KORea-Multi-Purpose-SATellite (KOMPSAT)-5 is the first Korean satellite to perform synthetic aperture radar (SAR) mission and support radio occultation. In order to process SAR and radio occultation data, precise position and velocity are required. KOMPSAT-5 orbit determination system consists of Operational orbit determination (OOD) and precise orbit determination (POD). The satellite operational orbit supporting satellite operation is adjusted using satellite on-board global-positioning-system (GPS) navigation solutions data as well as ground-based satellite tracking and ranging data. KOMPSAT-5 carries two GPS receivers, TOPSTAR 3000 and IGOR, to perform orbit determination (OD) based on GPS data. IGOR dual-frequency GPS receiver is mainly operated for a primary mission support and TOPSTAR 3000 is a backup single-frequency GPS receiver. The POD result is validated using satellite laser ranging (SLR) data and the daily precise satellite position data are transferred to the international laser ranging service (ILRS) site. KOMPSAT-5 POD and OOD are designed to meet the requirements of 20 cm and 5 m (one-sigma) positioning accuracy in three-dimension, respectively. However, KOMPSAT-5 OD using ranging and antenna pointing data is normally operated when GPS data is not available or before GPS receiver is activated on. The position error based on the range, azimuth, and elevation data should be satisfied within ±1000m (three-sigma) for processing three-day measurement data. The requirement of OD performance is fully validated showing all OD requirements are satisfied for normal operation.

I. Introduction

THe KOrea-Multi-Purpose-SATellite (KOMPSAT)-5 is the first Korean satellite to produce 1-m resolution synthetic aperture radar (SAR) mission and support radio occultation. KOMPSAT-5 will be launched in 2012 and located in the 550 km altitude dawn-dusk circular orbit for Geographic information system, Ocean management, Land management, Disaster monitoring, and ENvironment monitoring (GOLDEN) missions [1,2]. Korea Aerospace Research Institute (KARI) built KOMPSAT-5 spacecraft and ground control system is developed by Electronics and Telecommunications Research Institute (ETRI). The ground control systems are consists of
real-time operation subsystem (ROS), mission planning subsystem (MPS), flight dynamics subsystem (FDS), and satellite simulator. FDS supports satellite operation such as satellite ephemeris, event, and fuel accounting. In most operation all events and data proceeding are calculated and accomplished using satellite’s orbital elements. Thus, the estimation of satellite position is an important function in FDS. Orbit determination (OD) Software developed by ETRI was validated by many studies [1, 3]. Some research groups studied OD to obtain highly precise orbit for scientific missions as well as navigation. Rapid Science Orbit (RSO) for GOCE satellite proved that orbit error is less than 10 cm Root-Sum-Squares (RSS) using kinematic method [4]. Ionosphere-free precise orbit determination (POD) was also studied for CHAMP satellite and KOMPSAT-2 [3, 5]. The POD using single-frequency GPS data mostly showed at least 1 m positioning error. The orbit accuracy with GRACE satellite was validated by Satellite Lator Ranging (SLR) data and K-band ranging data [6]. The GRACE satellite POD accuracy showed better than 5 cm RSS in each direction [7].

In this paper, the KOMPSAT-5 OD of FDS is studied by two parts. One is to calculate operational orbit to support satellite operation and the other OD is to precisely estimate satellite position to process accurate imaging data using precise orbit result. An object-oriented design approach is used for KOMPSAT-5 orbit determination design on Linux system. Design, implementation, and validation of OD results including object-oriented graphical user interfaces (GUI) design are presented. The performance of OD demonstrated by the study that operational orbit determination (OOD) compared with POD and POD accuracy adjusted SLR data and error-free simulation POD result.

II. Design of Orbit Determination

A. Operational Orbit Determination domain model

Orbit Determination package is an independent program and provides definitive orbit of KOMPSAT-5 using GPS-based navigation solutions from telemetry or ground tracking data from TT&C station. The Orbit Determination package uses batch-type minimum variance estimator for deriving definitive orbit of KOMPSAT-5. The purpose of the orbit determination package is to estimate a set of orbital parameters and provide input values for satellite operation. Software architecture is designed by package, component, process, and deployment design. GUI interfaces all FDS functions with user. Figure 1 shows the logical view of OOD. Database system relates all input and output files processing OD. Logical view of OOD consists of measurement data processing, dynamics, estimation, and interface (figure 1). OOD domain model is designed with orbit prediction for KOMPSAT-5 operation as seen in figure 2. The OD package includes following modules:

