Fujitsu's Technologies and Systems for Orbit Determination, Prediction, and Analysis

● Seiji Katagiri ● Chiaki Aoshima ● Takafumi Ohnishi ● Yosuke Yamamoto

Advancements in space technologies have led to a broadening in the scope of exploration missions and in the operations of artificial satellites. Satellites now require precise orbit determination, prediction, and analysis using flight dynamics technologies, and the requirements for these technologies are becoming more and more complex, sophisticated, and diverse. Fujitsu has long participated in Japan's space exploration program and has made contributions to the development of orbital dynamics calculation systems for satellite operations. Our efforts continue today as we develop various systems such as orbit determination/prediction systems for reliably locating and tracking satellites and systems for precisely determining the orbits of space probes more than 400 million km from Earth. This paper presents the technologies and systems we have developed for determining, predicting, and analyzing the orbits of artificial satellites and space probes. The paper also describes relevant case studies and mentions the latest trends.

1. Introduction

Space development in Japan began in earnest with the establishment of the National Space Development Agency of Japan (NASDA)[note)] in 1969. Artificial satellites lie at the core of space development, but the determination, prediction, and control of satellite orbits require complex computations. Wishing to play a part in space development, Fujitsu moved into system development by delivering general-purpose computers to NASDA and developing orbit determination techniques.

In this paper, we describe orbit determination, prediction, and analysis technologies that are essential for operating satellites and probes and introduce Fujitsu's orbit determination systems developed with these technologies. We present case studies of applying these technologies and touch upon the latest trends in this field.

note) In 2003, NASDA, the Institute of Space and Astronautical Science (ISAS), and the National Aerospace Laboratory of Japan (NAL) merged to establish the Japan Aerospace Exploration Agency (JAXA).

2. Purpose and roles of an orbital dynamics calculation system

The operation of an artificial satellite combines the "satellite system" in space consisting of the satellite itself and mounted devices and the "ground system" on earth that issues instructions to and receives/processes data from the satellite. The ground system includes the "orbital dynamics calculation system," which has the important roles of calculating and providing essential orbit information (accurate information on the satellite's past and future flight path) for the "satellite operation system" that directly controls and operates the satellite and the "mission data processing system" that prepares information for system users (**Figure 1**).

The orbital dynamics calculation system performs physical simulation of satellites in space. Using Newtonian dynamics, it performs detailed modeling and computer simulation of a variety of physical phenomena such as the deceleration effect of a rarefied atmosphere on a satellite, time offsets associated with relativity theory, and wobble in the Earth's rotation. This system has three major roles:

1) Orbit determination

The first role is accurately determining the orbit of the target satellite for a fixed period in the past and providing actual-orbit information to mission data processing.

2) Orbit prediction

The second role is calculating the future orbit of the satellite using the results of orbit determination and a physical model of space. The results of orbit prediction are used to create orbit-related information necessary for operation planning (e.g., antenna-drive angle predictions for locating and tracking the satellite from a ground station and information on when and where in the sky the satellite will pass) and long-term orbit-prediction values for creating mission observation plans.

Orbit prediction can also be used to devise an orbit control plan so as to align the future orbit with the originally planned orbit.

3) Orbit analysis

The third role is evaluating the accuracy of orbit determination and orbit prediction. This includes pre-analysis for establishing an operation plan and post-analysis for statistically evaluating the results of processing actual operation data. It may also include estimating and evaluating parameters other than those of the satellite orbit as in gravity field estimation for use in orbit determination.

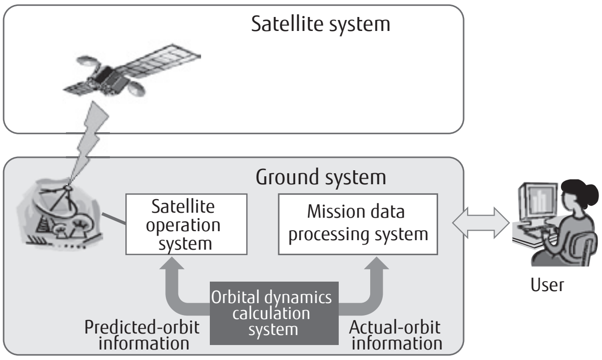

Figure 1
Role of orbital dynamics calculation system.

