Development of a Novel Core Component-based Flight Dynamics Subsystem Software Platform

Yoola HWANG\textsuperscript{1}\textsuperscript{*} and Byoung-Sun LEE\textsuperscript{1,2}

\textsuperscript{1}Unmanned Vehicle System Research Group, Electronics Telecommunications Research Institute, Daejeon 34129, South Korea
\textsuperscript{2}Aerospace System Engineering, University of Science and Technology, Daejeon 34113, South Korea

The flight dynamics subsystem (FDS) of a geostationary satellite ground control system conducts estimates of the orbital states, keeping within its mission box, and calculating the satellite operational parameters to be uploaded. A new FDS has been designed and implemented by dividing it into core- and bus-dependent modules for a recent Korean geostationary satellite ground control system. The core modules include orbit determination and prediction, event prediction, and station-keeping and relocation (SKR) planning; whereas the bus-dependent modules include fuel accounting, thruster modeling and maneuver reconstructions of SKR, and calculate all of the bus-dependent parameters. In particular, separate designs based on the components of the SKR planning and maneuver reconstruction using thruster modeling allow the system to be reusable and replaceable. We also designed and implemented a conjunction analysis tool and collocation control and monitoring units for multiple-satellite control. A FDS database has been developed and is managed using SQLite, which is freely distributed. The FDS is easy to develop and operate thanks to a novel separation concept introduced for the core-platform and spacecraft bus-dependent modules. It is the same concept used for operation and the graphical user interfaces (GUIs) applicable to the FDS. All of the FDS modules for new geostationary satellites have been validated through function and performance testing, and have proven to work successfully after the launch of satellites.

Key Words: Flight Dynamics Subsystem, GEO, Reuse, Replacement, Core-Platform

1. Introduction

One of Korea’s new commercial geostationary Earth orbiting (GEO) satellites was inserted at 113° east (E.) longitude for Ku- and Ka-band communication channels, and the other was stationed at 116°E. longitude in 2017. However, Koreasat-5 (KRS) and PALAPA-D, an Indonesian satellite, are already collocated at 113°E. They are operated using a longitude separation method. The Thales Alenia Space (TAS) spacebus 4000 platform is used for new Korean commercial GEO satellites. The lifetime of the satellites is 15 years. The ground control system consists of three subsystems: a telemetry, tracking and command subsystem (TTC) including monitoring and control (M&C) functions, a real-time subsystem (RTS), and a flight dynamics subsystem (FDS). The TTC is directly linked to the satellite through the Ku-band frequency. It modulates telecommands for a signal transmission and demodulates the telemetry stream. The RTS provides real-time monitoring of the satellite status and transmits telecommands to control the satellite. The RTS has communication links to the TTC, extracts satellite state of health data from the telemetry, and displays the telemetry for monitoring purposes. The FDS provides spacecraft flight dynamics operation support.

The FDS mainly consists of the following functions: spacecraft orbit determination and prediction (ODP), event prediction (EP), fuel accounting (FA), station keeping and relocation (SKR), collocation, and conjunction and monitoring. It also provides satellite operation-related functions such as onboard orbit propagation (OOP), solar torque estimation and prediction (H management), and Earth acquisition during an emergency event due to the loss of pitch lock. The FDS was newly designed to focus on the development of core-platform software for reuse and replacement, and a collocation and conjunction analysis (CA) tool from previous COMS heritage was added.\textsuperscript{1)} The core platform developed for the FDS is efficient, saves cost and time, and is partially able to be reused whenever a new satellite ground control system is developed.

A novel separation concept incorporated for the core-platform and spacecraft bus-dependent modules makes the ground control system more reliable and verifiable. Core-platform modules are reused for any geostationary satellite program and the only bus-dependent modules are developed based on documentation from the satellite manufacturer. The database is already defined in the core platform and only interface tests are conducted for the bus-dependent modules.

The FDS for GEO satellite operation is a computer-based system comprised of flight dynamics software and computer hardware. The hardware consists of two computer workstations and their peripherals. One is a primary FDS computer and the other is a redundant FDS computer. Normally, a primary FDS workstation with two display monitors is used for FDS operations. The redundant FDS workstation has copies of the same FDS executables and data files as the primary FDS computer. The FDS software was designed using Enter-
prerequisite architect and implemented through the C# program language on a .NET framework environment.

