for example, unnecessary ports are closed on the external interfaces.

4. GUTS core technologies

This section describes the GUTS core technologies that have been mastered by Fujitsu. There are six core technologies: preprocessing of observation data, nominal orbit determination, orbit generation, theoretical calculation of observed data, rejection of bad data using observation residuals, and batch sequential filter and smoother.

1) Preprocessing of observation data

In the preprocessing process of observation data, GPS data obtained from GPS receivers on ground GPS stations and user satellites, and SLR data obtained from SLR stations are preprocessed. The preprocessing algorithm shown in **Table 1** is used.

2) Nominal orbit determination

While the orbit estimation of the satellites has a non-linear nature and is based on estimates of a large number of variables, linear processing is conducted to reduce the computation time.

Table 1
List of preprocessing algorithms.

Algorithm	Description
Carrier smoothing	Decreases error of pseudo range data using carrier phase measurements
Detection and correction of cycle slip	Detects slip of carrier phase and corrects the slip as much as possible
Ionospheric delay correction	Disable effect of ionospheric delay using so-called ionospheric-free linear combination
Correction of phase center variation[note)]	Corrects elevation dependency of GPS antenna
DCB correction[note)]	Corrects bias factors specific to GPS transmitter that are included in pseudo range data
Quality check[note)]	Checks quality of each GPS station and determines the best configuration of GPS stations for orbit determination

note) Staged extension in the process of GUTS operation

Because the difference from the initial value is estimated in linear processing, only a poor convergency is obtained when the initial value widely deviates from the true value, resulting in even a wrong convergence point in some cases. For this reason, the initial value should be as close as possible to the true value. The nominal orbit determination is an algorithm to obtain the initial orbit of each satellite which is close to the true value based on the GPS satellite's position broadcast from the GPS satellite and the navigation data (satellite position) of the onboard GPS receivers of satellites such as ALOS.

3) Orbit generation

Precise computation of a satellite's orbit is carried out through numerical integration by adding various dynamical models shown in **Table 2**. As mentioned before, the precise orbit generation for an initial orbit has significant influence on the accuracy of the satellite's orbit determination.

4) Theoretical calculation of observed data

Theoretical calculation of GPS observed data (pseudo range and carrier phase) and SLR observed data (laser beam round-trip time) is carried out by giving consideration to various models and observation residuals (difference between the observation data and the theoretical value) necessary for estimation is generated. The models used for the calculation of theoretical value are shown in **Table 3**.

5) Rejection of bad data using observation residuals

Double difference value often used for differential GPS[note 1)] is used to judge and reject bad data from GPS data. Meanwhile, in the case of SLR data, the time-series shape of observation residuals is used. These algorithms are developed from analysis of the actual data obtained during operation, and greatly contribute to system automation.

6) Batch sequential filter and smoother

Parameters estimated in the precise orbit determination consist of various coefficients listed in Table 2 and Table 3 in addition to the satellite's position and velocity and clock offset. The number of parameters reaches approximately 1000 in total. The estimation processing is basically an array calculation and to reduce the computation workload, technologies such as batch sequential filters and smoother and pseudo epoch are used.

5. Accuracy of precise orbit determination

Since the initial release of GUTS in October 2000, Fujitsu has been engaged in operations and experiments related to precise orbit determination using this system. In the operation of precise orbit determination, stable operation of ALOS has been realized within the required level of accuracy and significant contributions have been made in image processing of Earth remote sensing data. Meanwhile, in the experiments

note 1) A method where a GPS receiver is arranged at a point whose position is precisely known and a location whose position you want to measure, and the relative position of these two points is calculated precisely based on the difference of the data obtained from each of these receivers.

Table 2
List of dynamical models.

Model	Description
Earth gravity potential[note)]	Model of uneven density inside the Earth
Gravity of other astronomical objects	Gravity of the Sun, the Moon and all the planets
Tides	Variation of Earth's gravity potential caused by the tidal effects (solid earth tide, ocean loading and tidal effect by polar motion are available)
Solar radiation pressure	Effect of acceleration generated when solar photon hits the satellite body GPS satellite: GPS-specific model[note)] User satellite: sphere + polyhedron model
Earth radiation pressure	Effect of acceleration generated by albedo and radiation of Earth's infrared beam GPS satellite: GPS-specific model[note)] User satellite: sphere + polyhedron model
Air drag	Effect of acceleration generated when air molecules hit satellite body Affects low orbital satellites User satellite: sphere + polyhedron model
Relativistic effect	Variation of satellite acceleration caused by relativistic theory (Considers three models)
Empirical acceleration	Acceleration depending on the satellite period for which modeling is not possible
Satellite attitude	Considers attitudes of GPS satellites and user satellites

note) Staged extension in the process of GUTS operation

Table 3
List of observation models.

