Orbit Determination Accuracy Improvement for Geostationary Satellite with Single Station Antenna Tracking Data

Yoola Hwang, Byoung-Sun Lee, Hae-Yeon Kim, Haedong Kim, and Jaehoon Kim

An operational orbit determination (OD) and prediction system for the geostationary Communication, Ocean, and Meteorological Satellite (COMS) mission requires accurate satellite positioning knowledge to accomplish image navigation registration on the ground. Ranging and tracking data from a single ground station is used for COMS OD in normal operation. However, the orbital longitude of the COMS is so close to that of satellite tracking sites that geometric singularity affects observability. A method to solve the azimuth bias of a single station in singularity is to periodically apply an estimated azimuth bias using the ranging and tracking data of two stations. Velocity increments of a wheel off-loading maneuver which is performed twice a day are fixed by planned values without considering maneuver efficiency during OD. Using only single-station data with the correction of the azimuth bias, OD can achieve three-sigma position accuracy on the order of 1.5 km root-sum-square.

Keywords: Orbit determination, geometric singularity, bias estimation, single station tracking, satellite control.

I. Introduction

The Communication, Ocean, and Meteorological Satellite (COMS), which will be placed on the geostationary orbit at 128.2° east longitude, is scheduled to be launched in 2009. The COMS, based on the latest version of EADS Atrium's spacecraft platform Eurostar 3000 series, will carry three payloads related to Ka-band communication services, meteorological monitoring, and ocean observation. However, the COMS is the first satellite to perform those missions together. EADS Astrium has built the spacecraft bus and oceanography payload. Electronics Telecommunications Research Institute (ETRI) has developed the satellite ground control system (SGCS) of the COMS and Ka-band communication service payload. The SGCS will control the payloads and satellite bus system. The flight dynamics subsystem supports orbit determination and prediction (ODP), station keeping (SK), and event prediction [1]. The COMS operational orbit determination (OD) is accomplished using ranging and angle tracking data from a single station with a 13 m antenna everyday. The results of OD that provide the definitive orbit information are propagated for a 48-hour predicted orbit. The orbit prediction results are delivered to the image data acquisition center to accomplish image navigation registration (INR) on the ground, whereas typical geostationary meteorological satellites process INR on board. Thus, since the accuracy of the COMS ODP sensitively affects the processing of image data, the requirements of the COMS ODP should be met for mission operations. However, the orbital longitude of the COMS is located at 128.2° east, and only one site at

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Yoola Hwang (phone: + 82 42 860 6832, email: ylhwang@etri.re.kr), Byoung-Sun Lee (email: lbs@etri.re.kr), Hae-Yeon Kim (email: specialk@etri.re.kr), Jaehoon Kim (email: jhkim@etri.re.kr) are with the Broadcasting & Telecommunications Convergence Research Laboratory, ETRI, Daejeon, Rep. of Korea.

Haedong Kim (email: haedong@sejong.ac.kr) is with the Department of Aerospace Engineering, Sejong University, Seoul, Rep. of Korea.

127.36° east is used for satellite tracking. Thus, the small longitude difference between the satellite and tracking site raises geometric singularity in observability [2]. We cannot solve the azimuth bias with only one station due to geometric singularity. Therefore, we must correct the azimuth bias periodically using another external site.

In Europe, to calibrate the angle tracking bias with a 13 m antenna for the Pedu (Belgium) station, a highly accurate orbit determination with ranging data was performed for the ECS-1 and OTS-2 communication satellites using the external Villafranca (Spain) station. The simulated angle tracking data using the accurate orbit was calculated and subtracted from real measurement [3]. In this research, the angle tracking bias is estimated directly during OD without additional simulation data generation that can include dynamic model error.

The COMS consists of a box and a one-side solar array as shown in Fig. 1, which is noticeably different from typical geostationary satellites. This special configuration brings an attitude error due to the torque around the center of mass caused by solar radiation pressure acting on the solar panel. A momentum wheel control is operated in the COMS to compensate the torque caused by solar radiation pressure. However, in the process of absorbing the rotational momentum of the COMS, the rotational speed of the momentum wheel eventually surpasses the operation limits and becomes uncontrollable after a certain time. To reduce the accelerating rotation speed of the momentum wheel, a thruster should be periodically fired. Thus, the COMS fires a thruster twice every day in a so-called wheel off-loading (WOL) maneuver. The COMS performs WOL and SK maneuvers for north-south (NS) and east-west (EW) directions every week. Therefore, those velocity increments resulting from the frequent maneuvers cannot be ignored to fulfill the mission requirement for the COMS ODP. In multi-station error analysis, if at least 2 km (1σ) position accuracy is required, two stations should be chosen [4]. However, our goal is to satisfy the INR OD requirement, that is, roughly 5 km root-sum-square (RSS) (3σ) including frequent maneuvers from single-ground station data.