In this paper, we introduce the newly designed FDS based on the previous COMS FDS for the core platform development of FDS software. The new FDS is being used for the Korean GEO satellites located at 113° and 116° E. The new GEO satellite at 113° E. is collocated with the KR5 and Palapa-D satellites. The FDS enables the monitoring of three satellites at the same time, and controls the eccentricity and inclination vectors in the SK unit for multiple-satellite control. We designed, implemented, and tested the GEO satellite FDS modules, including collocation and conjunction monitoring for two or three satellites. The main functions of the FDS are validated according to the performance criteria, and appear to satisfy the required specifications.

2. FDS Functional Analysis and Design

2.1. Functional analysis

The FDS is made up of six major units and four support units. The major units are the orbit determination (OD), orbit prediction (OP) and EP, station-keeping (SK) maneuvering, station-relocation (SR) and decommissioning maneuvering, collocation and CA, and FA. Each unit consists of common or independent modules used to achieve the mission operations. The four support units are the system management (SM), database management (DM), thruster modeling, and FDS utility. Figure 1 shows the functional structure of the FDS. The FDS units shown in dark pink can be used for the core-platform module, and the partial modules shown in light pink can be generalized for reuse. Thruster modeling, which is only a support unit, shown in dark green, is dependent on the space-bus module, and is included in SKR maneuver preparation and reconstruction, and the FA algorithm.

2.1.1. Orbit determination and prediction

OD using ranging and angle tracking data estimates the satellite position, velocity, and solar radiation pressure coefficient, as well as additional measurement bias, if necessary. Batch least-square estimator (BLSE) is used for normal operational OD, and an extended Kalman filter (EKF) is utilized for real-time OD. The OP provides propagated orbit ephemeris and generates the ground track data, antenna pointing data, and orbit states in a type of two-line element (TLE) to provide to the TTC M&C of the ground station. The resulting files from the OP are used to find the position of the satellite and accomplish the satellite mission.

2.1.2. Event prediction

EP provides the eclipse time, sun interference time, and sensor intrusion time based on the positions of the Earth, sun, and moon. The power percentage necessary for mission operations is calculated during an eclipse event. EP also provides various satellite events such as the nodal crossing time and apsidal passing time.

2.1.3. Station-keeping

SK provides the planned maneuver time and magnitude of velocity increments to keep the satellite within its mission box. East-west SK (EWSK) planning is used to control satellite drift towards a stable point, and the eccentricity using the sun-pointing perigee strategy based on a one- or two-burn algorithm. The iterative process of COMS EWSK is inherited, and a target bias setup was additionally developed. For satellite collocation operation, the targeting eccentricity and inclination vectors of SK are controlled to set up the targeting biases. North-south SK (NSSK) planning keeps the satellite at 0.01° latitude using the minimum fuel target (MFT), trackback cord target (TBCT), and maximum compensation target (MCT) methods based on user options.

2.1.4. Station relocation and decommissioning orbit

The SR unit with a decommissioning maneuver provides the planned maneuver time and magnitude of the velocity increments for a drift positioning maneuver and decommissioning maneuver, respectively. The target longitude and tasking period are user inputs as well. In addition, SR calculates the per-day limit of the velocity increments and the possible arrival time using a circular drift or eccentric drift algorithm. At the end of the boost life, the decommissioning maneuver is conducted to raise the satellite into a super-geosynchronous orbit. The decommissioning maneuver module selects the super-synchronous orbit altitude and tasking period. The velocity increments and time to maneuver are then determined.

2.1.5. Maneuver preparation and reconstruction

Maneuver preparation provides the thruster start time and duration, reconstructing magnitude of the velocity increments, each thruster force and torque according to the different mode types including drift-positioning or normal-operation mode, the sets of thrusters to be used, and maneuver type such as NS/SN or EW/WE. The boost start time, duration, and velocity increments for a wheel-unloading maneuver are also determined based on thruster modeling. It estimates the oxygen to be consumed and fuel mass to be fired using thruster modeling.

2.1.6. Collocation and conjunction analysis

Collocation strategies depend on the satellite longitude location allotted. Two satellites are usually separated into two longitude divisions. More than three satellites are designed to control the inclination and eccentricity vectors. Collocation displays the variation in longitude of more than two satel-
lites, and the evolution of the inclination and eccentricity vectors. The CA tool monitors more than two satellites based on the Joint Space Operations Center (JSpOC) conjunction summary message (CSM) or TLE data from the North-American Aerospace Defense Command (NORAD). The CA tool plots the radial, along-track, and cross-track differences, and the distances between the operating satellite and the approaching satellites.