3. Development of orbital dynamics calculation systems at Fujitsu

Fujitsu's involvement with orbital dynamics calculation technology began around the time that NASDA was established (**Figure 2**). Since being commissioned by NASDA to develop an orbital dynamics system for earth orbiting satellites, Fujitsu has made a variety of functional extensions and algorithm upgrades. It has been continuously in charge of development work for orbital dynamics calculation systems for about 40 years.

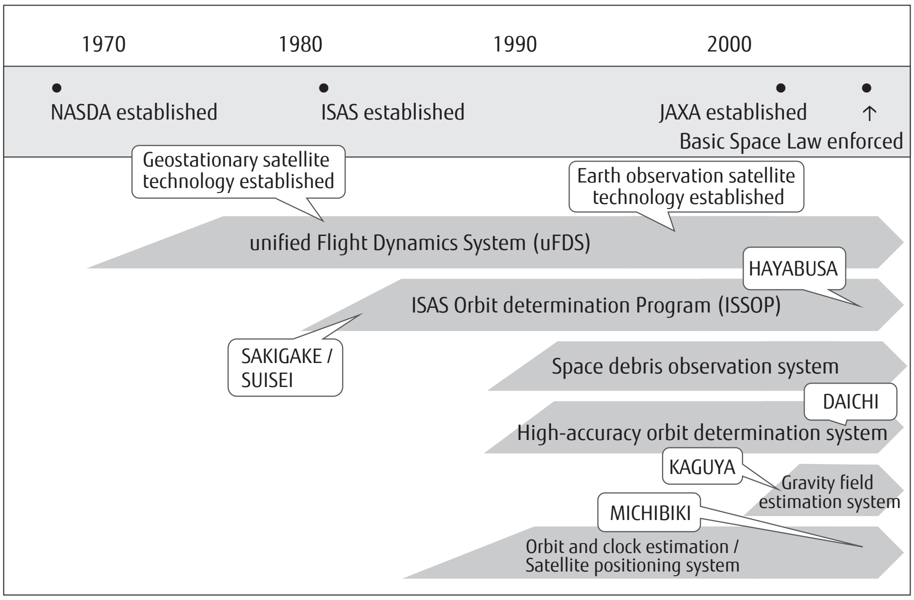

Figure 2
Development of Fujitsu's orbital dynamics calculation system.

The 1980s saw the establishment of the Institute of Space and Astronautical Science (ISAS), independent of the University of Tokyo. It was in this period that Fujitsu developed the ISAS Orbit determination Program (ISSOP) for ISAS scientific missions exploring celestial bodies other than Earth. The ISSOP system has undergone a number of functional improvements and is still being used for advanced deep-space missions.

In the 1990s, attention began to turn to the problem of space debris. At the same time, the GPS constructed by the United States went into initial service and began to be used for orbit determination of low earth orbit satellites. To keep up with these developments, a space debris observation system and high-accuracy orbit determination system were developed at NASDA (Figure 2). Each of these systems handled an amount of data or computational complexity about 10^8 times that of the existing core system, and Fujitsu responded by providing world-class computers and orbital dynamics calculation technologies.

The 2000s can be called an era in which the technologies developed to date came to be known by the public at large. The first orbit and clock estimation system for the Quasi-Zenith Satellite-1 "MICHIBIKI," of the Japanese GPS system, was achieved by using the algorithms of the high-accuracy orbit determination system. Meanwhile, gravity field estimation for the SELenological and ENgineering Explorer (SELENE) "KAGUYA" lunar orbiters was achieved by merging the unified Flight Dynamics System (uFDS) with deep-space orbit determination technology (**Figure 3**). In addition, a new computational model was added to ISSOP for the Asteroid Explorer "HAYABUSA" (MUSES-C) and the Venus Climate Orbiter "AKATSUKI" (PLANET-C) to enable these probes to be placed into their target orbits.

4. Features of developed systems

The various orbital dynamics calculation systems developed by Fujitsu have a number of advanced features.

4.1 unified Flight Dynamics System

The uFDS developed by Fujitsu is a JAXA system that performs all three roles described above. Here we describe the method used for orbit determination.

Range data has historically been used to determine the orbit of earth orbiting satellites. Nowadays though, the position estimated by a GPS receiver mounted on the satellite is commonly used to determine the orbit. Nevertheless, range data is still used for orbit determination immediately after launch and as backup in the event of a faulty GPS receiver.