Model	Description
Bias	Considers pseudo range, carrier phase and SLR bias
Satellite attitude	Considers attitudes of GPS satellites and user satellites
Variation of center of mass position	Considers variation of center of mass position accompanying the satellite operation
Tropospheric delay[note)]	Effects of radio wave delay owing to troposphere (considers zenith delay and mapping function)
Tropospheric gradient[note)]	Tropospheric delay model considering distribution of atmospheric pressure and humidity near terrestrial GPS stations
Phase center offset and optical origin offset	Coordinate offset between satellite center of mass and phase center of GPS antenna or reflection point of laser reflector
Tides[note)]	Variation of station position owing to the following factors: solid earth tide, ocean loading tide, and tidal effect caused by polar motion *While the system was compliant with IERS Conventions 1996 at launch, it is compliant with IERS Conventions 2003 currently
Plate motion	Considers variation of ground GPS stations and SLR stations caused by plate motions
Polar motion	Variation caused by Earth's rotational axis (IAU1980 compliant)
Clock offset	Clock offset between satellites or ground GPS stations and a ground reference GPS station
Relativistic effect	Deviation of propagation time of positioning signal Clock drift caused by satellite velocity and eccentricity
Correction of phase rotation[note)]	Correction of phase drift owing to rotation of the recipient side, when GPS signal with right-hand circular polarization is received by user satellites or ground GPS receivers

note) Staged extension in the process of GUTS operation

of precise orbit determination, technologies to precisely determine the orbits of various satellites have been mastered including those for GPS satellites, ADEOS-II, SAC-C, ALOS and GRACE-B. Further, Fujitsu has been engaged in researching the trends of various algorithms shown in Table 1 through Table 3, for which international researchers have continuously made efforts for improvement so that the latest trends can be reflected in the system to enhance its accuracy.

The targeted accuracy of GPS satellites is of a level where the deviation from the values published by the Analysis Center of International GNSS[note 2)] Service (IGS) is maintained within 5 cm RMS[note 3)] on a stable basis. IGS is an organi-

note 2) Global Navigation Satellite System.
note 3) Root Mean Square.

zation that publishes precise positions of GPS satellites. At the start of the GUTS experiments, the deviation was 30 cm RMS. Thereafter, tuning of the estimation parameters and the addition of new algorithms have made it possible to achieve the targeted accuracy in near future.

The accuracy achieved by low orbital satellites is approximately 40 cm RMS[4] by ADEOS-II, 30 cm P-P[note 4), 5)] by ALOS, and 4 cm RMS[6] by GRACE-B. Concerning ADEOS-II and ALOS, which gave us the incentive to establish GUTS, we achieved an excellent accuracy that significantly exceeded the required accuracy. While correct modeling of the complicated satellite shape, mass change and attitude control operation (yaw steering) were the challenges to be addressed by ALOS, the above-mentioned accuracy was finally achieved by overcoming these challenges.

6. Overview of precise positioning experiment system

In the meeting of the Committee on Space Development held in March 1997, a decision was made to start domestic development of a new positioning technology equivalent to GPS using positioning signals from satellites. The positioning technology using positioning signals from satellites approached by Japan has an objective to improve the available time for positioning signals in Asia and Oceania by reinforcing and supplementing the GPS positioning system. For this purpose, geostationary orbits and quasi zenith orbits are suitable as satellite orbits. There are three core technologies necessary for the satellite positioning system: onboard atomic clock, time management technology of multi-satellites, and technology of precise orbit and time determination. Although basic technologies have been established in the framework of GUTS about the last two elements, they need to be more sophisticated to be used in the positioning system. Namely, instead of working off-line, the orbit and clock should be estimated on a real-time basis. Then, the determined orbit and time information should be uploaded to the satellites and modulated with the positioning signals so that the information can be delivered to the positioning users.

By using the technologies accumulated through GUTS, since 1999 Fujitsu has been participating in the development of ETS-VIII and HAC experimental ground system (**Figure 2**), which is an experimental satellite positioning system and announced the results in 2003. In addition, Fujitsu has just started developing the positioning part in the quasi zenith positioning experiment system, which is a practical satellite positioning system.

7. Conclusion

This paper introduced the precise orbit determination technologies that Fujitsu has accumulated through its involvement in the establishment, operation and experiments of GUTS.