- OD_CTRL: Orbit Determination Controller for FORTRAN Code
- ORB_ITG: Orbit Propagation for Calculated Orbit Elements Generation
- OD_ESTIM: Estimation for Orbit Determination
- MEAS_MDL: Measurement Data Modeling and Residuals Calculation

![Diagram](image.png)  
Figure 1. Logical view of OOD.
Operational orbit domain is designed to perform the adjustment of the operational orbit parameters of spacecraft by using the GPS navigation solution data or ground based antenna tracking and ranging data. GPS navigation solution of PCE format and tracking and ranging data of GEOS-C format are converted into TDP form to execute OOD. Using orbit state from the spacecraft orbit stack data or manual entry, the equation of spacecraft motion is numerically integrated. The perturbation models of OOD dynamics are accessed to the Earth’s gravity, luni-solar gravity, atmospheric drag, and the solar radiation pressure. The resultant operational orbit of the spacecraft is transferred to MPS, image reception and processing elements (IRPE) and external ground station.

B. Precise Orbit Determination domain model

The logical view of POD was introduced in [1]. POD is also interfaced using GUI and data are managed via database of system management module. In order to process GPS double-differenced data, the data are edited and cycle slip is corrected by polynomial fitting. Bad data due to the geometry or clock error are rejected. Batch least square estimator is used to determine the precise orbit. Precise dynamic models are applied to integrate equation of motion numerically.
Figure 3. Object diagram of precision orbit determination.

POD domain is designed to determine the precise orbit using differential GPS technique. DGPS techniques are performed using the GPS raw data such as the pseudo-ranges and carrier phases and the data collected by world-wide GPS reference ground stations. The resultant precise orbits are transferred to IRPE and radio occultation research center. Simulation of GPS data is possible to generate simulated spacecraft GPS raw data as well as GPD reference data. POD result using SLR Data can be validated. SLR data collected by ILRS [8] site are transferred to FDS.

Figure 4 shows FDS data flow for orbit determination and prediction. Initial orbit by OOD using GPS navigation data is stored to the database of KOMPSAT-5 system management. The operational initial orbit is used for orbit prediction, orbit maneuver, and ground track maintenance. The precise initial orbit is used into POD module and transferred to the external sites. KOMPSAT-5 carrying two GPS receivers normally uses dual-frequency IGOR GPS receiver [9]. TOPSTAR 3000 [10] single-frequency GPS receiver is redundant receiver. The GPS receiver can not be activated at the same time because of the size of telemetry. The POD results using IGOR receiver was studied through TerraSAR-X, SAC-C, and GRACE satellites [3, 5, 6, 7, 9]. TOPSTAR 3000 is carried on KOMPSAT-2. The POD of KOMPSAT-2 has been successfully executed since the launch of 28 July, 2008 [3].
III. Implementation and Validation of Orbit Determination

A. Operational Orbit Determination GUI

User interfaces with FDS functions through GUI. OOD main GUI is shown in figure 5. As an option, GPS data and ground station measurements can be chosen. Bad data can be rejected according to the sigma multiplier, initial Rot-Mean-Square (RMS), and convergence criteria as seen in figure 5. It is possible for OOD to iterate maximum 9 times.
Figure 6 shows data editing GUI when ground tracking GEOS-C data are selected. Range rate data is not used as measurement. For tracking ground, range, azimuth, and elevation data are usually adjusted for OD. If GPS data was selected, the editing tracking GPS data is position and velocity based on the chosen measurement arc length.

Figure 6. Data editing GUI for ground tracking data.

Figure 7 shows dynamic model used for OOD. Earth gravity is modeled by Earth-gravity-model 96 (EGM96) [11] 70 orders and 70 degrees. Sun and Moon gravity, solar radiation pressure, and air drag are considered as perturbation models. Air drag model uses Jacchia 76.

Figure 7. Estimation setting for OOD.

To validate the OOD result using ground tracking data, simulation data are generated and estimated. Simulation data are prepared as following:
- Initial orbit is propagated by True-of-date (TOD) coordinates and converted into Earth-Centered-Earth-Fixed (ECEF) coordinates
- Checking elevation angle is greater than zero-degree and selecting the data
- Noises and biases are added as given by Table 1

Table 1 Measurement noise and bias

<table>
<thead>
<tr>
<th></th>
<th>Noise</th>
<th>Bias</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range</td>
<td>500 (m)</td>
<td>500 (m)</td>
</tr>
<tr>
<td>Azimuth</td>
<td>0.1 (degree)</td>
<td>0.05 (degree)</td>
</tr>
<tr>
<td>Elevation</td>
<td>0.1 (degree)</td>
<td>0.05 (degree)</td>
</tr>
</tbody>
</table>

Here, truth orbit is assumed by propagated orbit from orbit prediction module. Truth orbit and OOD result was compared as provided in figure 8. The difference orbit shows 312.4m RSS (one-sigma) in three-dimension. It can
be said that the accuracy of OOD using ground station three-day tracking data should be less than 1km (in three-sigma) RSS is roughly met.