Range data is obtained by measuring the time taken for a radio signal to be transmitted from a ground station to the satellite and retransmitted from the satellite back to the ground station and converting that time to distance. For satellites without a radio transceiver but with a laser reflector, range data is obtained by using an optical telescope to measure the round-trip time of laser light projected at the satellite and reflected back.

An artificial satellite in orbit is subjected to a

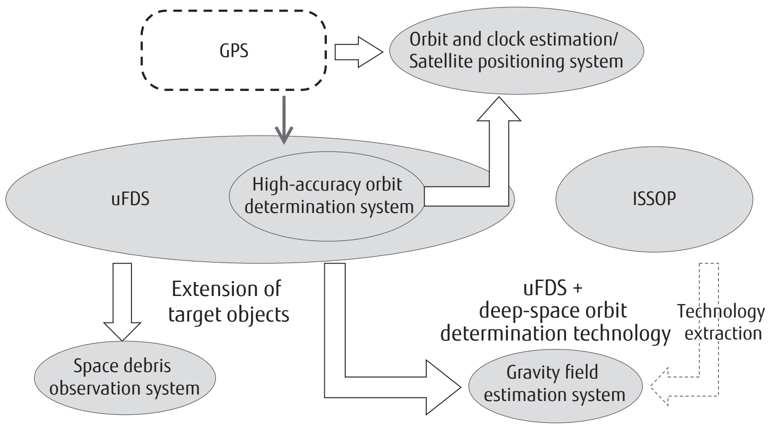

Figure 3
Evolution of orbit determination technologies (systems).

variety of forces (gravitational pull, radiation pressure, and atmospheric drag). Additionally, a ground station viewed from space moves in accordance with the rotation of the Earth, and radio waves or laser light exchanged between a ground station and satellite are affected in various ways as they pass through the Earth's ionosphere and atmosphere. Orbit determination based on range data or positions estimated by a GPS receiver is therefore accomplished by modeling such phenomena and calculating the predicted distance and position, continuously comparing those predicted values with the actually observed distance and position, and using a least-squares method to fit the parameters expressing the satellite's orbit so as to minimize the difference between the actual and predicted values.

4.2 ISAS Orbit determination Program (ISSOP)

Orbit determination in the case of deep space flights supplements the use of range data with "Doppler data" obtained by measuring the Doppler effect, the change in frequency of radio waves making a round trip between the ground station and the probe. Since the ground station and probe both revolve around the sun at a speed of about 30 km/s, their relative speed is of the order of several tens of km/s, but the use of Doppler data makes it possible to measure their relative speed with an error of less than 1 mm/s. These high-accuracy measurement data and a rigorous calculation model make it possible to determine the orbit of a probe hundreds of millions of km from Earth.

Furthermore, for the Asteroid Explorer "HAYABUSA" (MUSES-C), which visited the asteroid Itokawa in 2005, optical data obtained by observing the asteroid from the probe were added to the scheme described above to perform orbit determination. As a result, the accuracy of determining the position of the probe, which was about 400 million km from Earth, was improved from a value of the order of several hundred km to several km, helping to accurately guide the probe toward the asteroid. In 2015, a new observation model called Delta Differential One-way Range (DDOR) was introduced in ISSOP[1)] and put into practical use for operation of the Asteroid Explorer "HAYABUSA2." Developed by NASA's Jet Propulsion Laboratory, the DDOR model consists of two widely separated ground stations on Earth that are made to simultaneously and alternately receive probe signals and quasar signals (a quasar is a celestial body that emits radio waves). Adding DDOR data to range data and Doppler data greatly improves the accuracy of probe positioning.

In addition, a maneuver monitoring system that performs real-time monitoring of changes in a probe's orbit plays an active role in the operation of lunar and planetary probes alongside the orbit determination system. This system performs simulations beforehand to calculate the changes that can be expected to occur in Doppler data at a ground station due to changes in a probe's orbit. Then, at the time of a planned change in orbit, the system monitors the Doppler data received at the ground station in real time and immediately determines whether the change in orbit has done according to plan, that is, whether the probe entered its target orbit. This maneuver monitoring system played a key role in inserting the Akatsuki probe into orbit around Venus in December 2015 by monitoring the orbit-control situation in real time. This made it possible to quickly confirm that orbit control had been executed as planned and to determine that no other control measures were needed.