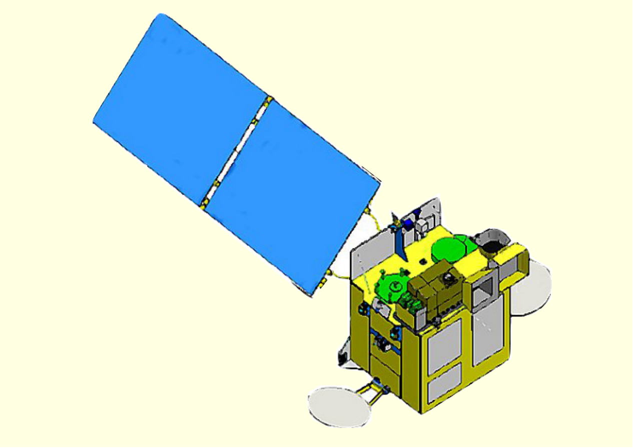


Fig. 1. Configuration of COMS (image courtesy of KARI).

Table 1. COMS orbital elements (Epoch: UTC 00:00:00 1 Jan., 2006).

Orbit type		Geostationary	
Spacecraft mass		1547 kg	
Cross-sectional area		18.941 m^2	
Cartesian (TOD)		Keplerian (TOD)	
X	-27828.9136 (km)	a	42165.0 (km)
Y	-31685.02205 (km)	e	0.00014142
Z	3.51107 (km)	i	0.036056 (°)
Vx	2.30981 (km/s)	Ω	56.30993 (°)
Vy	-2.02866 (km/s)	ω	348.69007 (°)
Vz	-0.00192 (km/s)	M	183.70825 (°)

This paper presents a method of data simulation for ranging and tracking, including noise, constant bias, and non-repeatable error. To validate the OD results, we use previously studied covariance analysis. Also, the OD strategies to be used in the COMS operational system and examples of the ODP accuracy achieved are discussed.

II. Ranging and Tracking Data Generation

Ranging and angle tracking data during the period of Jan. 1-4, 2006 for the COMS at 128.2° east longitude and the ground station at 127.36° east longitude and 36.4° north latitude were prepared. Reference orbit elements are shown in Table 1. We assumed the cross-sectional area-to-mass ratio to be 0.0122 m^2/kg for the COMS data generation. We defined the satellite position for Jan. 1, 2006 using the Cartesian or Keplerian coordinates of the true-of-date (TOD) system.

Data sets for the days of Jan. 1-4, 2006 were simulated using the following dynamic perturbations: Earth Gravity Model 96 (EGM96) [5], [6] model complete to degree and order six, Luni-Solar gravitational perturbation using Jet Propulsion Laboratory (JPL)'s DE 405 model, solar radiation pressure [7], and velocity increments (ΔV) of the WOL and SK maneuvers. Solar radiation pressure error was simulated to be 10% error for area-to-mass. Maneuver time and velocity increments for each direction component of WOL, and east-west station-keeping (EWSK) and north-south station-keeping (NSSK) were simulated as shown in Table 2. The WOL maneuver was performed twice per day to remove the accelerating momentum along three-axis direction at UTC 00:45 and 06:45 during a total of 10 minutes in the January period (see Table 2) [8]. To maintain the location of COMS within a ± 0.05°

Table 2. Velocity increments according to the maneuver plan (year: 2006).

Time (UTC)	Type	Radial (m/s)	Along-track (m/s)	Cross-track (m/s)
00:45:00.00 (daily)	WOL	-0.00193	-0.00158	0.00967
06:45:00.00 (daily)	WOL	-0.000539	0.00062	0.00301
18:10:00.00, Jan. 1	NSSK	0.0	0.0	-1.0
18:10:00.00, Jan. 3	EWSK	0.0	0.05	0.0

Table 3. Maneuver realization error size for direction components [8]

Type	Radial	Along-track	Cross-track
NSSK	2% of $\lvert\Delta V\rvert$	1% of $\lvert\Delta V\rvert$	2% of $\lvert\Delta V\rvert$
EWSK	10% of $\lvert\Delta V\rvert$	2% of $\lvert\Delta V\rvert$	2% of $\lvert\Delta V\rvert$
WOL	20% of $\lvert\Delta V\rvert$	20% of $\lvert\Delta V\rvert$	20% of $\lvert\Delta V\rvert$

Table 4. Antenna noise, bias, and non-repeatable error [10].

	Range (m)	Azimuth (°)	Elevation (°)
Noise	10	0.011	0.011
Constant bias	20	0.004	No requirements
Non-repeatable error	N.A.	~0.0079	~0.0081
Thermal distortion	N.A.	Periodic: 0.002 Random error: 0.002	Periodic: 0.002 Random error: 0.002
Wind effect	N.A.	Random error: 0.004	Random error: 0.004

control box, NSSK and EWSK should be performed every week according to the maneuver plan.