2.1.7. Fuel accounting
The FA unit calculates the fuel history consumed by a spacecraft. Telemetry provides the tank pressure, temperature, and thruster-on-time (TOT) information such as the pulse count and accumulated thruster-on time. It also calculates the remaining fuel and oxygen mass using the telemetry TOT information mentioned above, doing so according to thruster modeling. The ground FA results should match the satellite’s onboard software results.

2.1.8. FDS utility
The FDS utility provides orbital and related parameters to correct the differences in the satellite’s onboard orbit and time from the orbit estimated on the ground. Earth acquisition parameters are calculated to target the Earth during an emergency. The H management module estimates and predicts the angular momentum vectors of the target wheels during a wheel unloading maneuver, but is used only as an option.

2.1.9. FDS system management
The FDS SM function provides management of the FDS processes and controls system operations. This function starts up and shuts down the FDS, and manages the functional processes, configuration file, backup and recovery files, and log histories. The process management unit monitors the FDS operator and controls the software processes related to all FDS jobs.

2.1.10. FDS data management
The FDS DM unit supplies all FDS-related database information, such as the spacecraft, astronomical data, and dynamic data updates. The interface management involves all data files through standard file transfer protocol (FTP) exchanges among other systems. The database is managed using SQLite, which is freely distributed, and consists of common operational parameters used as a graphical-user-interface (GUI) input, necessary constant or input data of the spacecraft, and historical operational results recorded.

2.2. FDS use-case design
The FDS consists of the following package diagrams: orbit analysis (OA), orbit maneuver (OM), FA, FDS Utility, and SM packages. The satellite ephemeris is an important factor for mission operations and maneuvers related to the lifetime of the satellite. The OA package was designed to include ODP and EP. The OM package is made up of the following functions: SK and SR, thrust modeling, collocation analysis, and satellite CA. The FA package estimates the consumption of satellite fuel using thruster modeling. The FDS Utility package comprises OOP initialization, Earth attitude acquisition, angular momentum management, and utilities including plot services, coordinate transformation, and measurement conversion. The SM package is related to the DM, FDS process, and file interfaces.

2.2.1. Orbit analysis package
The OA package is designed to generate spacecraft ephemeris in order to operate the satellite using the ground FDS. The units of the OA package were developed to be core-platform software. The OD unit is designed to provide initial orbital elements determined using ranging and tracking data obtained from the TTC. The initial orbit determined is propagated using dynamic models. Antenna pointing data are converted based on the ephemeris propagated. The EP unit applies the same satellite ephemeris to predict event times, such as an eclipse, sensor intrusion or sun interference. As shown in Fig. 2, the package diagram of the OA shows that the OD and EP units are designed to include the OP unit. The OP unit is commonly used in most modules of the FDS.

2.2.2. Orbit maneuver package
The OM package is related to maintaining, relocating and monitoring the satellite, as shown in Fig. 3. In particular, the OM package distinguishes the SKR as two separate parts: core and bus-dependent for reuse and replacement. A planned maneuver is part of the core platform and is reused, and maneuver preparation includes reconstructing the velocity increment parameters using thruster modeling, which is a satellite-dependent part and is replaceable. The SK maneuver plan is designed to calculate the magnitude of the satellite velocity increments and maneuver time. In the SK unit, the

---

**Fig. 2.** Use-case diagram of orbit analysis.
The SR maneuver plan calculates the velocity increments and time to maneuver for satellite relocation using the mean orbit. Thruster modeling changes the velocity increments planned by the SK and SR units into the force and torque to be used by each thruster. Here, the ephemeris result of the OP unit is included to support use of the SK, SR and CA modules. In addition, multiple-satellite operations are monitored using the CA tool and collocation units.

2.3. FDS component design

FDS units are usually reusable and replaceable using a component-based design for the core functions. Figure 4
shows an FDS component diagram. The initial orbit result of the OD unit is used as an input for most other functions, and is stored in a stack file. In the OA component, the orbit dynamics related to satellite perturbations are included for all units, such as the OP, OD, and EP components that propagate the orbit.

The OM package includes the OA unit to enable use of the orbit propagation results. Thruster modeling is included in maneuver preparation and FA, which estimates the remaining fuel based on the OM components. The SK and SR units calculate the velocity increments for the maneuver plan in advance to fire the thruster and determine maneuver time.