Figure 8. Orbit difference between truth and OOD result.

B. Precise Orbit Determination GUI

Figure 9 shows preprocessing GUI of POD. The preprocessing module edits GPS data. GPS data can be selected whether single-frequency or dual-frequency GPS data not. For generation of double-differenced GPS data, International GNSS Services (IGS) ground reference GPS data can be chosen. If GPS data includes bad data or there are maneuver for GPS satellite, or clock error, those GPS data are rejected for specific GPS vehicle and editing time by user. Cycle slip and bad data are detected and cycle slip is repaired using polynomial fitting.

Figure 9. Preprocessing GUI of POD.

Figure 10 shows estimation GUI for POD. According to the GPS receiver data type, dual or single frequency is selected and measurement noise is given by 0.02 m. In the POD estimation, double-differenced ionosphere-free carrier-phase data are processed. Since TOPSTAR 3000 has two GPS receiving antenna, to adjust precise orbit, it
should consider antenna offset value if backup GPS receiver is activated. Attitude information relating to the satellite’s observation data as well as satellite dynamic model can also be considered. In this paper, Earth pointing attitude is assumed [3, 7].

Figure 10. GUI of POD estimation.

To estimate POD following dynamic and observation models are applied (figure 11). Detailed descriptions of each model are provided by Table 2. For KOMPSAT-2 and simulated KOMPSAT-5 data, models in table 2 are applied, respectively. For single frequency GPS data, in order to eliminate ionosphere delay error, GRAPHIC method [2] was used. General empirical acceleration estimates every 15 minutes for sine and cosine terms according to the along-track and cross-track components. 15-minute was selected by several simulations in our POD module. Troposphere delay is only applied to the ground station IGS data and estimated every 1.5 hour. Ambiguity resolution is solved during OD. The ionosphere-free linear combination data is used to estimate the floating ambiguity.

Figure 11. GUI for dynamics and observation model of POD.
Table 2  POD dynamic and measurement models [1, 3]

<table>
<thead>
<tr>
<th>Items</th>
<th>Descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geopotential gravity model</td>
<td>EGM-96 (70×70) [11]</td>
</tr>
<tr>
<td>Earth orientation parameters</td>
<td>IERS Bulletin final (Polar motion, UT1-TAI)</td>
</tr>
<tr>
<td>Cycle slip detection</td>
<td>Polynomial fitting detection and repair</td>
</tr>
<tr>
<td>Ionosphere delay</td>
<td>Linear combination of L1 and L2 for dual frequency GPS data</td>
</tr>
<tr>
<td>Troposphere delay</td>
<td>GRAPHIC method for TOPSTAR3000: [2]</td>
</tr>
<tr>
<td>Relativity effect</td>
<td>Earth rotation and velocity of light</td>
</tr>
<tr>
<td>Rotational deformation</td>
<td>Pole tide model</td>
</tr>
<tr>
<td>Earth solid tide, ocean tide</td>
<td>Colombo model [13]</td>
</tr>
<tr>
<td>Solar radiation pressure</td>
<td>Conical shadow model</td>
</tr>
<tr>
<td>Earth radiation pressure</td>
<td>Knocke’s 2nd order zonal model [14]</td>
</tr>
<tr>
<td>Atmospheric density</td>
<td>MSIS-90 [15]</td>
</tr>
<tr>
<td>N-body, planet ephemeris</td>
<td>Sun, Moon, seven-planet, JPL’s DE405</td>
</tr>
<tr>
<td>Precession and nutation</td>
<td>1982 IAU</td>
</tr>
<tr>
<td>Reference coordinates</td>
<td>J2000 coordinate</td>
</tr>
<tr>
<td>Ground coordinates</td>
<td>ITRF2005 [16]</td>
</tr>
<tr>
<td>General acceleration</td>
<td>Sine, and cosine coefficients for along-track and cross-track (15-min for KOMPSAT-2 and simulated KOMPSAT-5 data)</td>
</tr>
</tbody>
</table>