We assumed that there was 10% maneuver realization error for the radial direction and 2% maneuver realization error for the along-track component when the EWSK was in actual operation. Here, maneuver realization error means the difference between the maneuver predicted theoretically and the velocity increment actually performed. Table 3 gives an example of the maneuver realization error size at each direction component for the COMS based on the Eurostar 3000 platform, which was provided by EADS Astrium. For instance, the NSSK maneuver realization errors of the radial and cross-track directions were expected to be 2% of absolute value of total ΔV.

Noise, constant bias, and non-repeatable error shown in Table 4 were applied to the tracking and ranging data generation for the nominal 13 m antenna at a site in Daejeon, Rep. of Korea. Here, angle tracking data was used to supplement the ranging, and together they could achieve the orbit accuracy required for COMS [3], [9]. Gaussian white noise was used to generate random noise of measurement. The noise of the azimuth and elevation angle tracking data had a 0.011° root mean square (RMS). Where the constant bias for azimuth tracking data was simulated to have a 0.004° RMS, non-repeatable error that mainly retains thermal distortion and wind effect was also modeled. We distinguished thermal distortion error from periodic and random error. The periodic thermal distortion was modeled by a sinusoidal curve. This error gives a peak amplitude of thermal distortion for the local time from 14:00 to 15:00. The amplitude of periodic thermal distortion has a 0.002° RMS. During the night, we ignored the thermal periodic error. Random error for thermal distortion was modeled to have a 0.002° RMS. However, we simulated non-repeatable error for total thermal distortion such that it had an approximately 0.003° RMS. Error of the wind effect considered as a random number correlated for a burst but uncorrelated between bursts was generated to have a 0.004° RMS. Thus, we modeled the total non-repeatable error so that it had an RMS of up to 0.0078° for angle tracking data. However, the angular tracking bias including non-repeatable error should be less than an RMS of 0.012° in 3σ.

We generated 10-minute burst data per hour for two-day data arcs. We used a ground station in Perth, Australia, located at 115.885° longitude and -31.802° latitude as an external site. The Perth station data was simulated to have only 0.011° of noise for angle tracking data, and a 10 meter noise range. We assumed that the bias of the Perth station was accurately known.

III. Orbit Determination Using Ranging and Angle-Tracking Data

The primary OD requirement for the COMS mission is that the accuracy of the satellite position is better than 4 km along the NS direction and 4 km along the EW direction in 3σ using ranging and tracking data from a single ground station. Here, the error of the NS direction is the sum of the OD error and the NS maneuver efficiency error. We used the same fidelity dynamic model introduced in data simulation. In the OD process, the orbit state includes position, velocity, the solar radiation pressure coefficient, as well as the bias set of range, azimuth, and elevation angle for each station, and velocity increments due to the SK maneuver. The batch least square estimator method is used to reduce the error between the calculated dynamic model and measurement. The variable Runge-Kutta7-8 method is used for the orbit integration.

In particular, the azimuth tracking bias of the Daejeon single station is not estimated because of the singularity problem that results from the lack of observability. During OD with the measurement of a single ground station, the azimuth bias is just ignored if the azimuth bias is not estimated using an external ground station. Here, we mention the estimation of the azimuth bias using two ground stations and analyze how much orbit accuracy is improved.

1. Measurement Modeling

With only range measurement, it is hard to determine the exact orbit solution in a single station. Angle-tracking data is used to compensate for the orbit accuracy. The position vector of a single station is defined as a R_{GS} in an earth-centered earth-fixed (ECEF) coordinate, where spacecraft position, R, can also be expressed in the ECEF coordinate system. The range vector of the distance between the spacecraft and the ground station is

$$\rho = \left\| R - R_{GS} \right\| + \Delta\rho + v_{\rho}\,. \tag{1}$$

Here, $\Delta\rho$ is the range offset, and v_{ρ} represents the range noise. We denote the station to spacecraft vector of the topocentric frame using a coordinate transformation, $\mathbf{C}_{\mathrm{ECEF}}^{\mathrm{Topocentric}}$ as

$$\vec{\rho}_{\mathrm{Topocentric}} = \mathbf{C}_{\mathrm{ECEF}}^{\mathrm{Topocentric}} \left(\vec{R} - \vec{R}_{GS} \right). \tag{2}$$

Angle-tracking data, azimuth, and elevation are obtained from the combination of each range direction vector:

$$\begin{aligned} Az &= \operatorname{atan} 2\left(\rho_y, \rho_x \right) + \Delta Az + v_{Az}, \\ El &= \sin^{-1}\left(\frac{\rho_z}{\rho} \right) + \Delta El + v_{El}. \end{aligned} \tag{3}$$

An observation mapping matrix for each measurement is expressed as

$$\mathbf{H} = \frac{\partial \mathbf{G}(t,\mathbf{z})}{\partial \mathbf{z}} = \begin{bmatrix} \dfrac{\partial \rho}{\partial \mathbf{z}} & \dfrac{\partial Az}{\partial \mathbf{z}} & \dfrac{\partial El}{\partial \mathbf{z}} \end{bmatrix}. \tag{4}$$

During OD using single-station ranging and antenna tracking data, the observation mapping matrix of (4) is used to calculate the error between measurement and the dynamic model.