Maneuver reconstruction applying the thruster modeling dependent on the satellite bus is designed to be separate from the maneuver plan, and transmits output to the RTS unit in order to command the satellite. The satellite collocation component is designed to display the evolution of the eccentricity and inclination vectors, longitude variation, and distances between satellites. The CA component is independently designed to monitor the distances between two or more satellites based on user input or the FDS system, doing so apart from the collocation component. The FDS utility component, which is dependent on the satellite bus, consists of the OOP, H management (wheel management), Earth acquisition, and FDS utilities dealing with coordinate conversion, data merging and format conversion. In addition, the DM and SM are components of the FDS.

The components designed are independently implemented and generated in a dynamic link library (dll). Dlls are classified into commercial-off-the-shell (COTS) libraries and FDS libraries in the FDS. COTS libraries are generated through compilation using Visual Studio, and depend on the versions of Visual Studio, .NET framework and SQLite.

Table 1 shows the libraries for the FDS core dlls. Table 2 lists the satellite bus-dependent dlls, such as the GUI and bus-dependent module executables that can be replaced by developing new satellite parameters. The CA tool and TLE conversion are independently used to monitor other satellites or space debris.
3. Implementation, Testing and Performance Verification

The main FDS login window connects each unit such as the OD, OP, SK, SR, FA, SM, and FDS Util. The FDS testing after implementation validates the functional and performance characteristics following the test scenario shown in Fig. 5, doing so based on COMS heritage.1,11,12) The solid lines indicate the flow of internal data files and the dotted green lines show the results for verification of the allocated functions with respect to the modules or units. The FDS test scenario, including the test harness, is provided as shown in Fig. 5. The OP unit demonstrates the dynamic modeling accuracy, coordinate conversions, and orbit propagation accuracy. In the OD unit, the adjustment results using ranging and tracking data are verified for the performance of position accuracy, and database management for orbit stacking is functionally checked for updating orbital elements. The EP unit checks if the time of an event is within the range of tolerance. To verify SK performance and functions, a two-week automatic maneuver is conducted, and it is checked whether or not the satellite maintains its longitude variation within the targeted longitude, the eccentricity vector follows the sun direction and maintains the radius of eccentricity control, and the inclination vector is within the vector control boundary. The SR shows when the current longitude is relocated at the new target longitude following the planned velocity increments and firing times. The FA unit conducts tests using telemetry from a simulator. Test cases of the Earth acquisition, wheel management, and OOP were provided from the satellite manufacturer. The SM and DM functionally demonstrate their file management, log-in and -out, process management, and logging reports.

3.1. Orbit determination and prediction

The OD unit concentrates on the following tests: antenna tracking and ranging data are obtained from Test Computer 1 (TTC 1), and the FDS OD unit estimates the satellite position, velocity, solar radiation pressure (SRP) coefficient, and if necessary, measurement biases, as shown in Fig. 5. The OD test functionally shows that the orbit states and SRP coefficient are estimated and updated to the stack file. The measurement biases are separately updated to the database of the ground station-related parameters. It checks the convergence of the initial orbit states and evaluates the residual statistics. The orbital elements in the orbit stack file are propagated using dynamic models: Earth-gravity-model (EGM)-96,13) solar radiation pressure,14) and perturbation from the sun and moon gravity calculated using JPL DE-405,15) doing so according to the start and end times. The orbital elements, converted into another coordinate system, can be displayed by the user options. Figure 6 shows the OD GUI including the orbital elements, dynamics, bias estimates, and residual results. Two-day tracking and ranging data are generally selected to estimate the initial orbit states after a maneuver. The start and end times are automatically displayed by choosing the observation file. After executing the OD, statistical information with residuals plots for the OD results is calculated in the OD GUI window (Fig. 6). The orbit ephemeris according to the observation arc length is generated into true-of-date (TOD) Cartesian and Keplerian coordinates.

Orbit propagation demonstrates the accuracy of coordinate conversion and dynamic modeling. To verify ODP performance, in this study, we compared our ODP results with the outputs of the ODP software developed by another organization. Each software independently estimates the biases for the ranging and tracking observation data. Initially or after calibration, a bias estimate using BLSE is normally conducted for a single ground station.2,16,17) Figure 7 shows the radial, along-track, and cross-track component differ-
ences between the two types of software. We used ranging and tracking data of the three-day arc length (20–22 Jan 2017). In the along-track direction, a difference of roughly 707 m is shown. However, the biases estimated during OD are slightly different between the two software types, and the difference of the along-track direction is due to the discrepancy in the bias estimated.