4.3 High-accuracy orbit determination system

The high-accuracy orbit determination system estimates the orbit of an artificial satellite with high precision using positioning signals (pseudorange and carrier phase) in the L1 and L2 frequency bands transmitted by United States GPS satellites from an altitude of 20,000 km. The results of such high-accuracy orbit determination are used for creating high-accuracy images of the Earth's surface and a high-accuracy distribution of the Earth's sea level.

Fujitsu was first put in charge of developing this high-accuracy orbit determination system for the Advanced Earth Observation Satellite-II (ADEOS-II) "Midori-II" launched in 2002. For the Advanced Land Observing Satellite (ALOS) "DAICHI," a position determination accuracy within 0.31 m (3σ) was achieved. With this high level of accuracy, the system contributed to the processing of 2,100,000 images obtained with synthetic aperture radar (SAR) for observations made of regions around the world. It also contributed to accurate determination of crustal movement by a technique called SAR interferometry before and after the Great East Japan Earthquake that hit in March 2011 as well as to an understanding of disaster conditions and identification of inspection points in relation to that unprecedented disaster.[2)]

For the Advanced Land Observing Satellite-2 (ALOS-2) "DAICHI-2," Fujitsu improved the accuracy of the orbit determination system by enhancing the software model, enabling high-accuracy orbital data to be quickly obtained. The system is thus contributing to improvements in both accuracy and convenience. Initial evaluations following the launch of DAICHI-2 showed that the system helped to achieve orbit determination accuracy within 10 cm (1σ).[3)] DAICHI-2 recently contributed to swift understanding of disaster conditions after the Kumamoto Earthquake hit in April 2016.[4)]

Future missions involving wide-area land observations and sea level measurements are expected to use SAR interferometry and thus will require world-class orbit determination accuracies of 10 cm and 3 cm in terms of position and altitude, respectively.[5)] At JAXA, research and development of advanced algorithms continue with the aim of achieving these high levels of accuracy on a routine basis. Fujitsu has been involved in this research and development effort and has acquired new elemental technologies needed for high-accuracy orbit determination. In doing so, Fujitsu has contributed to achieving an accuracy level within 2 cm for position in orbit determination of GRACE (Gravity Recovery and Climate Experiment) satellites.[6)]

4.4 Orbit and clock estimation system

Users of a positioning satellite system, like the GPS operated by the U.S., can accurately determine their position and the time (hereafter, positioning) anywhere in the world as long as they can receive positioning signals from artificial satellites used for positioning purposes (hereafter, positioning satellites). In addition to car navigation and mobile phones, positioning satellite systems are finding use in diverse fields including transport, construction, and disaster prevention.

The Quasi-Zenith Satellite System (QZSS) is Japan's first positioning satellite system for commercial use. "MICHIBIKI," the first QZSS satellite, travels in an orbit not travelled by previous satellites. In this "quasi-zenith orbit," the satellite is overhead in the Japanese sky for about eight hours a day. It transmits positioning signals compatible with GPS and performs positioning in combination with GPS satellites. The idea behind this quasi-zenith orbit is to enable positioning from locations with a restricted view of the sky such as "canyons" in urban areas and valleys in mountain areas.

Since beginning service on June 22, 2011, MICHIBIKI has been transmitting accurate position and clock information for individual users without interruption. Fujitsu is involved in the system maintenance of the ground system of QZSS and developed the orbit and clock estimation system for positioning satellites. This system uses MICHIBIKI positioning signals received by monitoring stations at nine locations in Japan and elsewhere in the world as observation data to estimate in real time the satellite's position and clock offset (offset from standard GPS time). The results of these real-time estimates are used as a source of orbit and clock information transmitted by MICHIBIKI and in the monitoring of system health. The processing used for orbit and clock estimation is based on algorithms developed and enhanced in the high-accuracy orbit determination system.

The error in the observation data for the positioning user originating in the predicted values of MICHIBIKI's orbit and clock is called the signal-in-space user range error (SIS-URE). The combination of MICHIBIKI and GPS satellites results in a lower SIS-URE than that of GPS alone.[7), 8)] The average SIS-URE is 30 to 40 cm. Furthermore, taking measures such as implementing system redundancy can provide positioning satellite services with very high operation availability.