2. Covariance Analysis

The predicted covariance of the COMS system using measurement data from a single station or two stations has been analyzed. Here, measurement biases are used as a consider parameter among the possible consider parameters. Thus, estimated states for OD error analysis are position, velocity, and solar radiation coefficients and consider states are angular biases. For each type of measurement (depending on the number of applied ground stations), we form partial derivatives of full state $\mathbf{z}$ with respect to the estimation parameter $\mathbf{x}$ and consider parameter $\mathbf{c}$ as shown in (5) through (7).

$$\mathbf{z} = \begin{bmatrix} \mathbf{x} \\ \mathbf{c} \end{bmatrix}, \quad \mathbf{H} = [\mathbf{H}_x \,\vdots\, \mathbf{H}_c], \tag{5}$$

$$\mathbf{H}_x = \begin{bmatrix} \dfrac{\partial \rho_1}{\partial \mathbf{x}}, \dfrac{\partial A_1}{\partial \mathbf{x}}, \dfrac{\partial E_1}{\partial \mathbf{x}}, \dfrac{\partial \rho_2}{\partial \mathbf{x},} \dfrac{\partial A_2}{\partial \mathbf{x}}, \dfrac{\partial E_2}{\partial \mathbf{x}} \end{bmatrix}^T, \tag{6}$$

$$\mathbf{H}_c = \begin{bmatrix} \dfrac{\partial \rho_1}{\partial \mathbf{c}}, \dfrac{\partial A_1}{\partial \mathbf{c}}, \dfrac{\partial E_1}{\partial \mathbf{c}}, \dfrac{\partial \rho_2}{\partial \mathbf{c},} \dfrac{\partial A_2}{\partial \mathbf{c}}, \dfrac{\partial E_2}{\partial \mathbf{c}} \end{bmatrix}^T. \tag{7}$$

Here, subscripts 1 and 2 mean two ground stations, namely, Daejeon and Perth. For the time-dependent state vector, measurement time j in observation mapping matrices (6) and (7) is mapped to the estimation epoch time k of the batch processor as expressed in [11] as

$$\mathbf{y}_j = \begin{bmatrix} \tilde{\mathbf{H}}_{x_j} & \tilde{\mathbf{H}}_{c_j} \end{bmatrix} \begin{bmatrix} \boldsymbol{\Phi}\left(t_j, t_k\right) & \boldsymbol{\theta}\left(t_j, t_k\right) \\ 0 & \mathbf{I} \end{bmatrix} \begin{bmatrix} \mathbf{x}_k \\ \mathbf{c} \end{bmatrix} + \boldsymbol{\varepsilon}_j, \tag{8}$$

where $\tilde{\mathbf{H}}_{x_j}$ and $\tilde{\mathbf{H}}_{c_j}$ are observation-state mapping matrices for measurement epoch j; $\mathbf{I}$ denotes an identity matrix; $\boldsymbol{\Phi}(t_j, t_k)$ and $\boldsymbol{\theta}(t_j, t_k)$ are mapping matrices with respect to dynamic and measurement models, respectively. The consider covariance matrix of the batch filter can be written as in [12] as

$$\begin{aligned} \mathbf{P}_c &= \mathbf{P} + (\mathbf{P}\mathbf{H}_x^T\mathbf{W})(\mathbf{H}_c\mathbf{C}\mathbf{H}_c^T)(\mathbf{P}\mathbf{H}_x^T\mathbf{W})^T, \\ \mathbf{P} &= (\mathbf{H}_x^T\mathbf{W}\mathbf{H}_x)^{-1}, \end{aligned} \tag{9}$$

where weighting matrix $\mathbf{W}$ is the inverse of measurement covariance, and the covariance $\mathbf{C}$ is uncorrelated with the measurement noise. The consider parameters and measurement noise should be distinguished. While data noise can be efficiently decreased by adopting a large number of measurements, consider parameters are assumed to be constant throughout the OD affected by the given uncertainty [12].