3.2. Station-keeping and relocation

The SK unit demonstrates that the satellite is maintained in a defined mission box. When the start and end times are inserted into the SK GUI, the orbital information of the closest time among the previous times is displayed. A priori orbit information is obtained from the OD stack file. Either the one- or two-burn algorithm is automatically selected based on the drift rate of the satellite and the change in eccentricity. If the eccentricity vector bias is added for collocation, the bias shifts the EW center within the eccentricity control limit. In addition, it is possible to control the inclination vector by selecting an algorithm, such as MFT, MCT or TBCT, according to the user’s choice. The NSSK was also implemented to enable collocation operation in the control box to be conducted by setting the inclination vector bias. The magnitude of the velocity and maneuver time planned by the EW and NS-SK are recalculated according to the thruster modeling, which depends on the satellite’s bus. The SK results depend on the mean orbit and SK algorithm used.

The results of maneuver preparation based on reconstruction using the planned result are dependent on the thruster modeling of the satellite manufacturer. Therefore, it is difficult to compare the absolute values with other software; however, it simply demonstrates the approximate trends within the tolerances of the reference longitude margin and the limits of the eccentricity and inclination vectors. Figure 8 shows the two-week automatically planned SK maneuver results at the center of 115.9°E. Only the planned velocity increments and maneuver time to validate the SK trends are calculated.

The SR unit demonstrates relocation from the original longitude to the target longitude when considering maximum velocity increments and firing times within the given periods. Our system displays all possible firing times and periods to move to the target longitude. The SR unit test demonstrates that the longitude is relocated to the target longitude and velocity increments are within the maximum value, which is a constraint during the SR task periods. Figure 9 shows SR moving from 113°E to 116°E within a 10-day period.
the test scenario, the total velocity increments should be less than 5 m/s and the firing number less than four times.

3.3. Maneuver preparation and reconstruction

The maneuver preparation module uses the planned SKR delta velocity and time to maneuver. It calculates outputs using the thruster modeling provided by the satellite manufacturer. This part of maneuver preparation can be replaced whenever a new GEO satellite FDS is developed. Table 3 shows the velocity increments and maneuver time planned for a normal-mode EWSK.

| Component | Input for maneuver preparation |
|-----------|--------------------------------|
| Time      | 2005-06-03 15:30:00.000 |
| DelVx (m/s) | -1.000003         |
| DelVy (m/s) | 0.049761           |
| DelVz (m/s) | -0.349907         |

Table 3. Planned delta velocity (normal-mode EWSK).

Table 4 shows the results of maneuver preparation using thruster modeling. It calculates the boost start time and duration, wheel unloading time and duration, and each thruster force. It also checks the change in the center of gravity based on the mass consumed. To maintain the attitude, it conducts a wheel-unloading maneuver using angular momentum telemetry from thruster modeling. This module is mainly performance-tested using thruster modeling.

| Type          | Reference | FDS output | Tol. |
|---------------|-----------|------------|------|
| Maneuver mode | NM.OCC    | NM.OCC     | 0    |
| Nominal or Back-up | Nominal | Nominal     | 0    |
| DeltaV command | 1.0      | 1.0         | 0    |
| Wheel unloading date | 2005-06-03 | 2005-06-03 | 0    |
| Wheel unloading start time | 14:21:21 | 14:21:21 | 1 (s) |
| (hh:mm:ss) Boost start time (hh:mm:ss) | 14:33:36 | 14:33:36 | 1 (s) |
| Boost end time (hh:mm:ss) | 16:24:36 | 16:24:36 | 1 (s) |
| S/C current mass (kg) | 2672.454 | 2672.454 | 0 |
| New CG: x (m) | 0.000764914 | 0.000764914 | 0.001 |
| New CG: y (m) | 1.838982197 | 1.838982197 | 0.001 |
| New CG: z (m) | 10.74223346 | 10.74223346 | 0.0001 |
| Thruster 1A (N) | 10.74223346 | 10.74223346 | 0.0001 |
| Thruster 2A (N) | 10.73199098 | 10.73199098 | 0.0001 |
| Thruster 3A (N) | 10.67905216 | 10.67905216 | 0.0001 |
| Thruster 4A (N) | 10.81537959 | 10.81537959 | 0.0001 |
| Thruster 1B (N) | 10.85675346 | 10.85675346 | 0.0001 |
| Thruster 2B (N) | 10.81803093 | 10.81803093 | 0.0001 |
| Thruster 3B (N) | 10.84522228 | 10.84522228 | 0.0001 |
| Thruster 4B (N) | 10.71059274 | 10.71059274 | 0.0001 |
| Thruster 1C (N) | 10.86048307 | 10.86048307 | 0.0001 |
| Thruster 2C (N) | 10.81839039 | 10.81839039 | 0.0001 |
| Thruster 3C (N) | 10.70005133 | 10.70005133 | 0.0001 |
| Thruster 4C (N) | 10.74944782 | 10.74944782 | 0.0001 |
| Thruster 1D (N) | 10.86048307 | 10.86048307 | 0.0001 |
| Thruster 2D (N) | 10.85675346 | 10.85675346 | 0.0001 |
| Thruster 3D (N) | 10.71059274 | 10.71059274 | 0.0001 |
| Thruster 4D (N) | 10.74223346 | 10.74223346 | 0.0001 |