4.5 Space debris observation system

Since studies and construction of a space debris observation system began in the 1990s at NASDA, Fujitsu has been involved in the development of debris-related technologies. Debris orbit determination using actual observation data began experimentally with optical observations in 2000 and radar observations in 2004. Later, as the amount of debris in space began to increase dramatically, JAXA began implementing conjunction assessment of debris. JAXA is currently implementing a collision avoidance control plan for satellites on the basis of the results of the debris conjunction assessment (done by Fujitsu).

The amount of debris in satellite orbits is estimated to be of the order of several trillion pieces including several tens of thousands of pieces that can be tracked (10 cm or larger) and tiny pieces of debris that are difficult to track. Damage to solar array panels and radiator plates on the International Space Station due to debris collisions have been reported.[9] A collision between a large piece of debris and an artificial satellite or the International Space Station can cause significant damage. The importance and necessity of space situational awareness (SSA) is thus increasing on an international basis. Japan's Space Plan for Basic Policy (January 2015) calls for construction by the early 2020s of SSA-related facilities and development of an operational framework for SSA.

Elemental technologies envisioned for SSA include (1) technology for orbit determination of space debris using radar or optical observations, (2) technology for predicting the proximity of space debris to satellites and estimating the risk of collision, and (3) technology for predicting the time and location of reentry into the atmosphere for space debris that may fall to earth without burning up. Fujitsu has already developed these technologies and is in the process of developing an SSA system for JAXA.

4.6 Lunar gravity field estimation system

The basic idea behind orbit determination as a technology for estimating the orbit of an artificial satellite is to minimize the difference (observable residuals) between observation data and computer simulations based on an accurate model of acceleration forces acting on the satellite. Gravity field estimation is a technology that conversely takes the observable residuals obtained as a result of orbit determination and estimates an acceleration model that makes that difference even smaller. Fujitsu developed on contract from JAXA a "lunar gravity field estimation system" for estimating gravity distributions on the moon by statistically processing more than one year's worth of observation data from both sides of the moon obtained from the KAGUYA lunar orbiters. Additionally, from 2007, Fujitsu engaged in JAXA-commissioned joint research with the National Astronomical Observatory of Japan (NAOJ) on estimating lunar gravity using actual observation data. At the time, calculating the lunar gravity distribution on the far side of the moon using observation data was a world's first.[10]

4.7 Orbit calculation software package ORBITER FORCE

Since the enactment of Japan's Basic Space Plan in 2008, the organizations involved in the development and operation of artificial satellites has expanded beyond JAXA and the Ministry of Education, Culture, Sports, Science and Technology (MEXT) to include other ministries and agencies, universities, and private-sector companies. In particular, interest in small

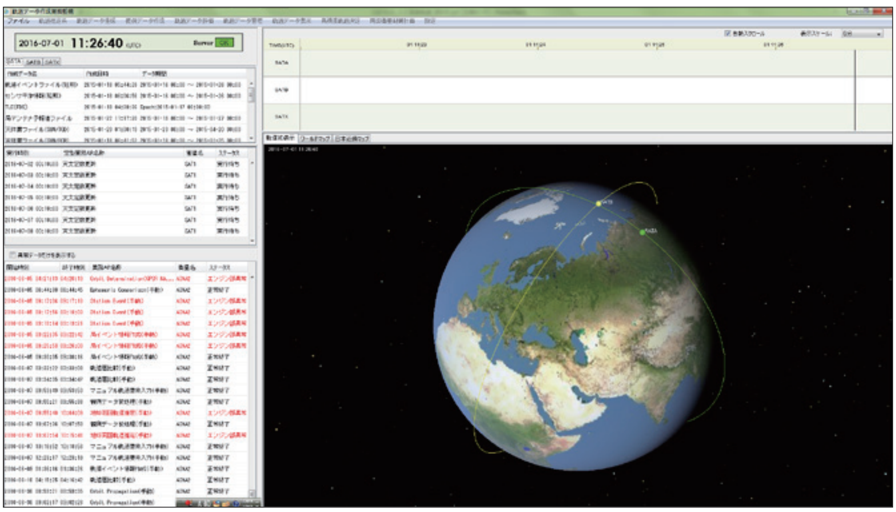

Figure 4
ORBITER FORCE screenshot.