For the covariance study, the predicted covariance was calculated for three cases as shown in Table 5. The positioning accuracy using 48-hour angle-tracking measurements with 0.012° bias (including constant bias and non-repeatable error) and the 0.011° noise of only the Daejeon station shows 5.38 km RSS for the considered uncertainty. In this case, we did not estimate any bias because of the singularity problem. When we investigated the two-station OD results, the error of the OD was within 1 km as shown in Table 5. This analysis shows that the estimation of the angle bias is essential to reduce the influence on systematic errors. The orbit error of the

Table 5. Position vector accuracy analysis (unit: km).

Estimate parameters	Ground station	Radial	Along-track	Cross-track	3-D (3σ)
No bias estimate (48 h)	Daejeon	0.145	5.191	1.399	5.378
Angle bias estimate (48 h)	Daejeon + Perth	0.021	0.466	0.015	0.467
Angle bias estimate (24 h)	Daejeon + Perth	0.022	0.583	0.021	0.584

24-hour data arc shows greater error caused by noise than the 48-hour arc due to the arc length.

3. Azimuth Bias Estimation Using Two-Station Tracking Data

According to the covariance analysis, we need to correct the azimuth bias for the OD using single-station measurements to satisfy the INR OD requirement. However, we cannot solve or calibrate the azimuth bias with a single station because the small geographic difference between the satellite and ground station leads to singularity. In other words, when the longitudinal location of the station and that of the satellite are near each other, the error becomes large. In this case, the longitude and its drift rate are not observable by ranging and can only be determined by azimuth tracking [2]. As an external site, we selected the Perth ground station to estimate the azimuth bias periodically or whenever necessary. Angle tracking data was compensated by the azimuth bias estimated using two ground stations for a 24-hour data arc which does not include a maneuver plan. Because a maneuver plan that does not consider maneuver efficiency degrades the OD results, we could not estimate the azimuth constant bias exactly. All noises and biases mentioned in data generation (Table 4) were applied to the Daejeon station for 24-hour arc. Since it was assumed that for the data set of the Perth station the bias of the angular tracking data could be known perfectly, we fixed the biases of Perth during estimation. Our goal was to estimate only the azimuth bias of the Daejeon site, and we did not consider the biases of range and elevation. Elevation bias is estimated independently during OD, and ranging bias can be calibrated and updated periodically. Table 6 shows the estimated orbit states and azimuth bias using two stations. The third column in Table 6 shows the differences between the estimated initial orbits and the orbits assumed *a priori* as the true orbits for data generation. The estimated orbit position error appears as 0.641 km RSS, whereas the covariance analysis shows 0.584 km RSS based on the 24-hour data arc (Table 5). The azimuth bias for the nominal 13 m antenna with error models shown in Table 4 was estimated to have a 0.0091° RMS for the 24-hour data arc.

Table 6. Estimated azimuth bias and OD results for a 24-hour arc which does not include any maneuvers. Biases of range and elevation angle are perfectly known during OD.

Epoch	UTC 00:00:00, Jan. 1, 2006	
	Estimated values (TOD)	Difference from *a priori* (absolute value)
X (km)	-27829.40838	0.49474
Y (km)	-31684.61580	0.40625
Z (km)	3.47799	0.03308
Vx (km/s)	2.30978	3.14576e-5
Vy (km/s)	-2.02870	3.46081e-5
Vz (km/s)	-0.00192	1.01345e-6
Az bias (deg)	0.0091	-

IV. Orbit Determination Accuracy

1. Orbit Comparison with True Orbit

Several data sets were tested to provide an accurate orbit for a two-day solution arc. A true reference orbit is defined as a simulated orbit that contains velocity increments due to SK and WOL maneuvers as well as maneuver realization error. The determined orbit and true orbit were compared to investigate orbit accuracy. Those orbits are compared in the TOD coordinate system, and internally, the J2000 coordinate system was used for OD.

Table 7 shows the results of the orbit differences between the true orbit and the determined orbit for 48-hour arcs using single-station measurement. The initial orbit fit to the measurement is biased by a maximum of 0.012° which includes non-repeatable error in the azimuth direction. This result matches with the covariance study result that the OD error of the Daejeon station with 0.012° azimuth bias is roughly 5 km RSS. However, the OD results do not fulfill the along-track INR requirement without azimuth bias correction.

To overcome the difficulties in accomplishing OD with the Daejeon site, we assumed that the Perth station would be used to estimate the azimuth bias. For a 24-hour data arc without any maneuver, a 0.091° azimuth bias was estimated (Table 6). The estimated bias value was added to the azimuth data of the Daejeon site as a constant. In Table 8, we compare the true orbit to the determined orbit using 48-hour measurement corrected by azimuth bias. This 48-hour data includes NSSK, EWSK, and maneuver realization error as presented in Tables

Table 7. Comparison of 48-hour OD solution for single station without azimuth bias estimation to true orbit (unit: km, year: 2006).