Fig. 8. SK planning output for two weeks.

Fig. 9. SR test results of relocation from 113° E. to 116° E.
3.4. Event prediction

The EP function checks events that occur during mission operation. Although recent satellites predict most events through onboard software, the ground control system generally calculates an eclipse of the sun based on the positions of the Earth and moon and the sun interference time. Figure 10 shows the eclipse results of the FDS. It functionally demonstrates the time of an eclipse during an eclipse period; that is, the time of the eclipse event is displayed on the text viewer of the EP result, as shown in Fig. 10. For performance verification, the times of sun interference determined using the algorithm of Lee and Lee were cross-checked with other software results, as shown in Table 5.

3.5. Conjunction analysis and monitoring

Both the KR5 and PALAPA-D satellites are located near 113.0° E., and should therefore be periodically monitored for collision avoidance. Figure 11 shows a demonstration of conjunction-monitoring analysis for a CA functional test. The CA tool shows that it collects the orbit information from two or three satellites using the CSM format, NORAD TLE, FDS system, or user input. It calculates their ephemeris distances and direction component differences for each epoch during the selected periods, and displays the evolution of longitude and latitude. The output of the minimum distance is written using the Earth-Centered-Earth-Fixed coordinate system. The minimum distance result of the CA tool based

| No | Event | Reference | FDS | Diff. (s) | Tol. (s) |
|----|-------|-----------|-----|----------|----------|
| 1  | Start | 2006-3-20 03:30:37 | 2006-03-20 03:30:29.00 | 8.0 | 60.0 |
|    | End   | 2006-3-20 03:38:01 | 2006-03-20 03:38:09.00 | 8.0 | 60.0 |
| 2  | Start | 2006-3-21 03:30:11 | 2006-03-21 03:30:03.00 | 8.0 | 60.0 |
|    | End   | 2006-3-21 03:37:52 | 2006-03-21 03:38:00.00 | 8.0 | 60.0 |
| 3  | Start | 2006-3-22 03:30:28 | 2006-03-22 03:30:19.00 | 9.0 | 60.0 |
|    | End   | 2006-3-22 03:37:01 | 2006-03-22 03:37:10.00 | 9.0 | 60.0 |
| 4  | Start | 2006-3-23 03:32:12 | 2006-03-23 03:31:50.00 | 22.0 | 60.0 |
|    | End   | 2006-3-23 03:34:43 | 2006-03-23 03:35:06.00 | 23.0 | 60.0 |

Fig. 10. Plot and report for eclipse time.

Fig. 11. Display of conjunction monitoring and analysis.
on the TLE information demonstrates a difference of 6.8 km during the one-year period of October 2015 to October 2016 for KR5 and PALAPA-D.

3.6. Collocation of satellites

When a new GEO satellite is located at around 113.05° E., three or more satellites are located around a similar longitude. The PALAPA-D satellite operated by Indonesia is currently centered at 112.95° E., while KR5 is currently centered at approximately 113.05° E. The newly launched GEO satellite and KR5, at 113.05° E. are propagated by adding the eccentricity and inclination vector bias in the SK unit. KR5 and the new GEO satellite are controllable by adding the y-axis biases of the eccentricity and inclination vectors.7,9,20) Figure 12 shows demonstration results for control using longitude separation (PALAPA-D) and eccentricity and inclination vector control (KR5 and the new GEO satellite). The results show that the mean orbit propagation, including automatic maneuvering plans for a one-year period.