satellites has been increasing at universities and private-sector companies, creating a need for satellite operations systems that can be inexpensively and easily constructed compared with conventional systems. At the same time, government ministries and agencies have been emphasizing transparency and clarity in technologies instead of black-box functions and promoting the development of rapid support systems. In response to these initiatives, Fujitsu began sales of an orbit calculation software package named FUJITSU Technical Computing Solution ORBITER FORCE in 2013 (**Figure 4**). ORBITER FORCE consists of a package of orbital calculation algorithms that have come to be used in actual satellite operations. Fujitsu compiled these algorithms using the JAXA intellectual property usage program. The package provides comprehensive support, from flexible handling of individual satellite requirements through customization to construction of a satellite operations system. ORBITER FORCE can provide broad satellite support, from small satellites to large-scale application satellites. Going forward, our plan is to extend and enhance ORBITER FORCE functions and to provide them to new players involved in satellite operations and orbit determination of space vehicles.

5. Conclusion

This paper described the technologies and systems cultivated and developed by Fujitsu in the field of orbit determination, prediction, and analysis for spacecraft such as artificial satellites and probes and for space debris. Fujitsu's satellite-related technologies continue to advance. The scope of their application is being broadened, and they are evolving in step with the expansion of satellite missions. Going forward, Fujitsu aims to systematize new technologies for satellite operations to ensure successful missions in such areas as detection and analysis of potential collisions with space debris, disaster monitoring, global environment monitoring, and deep space exploration. Fujitsu also seeks to develop solutions that will enable everyone to enjoy the benefits of these technologies as they do for GPS.

In closing, we would like to extend our deep appreciation to all concerned at JAXA for their technical cooperation and support and for providing technology-validation facilities in conjunction with the work consigned to Fujitsu, through which we have acquired and/or developed advanced orbital dynamics calculation technologies.

References

1) H. Takeuchi: VLBI Experiment Using the "IKAROS" Small Solar Sail Demonstrator. RF World, No. 20, Nov. 2012 (in Japanese).
2) Regarding Post Evaluation of Advanced Land Observing Satellite "DAICHI" (ALOS). Space Development Committee, Promotion Group, Jan. 16, 2012 (in Japanese).
3) K. Akiyama et al.: Preliminary Results of Precise Orbit Determination for ALOS-2. Proceedings of the 58th Space Science and Technology Conference, Nov. 2014 (in Japanese).
4) Ministry of Land, Infrastructure, Transport and Tourism, Geospatial Information Authority of Japan: Information on the 2016 Kumamoto Earthquake, Detection of Fluctuations by ALOS-2 SAR interferometry (in Japanese).
http://www.gsi.go.jp/BOUSAI/H27-kumamoto-earthquake-index.html#3
5) A. Uematsu et al.: Japanese Altimetry Mission, COMPIRA. International Workshop on Laser Ranging, 11-15 November 2013.
6) K. Akiyama et al.: Precise Orbit Determination for LEO Satellites Using Carrier-Phase Integer Ambiguity Resolution. Proceedings of the 57th Space Science and Technology Conference, Oct. 2013 (in Japanese).
7) S. Yamamoto et al.: Results of Final Investigation of Quasi-Zenith Satellite System. Council for Science and Technology, Subdivision on Research Planning and Evaluation, Expert Panel on Space Development and Utilization (13th meeting) December 24, 2013 (in Japanese).
8) N. Kajiwara et al.: Accuracy Evaluation of Precise Orbit and Clock Determination for QZS-1 "MICHIBIKI." Proceedings of the 59th Space Science and Technology Conference, Oct. 2015 (in Japanese).
9) NASA Orbital Debris Quarterly News. NASA, Volume 18, Issue 4, October 2014.
10) N. Namiki et al.: Farside Gravity Field of the Moon from Four-way Doppler Measurements of SELENE (Kaguya). Science, 323, pp. 900–905, 2009.

Seiji Katagiri
Fujitsu Ltd.
Mr. Katagiri is currently engaged in the development of orbital dynamics calculation systems.

Chiaki Aoshima
Fujitsu Ltd.
Ms. Aoshima is currently engaged in the development of orbital dynamics calculation systems.

Takafumi Ohnishi
Fujitsu Ltd.
Mr. Ohnishi is currently engaged in the development of orbital dynamics calculation systems.

Yosuke Yamamoto
Fujitsu Ltd.
Mr. Yamamoto is currently engaged in the development of orbital dynamics calculation systems.