Arc	Radial	Along-track	Cross-track	3-D (3σ)
Jan. 1-2	0.115	4.229	0.919	4.329
Jan. 2-3	0.104	5.122	0.996	5.219
Jan. 3-4	0.090	5.047	0.778	5.107
Jan. 4-5	0.127	4.744	1.209	4.898

Table 8. Comparison of 48-hour OD solution to true orbit after azimuth bias correction for single station (unit: km, year: 2006).

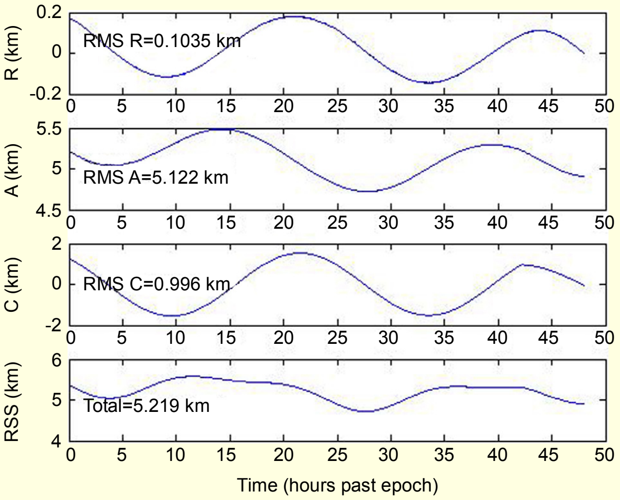
Arc	Radial	Along-track	Cross-track	3-D (3σ)
Jan. 1-2	0.115	0.434	0.918	1.022
Jan. 2-3	0.104	1.208	0.995	1.568
Jan. 3-4	0.090	1.147	0.777	1.388
Jan. 4-5	0.127	0.867	1.208	1.492

Table 9. Comparison of 48-hour OD solution using two ground station to true orbit (unit: km, year: 2006).

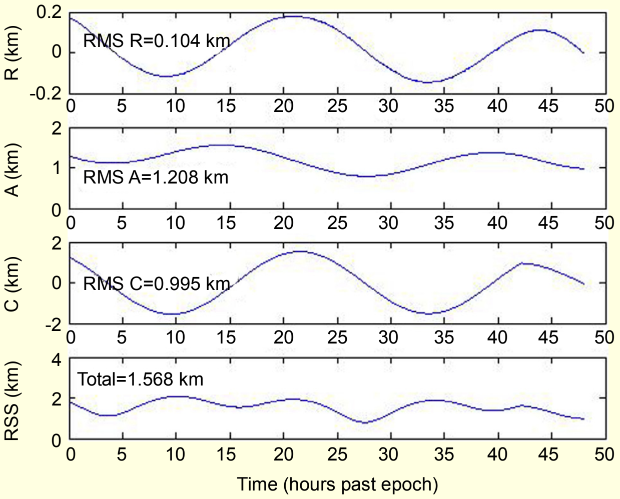
Arc	Radial	Along-track	Cross- track	3-D (3σ)
Jan. 1-2	0.019	0.561	0.045	0.563
Jan. 2-3	0.033	0.930	0.046	0.932
Jan. 3-4	0.023	0.733	0.032	0.734
Jan. 4-5	0.039	1.017	0.037	1.019

2 and 3. The OD accuracy is roughly between 1 km and 2 km RSS in a 3-D sense. When we compare Tables 7 and 8, the OD errors of radial and cross-track directions show almost the same orders of magnitude. The along-track error was noticeably reduced from 5 km to 1 km RMS.

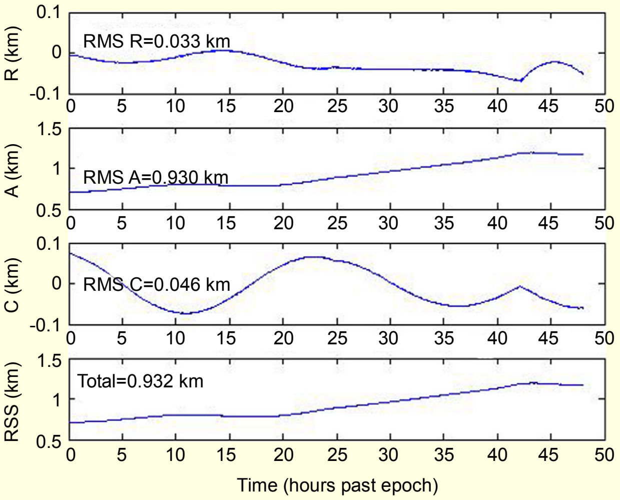
To investigate how much orbit accuracy is improved, we simulated the Perth data under normal operation to accomplish OD using ranging and tracking data of two ground stations. Also, the velocity increments of the WOL and SK maneuvers were maintained at previously defined values for the COMS mission (Tables 2 and 3). When OD was processed using tracking and ranging data of two stations, the orbit error showed results which are consistent with the results of OD using azimuth-bias-corrected measurements of a single station. The arc of Jan. 1-2, 2006 shows an accurate ephemeris difference of up to 0.56 km RSS when it is compared to the true orbit, while the arc of Jan. 4-5, 2006 has an orbit error of more than 1 km RSS in a 3-D sense due to the maneuver realization error incurred due to the WOL maneuver (Table 9). The velocity increments due to WOL maneuver were fixed