3.7. Onboard orbit propagator

During operation of a GEO satellite, the orbit parameters should be periodically updated to synchronize the difference in orbit after a maneuver between the ground and onboard satellite. The OOP operation scenario is as follows: It converts the osculating orbit for a particular epoch on the ground to the mean orbit and uploads it to the satellite. We verify the performance by comparing the results with reference results provided by the satellite manufacturer. For the OOP unit test, the GEO satellite is assumed to be located at 161.0° E., as provided by the satellite manufacturer. The orbital elements are converted into J2000 internally, and the J2000 orbit is then changed into the mean orbit and the related parameters are calculated to upload to the satellite. This test indicated that the results of the OOP satisfy the tolerances required, as shown in Table 6. However, the tolerances were also provided by the satellite manufacturer.

3.8. Fuel accounting

The FA unit is extremely difficult to test before the satellite is launched. We conducted a TOT functional demonstration only for the telemetry format and interface using a satellite simulator. Whenever a maneuver is performed, the remaining mass is calculated using the telemetry information. The remaining mass of the satellite and that calculated using the ground system should coincide with each other. Our operation concept is for a user to choose the telemetry file related to the thruster for a specific date; the FDS then calculates the mass consumed using the telemetry information provided by the thruster modeling unit.

The pressure is archived from the telemetry, and the oxy-

Fig. 12. Collocation for three geostationary satellites.

| Items               | Ref.         | FDS         | Diff.        | Tol.        |
|---------------------|--------------|-------------|--------------|-------------|
| Date.ref.           | 2015-10-11   | 2015-10-11  | NA           | NA          |
| ex.t0               | 0.00023487   | 0.00023487  | 1.58e−9      | 1.0e−7      |
| ey.t0               | 2.81e−05     | 2.81e−05    | 3.04e−10     | 1.0e−7      |
| ix.t0               | −0.371429    | −0.371428   | 2.86e−7      | 1.0e−4      |
| iy.t0               | 0.018405     | 0.01840469  | 3.12e−7      | 1.0e−4      |
| mean.longt0         | 161.0059     | 161.005864  | 3.61e−5      | 1.0e−3      |
| mean.anomt0         | 180.06574    | 180.065740  | 4.09e−7      | 1.0e−3      |
| Drift.t0            | −0.010979    | −0.010979   | 2.32e−8      | 1.0e−4      |
| Long.accel          | −5.90e−05    | −5.93e−05   | 2.65e−7      | 1.0e−6      |
| A.unit              | 6.49e−05     | 6.49e−05    | 7.76e−13     | 1.0e−8      |
functions and performance have been found to meet the requirements. The FDS can be operated in a Windows-based computer environment. The operator and FDS functions are interfaced through an easy-to-use GUI. All functions and performance have been found to meet the requirements and tolerances of the specifications. The FDS core-platform software is working successfully for two GEO satellites recently launched. Owing to the development of component-based FDS core-platform software, the cost and time required to develop the FDS for new satellites can be drastically reduced.

### 4. Conclusion

We have developed FDS core-platform software that is easy to use and replace. The FDS software includes the general functions for normal mission operations, as well as conjunction monitoring and collocation for multiple geostationary satellite control. The collocation and CA tool are used to monitor multiple satellites and evaluate their maneuvering results. Six core units and four support units are designed into separate component modules. The core-platform software can be used for most of the GEO FDSs implemented in the satellite control center, and the bus-dependent modules can be replaced with an algorithm provided by the satellite manufacturer. The FDS can be operated in a Windows-based computer environment. The operator and FDS functions are interfaced through an easy-to-use GUI. All functions and performance have been found to meet the requirements and tolerances of the specifications. The FDS core-platform software is working successfully for two GEO satellites recently launched. Owing to the development of component-based FDS core-platform software, the cost and time required to develop the FDS for new satellites can be drastically reduced.

### Acknowledgments

This work was supported by the Space Core Technology Development Program of NRF [NRF-2015M1A3A3A030 34729, Development of core S/W standard platform for GEO satellite ground control system].