Figure 12 validates the orbit accuracy by comparing between POD and OOD solution for the estimation using single-frequency GPS data (TOPSTAR 3000). OOD uses KOMPSAT-2 GPS navigation solution as explained by OOD estimation and dynamic GUI. POD is regarded as truth orbit in this comparison. KOMPSAT-2 GPS raw data are prepared from telemetry for the date of Nov. 1, 2009. The ephemeris difference shows roughly 3.48 m RMS in three-dimensions. The difference satisfied the requirement of 5 m (one-sigma) RSS in OOD.
C. GPS Data Simulation GUI

FDS OD module can generate simulation data using IGS ephemeris file. Orbital elements of Low-Earth-Orbiter (LEO) satellite are propagated using the detailed dynamic model. Figure 13 is the GUI of simulation POD data generation. If initial orbit epoch and IGS GPS ephemeris are provided, GPS raw data are generated according to the start and end time. Reference GPS raw data of the IGS ground station are also generated by choosing following stations (AUCK, BRUS, DAV1 … and so on) on GUI.

Figure 13. GUI for simulation GPS data.

Figure 14 shows dynamic and observation model, used to propagate orbit numerically using initial epoch in figure13. Ionosphere delay error is added using IRI-95 model. For the GPS raw data of IGS ground reference stations, troposphere delay is considered by selecting models as provided in GUI.

Figure 14. Dynamic and observation models for GPS data simulation.
In figure 15, error modeling values are given. For GPS satellite orbit, 15 cm error is considered and LEO satellite has 0.05 degree attitude error. Error of cycle slip is added by 0.01% and station position errors are also considered.

**Figure 15. Error models for GPS raw data simulation.**

**D. Validation of POD Using SLR Data**

In SAR mission, the position and velocity accuracy plays an important role. Thus, the results of POD should be demonstrated whether the requirement of POD is periodically satisfied or not. In KOMPSAT-5 POD module, the orbit accuracy is validated using SLR data. Figure 16 shows the SLR estimation GUI. After POD, all dynamic models are stored into SLR module and the determined orbit is propagated using the stored dynamic model and fitted to the SLR data. SLR sites fitting to the POD result can be chosen by user. As seen in figure 16, measurement residuals can be plotted and reported on GUI.

**Figure 16. GUI of orbit validation using SLR data.**
For GRACE satellite, the POD was performed and the result was validated using SLR data. Figure 17 shows the SLR estimation result for GRACE satellite for the date of 12-13 Jan, 2009. Most measurement residuals are less than 30 cm and RMS shows 17 cm as shown by Graphic Statistics on GUI.

![Residual Graph](image)

**Figure 17. Validation of precise orbit determination using SLR data.**

### E. Performance of POD accuracy

In order to investigate the dual-frequency POD performance, GPS simulation data was generated for the date of Feb. 07, 2010. Initial orbit epoch satisfying 421-revolution with 28-day repeat ground track was used [17]. The simulated KOMPSAT-5 and IGS reference ground sites’ GPS data type is dual-frequency. Double-differenced carrier phase data are used and all parameters related to estimation and dynamic models are applied as given by table 2 and figure 11. Figure 18 shows overlapping orbit results for four-hour common data out of 27-hour of 7 Feb. and 30-hour of 8 Feb., 2010. In three-dimension, the overlapping orbit error shows 13.5 cm RSS.

![Overlapping Orbit](image)

**Figure 18. Overlapping orbit solution for simulated KOMPSAT-5 satellite.**

Next, validation of POD is to compare POD result with truth orbit. The truth orbit was estimated using error-free GPS raw data. For one-day arc length, position error was estimated in 14.8 cm RSS (figure 19). Figure 20 shows the velocity difference with truth orbit. The velocity difference in three-dimension is 0.15 mm/s RSS. Thus, the requirements, to be required to perform KOMPSAT-5 missions, that position and velocity error should be less than 20 cm and 0.3 mm/s RSS in one-sigma are met.
IV. Conclusions

KOMPSAT-5 orbit determination was designed using object-oriented-analysis and design method and implemented by FORTRAN programming for OD and C++ for GUI. Logical view and object domain modeling are presented for orbit determination analysis of FDS. Interfaces between user and FDS modules are handled by GUI. The validation of the OD functions and performances are shown through GUI and some simulation results. The requirements of OOD and POD performances are fully satisfied and verified for KOMPSAT-5 normal operation.
References