(a) OD using single station without azimuth bias correction

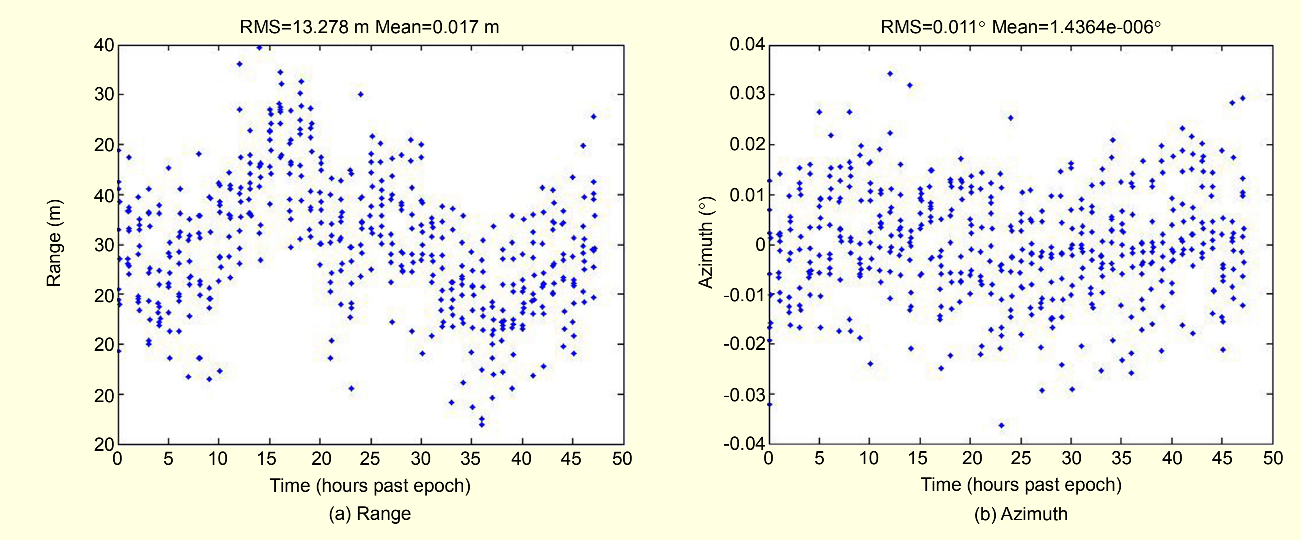


(b) OD using single station with azimuth bias correction



(c) OD using two stations with angle bias estimation

Fig. 2. Differences between true orbit and determined orbit for each case (Jan. 2-3, 2006). R: radial, A: along-track, C: cross-track.



(a) Range

(b) Azimuth

Fig. 3. Postfit residuals for two-day OD with azimuth bias correction (Jan. 1-2, 2006).

Table 10. RMS for measurements (year: 2006).

	Single station without azimuth bias correction			Single station with azimuth bias correction			Two stations with angle bias estimation		
Arc	Range (m)	Azimuth (°)	Elevation (°)	Range (m)	Azimuth (°)	Elevation (°)	Range (m)	Azimuth (°)	Elevation (°)
Jan. 1-2	13.277	0.0110	0.0110	13.278	0.0110	0.0110	14.195	0.0111	0.0111
Jan. 2-3	21.098	0.0116	0.0115	21.078	0.0116	0.0115	21.70	0.0116	0.0116
Jan. 3-4	11.318	0.0103	0.0102	11.331	0.0103	0.0102	12.408	0.0103	0.0103
Jan. 4-5	23.0	0.0111	0.0110	22.884	0.0111	0.0110	25.225	0.0111	0.0111

without any estimation. Thus, maneuver realization error brought greater orbit error in the arc of Jan. 4-5, 2006 despite the fact that it did not have any SK maneuver, when all measurement biases were corrected by two stations. We can induce changes in the velocity estimation by the SK maneuver, which absorbs velocity increment errors incurred due to the WOL maneuver, based on this result when there is no bias error.