### References

1. Lee, B.-S., Hwang, Y., Kim, H., and Kim, J.: Design and Implementation of the Flight Dynamics System for COMS Satellite Mission Operations, *Acta Astronautica*, 68 (2011), pp. 1292–1306.
2. Hwang, Y. and Lee, B.-S.: Validation of Geostationary Satellite Orbit Determination Using Single-station Antenna Tracking Data, *J. spacecraft Rockets*, 50 (2013), pp. 1248–1255.
3. Montenbruck, O. and Gill, E.: *Satellite Orbits Models Methods Applications*, 1st ed., Springer-Verlag, New York, 2000, pp. 299–302.
4. Tapley, B. D., Schutz, B. E., and Born, G. H.: *Statistical Orbit Determination*, 1st ed., Elsevier Academic Press, New York, 2004, pp. 183–199.
5. Soop, E. M.: *Handbook of Geostationary Orbits*, 1st ed., Kluwer Academic Publishers, Boston, 1994, pp. 183–211.
6. Lee, B.-S., Hwang, Y., Kim, H., and Park, S.: *East-West Station-Keeping Maneuver Strategy for COMS Satellite Using Iterative Process*, *Adv. Space Res.*, 47 (2011), pp. 149–159.
7. Hwang, Y., Lee, B.-S., and Lee, U.: Satellite Collocation Control Strategy in COMS, SpaceOps Conferences, 16–20 May, Daejeon, Korea, 2016-2452, 2016.
8. Pocha, J. J.: An Introduction to Mission Design for Geostationary Satellites, Dordrecht, 1987, pp. 67–118.
9. Lee, B.-S., Lee, J.-S., and Choi, K.-H.: Analysis of Station-keeping Maneuver Strategy for Collocation of Three Geostationary Satellites, *Control Engineering Practice*, 7 (1999), pp. 1153–1161.
10. Kelso, T. S. and Alfano, S.: Satellite Orbital Conjunction Reports Assessing Threatening Encounters in Space (SOCRATES), *Adv. Astronaut. Sci.*, 120 (2005), pp. 317–326.
11. Lee, B.-S., Kim, H., Hwang, Y., and Kim, J.: Flight Dynamics Operations for COMS Satellite Mission Control, Proceedings of 26th AIAA International Communications Satellite Systems Conference (ICSSC), AIAA 2008-5502, 2008.
12. Lee, B.-S., Hwang, Y., Kim, H., and Kim, J.: Test of the COMS Flight Dynamics Software, Proceedings of 2008 KSAS Spring Conference, KSAS08-1914, 2008, pp. 980–983.
13. Lemoine, F. G., Kenyon, S. C., Factor, J. K., Trimmer, R. G., Pavlis, N. K., Chinn, D. S., Cox, C. M., Klosko, S. M., Luthcke, S. B., Torrence, M. H., Wang, Y. M., Williamson, R. G., Pavlis, E. C., Rapp, R. H., and Olson, T. R.: The Development of the Joint NASA/GSFC and the National Imagery and Mapping Agency (NIMA) Geopotential Models, EGM96, NASA, TP-1998-206681, 575, July 1998.
14. Wertz, J. R. and Larson, W. J.: *Space Mission Analysis and Design*, Kluwer Academic Publisher, Dordrecht, 1991, pp. 145–146.
15. Standish, E. M.: *JPL Planetary and Lunar Ephemerides*, DE405/LE405, JPL IOM 312.F-98-048, 1998.
16. Kawase, S.: Bias Estimation Technique for Geosynchronous Orbit Determination, Advances in Astronautical Sciences, edited by Bishop, R. H., Culp, R. D., Mackson, D. L., and Evans, M., Vol. 102, 1999, pp. 1201–1210.
17. Soop, E. M.: Geostationary-orbit Determination by Single-ground-station Tracking, *ESA J.*, 4, 2 (1980), pp. 159–169.
18. Kamel, A. A. and Wagner, C. A.: On the Orbital Eccentricity Control of Synchronous Satellites, *J. Astronaut. Sci.*, 35 (1982), pp. 61–73.
19. Lee, B.-S. and Lee, J. S.: Sun Interference Predictions for the KOMP-SAT TT&C Station, *J. Astronomy Space Sci.*, 14 (1997), pp. 158–165 (in Korean).
20. Montenbruck, O., Eckstein, M. C., and Gonner, J.: The Geo-Control System for Stationkeeping and Collocation of Geostationary Satellites, Available from https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20040019454.pdf (accessed November 6, 2017).

Shinichi Nakasuka
*Associate Editor*