The responsibility of Fujitsu in the precise orbit determination-related systems ranges from the planning phase of system implementation to system operation. GUTS cannot be implemented or operated without core technologies for a flight dynamics system. Fujitsu has a great advantage because it acquired these technologies ahead of its competitors. In this process, Fujitsu has succeeded in gaining customers' trust through its commitment to finding solutions for various problems and challenges with customers. Particularly in the technologies for using GPS and for operating positioning systems, Fujitsu has maintained close tie-ups with the customers to address these challenges. Fujitsu is eager to keep such close relationships with its customers also in the ongoing development of a quasi zenith positioning system and flight dynamics system

note 4) Peak-to-Peak. If the distribution of errors indicates a normal distribution, it is equivalent to six times the RMS.

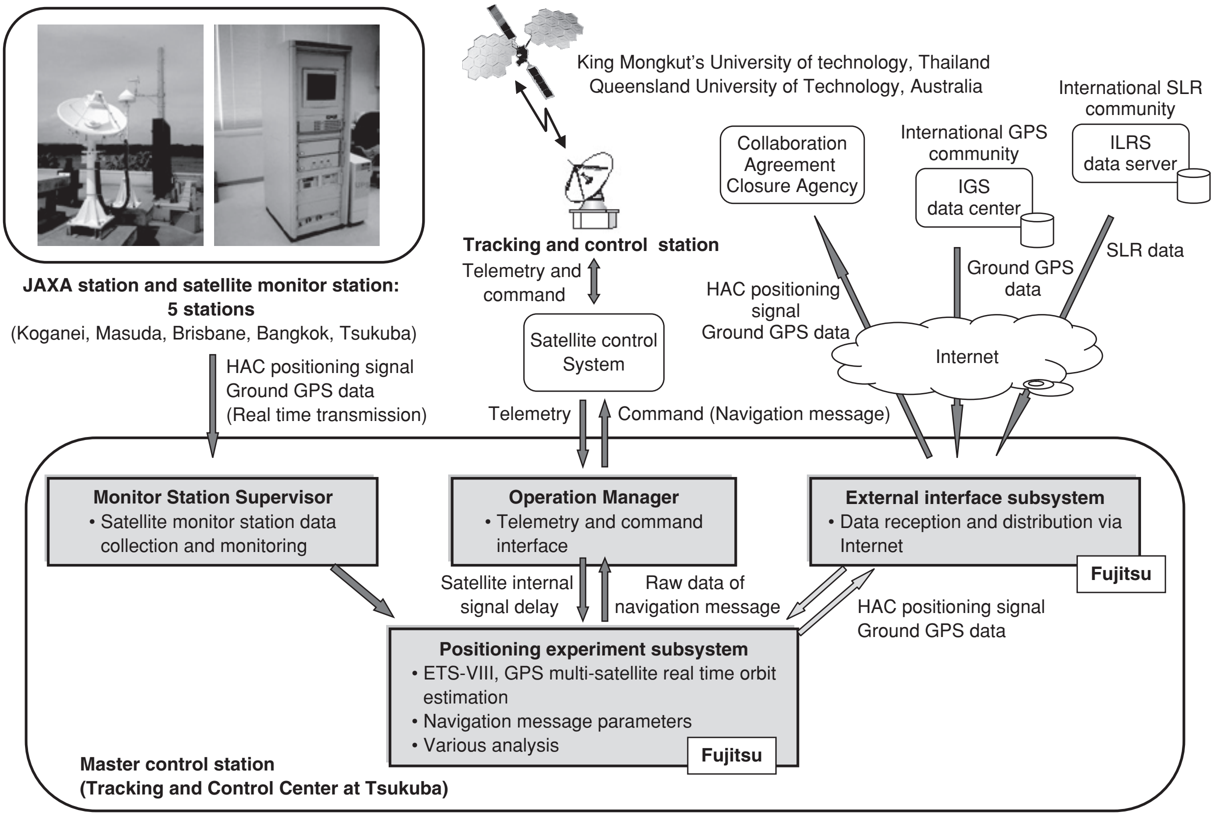

Figure 2
HAC experiment ground system.

for space Very Long Baseline Interferometry (VLBI) satellites (ASTRO-G).

To conclude this paper, we would like to express our deep appreciation to the people in the Consolidated Space Tracking and Data Acquisition Department in the Japan Aerospace Exploration Agency for their great support and cooperation which helped us to master the precise orbit determination technologies described in this paper.

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