Figure 2 shows orbit errors compared to the true orbit for the arc of Jan. 2-3, 2006 as an example OD solution. Figure 2(a) shows the results of OD using measurement by a single station without bias correction. Clearly, there is a maneuver through the peak of the cross-track direction. As shown in Table 2, EWSK was performed at 18:10:00.00, Jan. 3, 2006. Even though the velocity increments due to the EWSK maneuver were estimated, the bias error and maneuver realization error of WOL affected the OD accuracy. Figure 2(b) shows smaller OD error than Fig. 2(a) in along-track direction. This shows that the azimuth bias was corrected, but there were errors due to the WOL and other measurement noise. Figure 2(c) shows the OD error incurred using measurement by two stations. The velocity increment errors resulting from maneuvers, such as WOL, occupies all OD error terms in Fig. 2(c).

2. Measurement Residuals

Measurement residual is one indicator of orbit determination accuracy. An analysis was conducted to determine typical noise levels for range, azimuth, and elevation data that would result in orbits with the desired level of accuracy. Figures 3(a) and (b) show post-fit residuals of a two-day arc for ranging and angle-tracking data. For brevity, only post-fit residuals of the Jan. 1-2 arc are plotted. Table 10 shows post-fit residuals for each OD result for various measurement cases. For all measurement cases, the post-fit residuals show almost the same results because their biases rely on a constant. The results of the post-fit residuals show noise levels of about 15 m range RMS and 0.011° angle-tracking RMS.

3. Estimated Maneuver Parameters

During the nominal operation, the estimation of maneuver parameters is important in processing OD since the estimated

Table 11. Estimated maneuver parameters for two-day OD.

Data arc	Axis	Real applied Δv_t (m/s)	No azimuth bias correction of single station Δv_{est} (m/s)	Azimuth bias correction of single station Δv_{est} (m/s)	Two stations Δv_{est} (m/s)
Jan. 1-2, 2006 (NSSK)	Radial	$\pm\|0.02\|$	0.0223	0.0223	0.0231
	Along-track	$\pm\|0.01\|$	0.00913	0.00913	0.00925
	Cross-track	$-1\pm\|0.02\|$	-1.0165	-1.0165	-1.0146
Jan. 2-3, 2006 (EWSK)	Radial	$\pm\|0.005\|$	0.00516	0.00516	-0.00444
	Along-track	$0.05\pm\|0.001\|$	0.0550	0.0550	0.0552
	Cross-track	$\pm\|0.001\|$	0.0912	0.0912	0.00889
Jan. 3-4, 2006 (EWSK)	Radial	$\pm\|0.005\|$	-0.00360	-0.00360	0.00877
	Along-track	$0.05\pm\|0.001\|$	0.0501	0.0501	0.0501
	Cross-track	$\pm\|0.001\|$	-0.1201	-0.120	-0.0034

velocity increments directly affect orbit propagation. Table 11 shows the estimation of velocity increments for NSSK and EWSK maneuvers during 48-hour OD. We notice that the estimated velocity parameters, Δv_{est}, are roughly consistent with real applied velocity increments, Δv_t, including maneuver realization error.

As shown in Table 11, for EWSK and NSSK maneuvers, the estimated velocity increments based on two-day OD results have an order of magnitude that is roughly as we expected. In the third column, the absolute value is the maneuver realization error. When we estimate velocity changes due to the NSSK maneuver, the results are close to the real velocity increments that are input. However, EWSK shows more errors in radial and cross-track components because they absorb the error of the WOL maneuver for relatively small velocity increments.

V. Concluding Remarks

An operational OD system for the COMS mission has been studied to meet the requirement for each 4 km RMS along the EW and NS direction in 3σ. We analyzed the OD solution through both measurement residual quality and comparison of the determined orbits to true orbits. Also, we investigated the estimate parameters for the maneuver velocity increment. Measurement residuals for ranging and angle-tracking bias show roughly 15 m and 0.011° RMS, which are comparable to the data noise levels.

Even when the longitude of the satellite is near that of the ground station, OD based on simulation data with a 0.011° constant bias and non-repeatable random error shows 5 km RSS in a 3-D sense (3σ). Thus, the accuracy of OD is determined by the constant bias of the azimuth angle in the COMS. When the bias of the azimuth angle is corrected by OD using measurement by two stations, the satellite position error was reduced to a range between 1 km and 1.5 km RSS (3σ). This result indicates that the requirement for the 48-hour determined satellite positioning error to be less than 5.6 km RSS (3σ) in a 3-D sense could be met despite the singularity problem and the performance of the WOL maneuver twice daily.

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Yoola Hwang received the BS degree in astronomy and space sciences from Yonsei University, Seoul, Korea. She received her MS degree in aeronautics and astronautics from Purdue University, W. Lafayette and the PhD degree in aerospace engineering sciences from University of Colorado, Boulder, USA, respectively. She joined ETRI in 2004, where she has been involved in developing the COMS ground control system. She is currently working for flight dynamics of the LEO and GEO satellite ground control system and the GNSS project. Her research interests are orbit determination and prediction, navigation, interplanetary mission design, and GNSS application. She is a member of the Korean Space Science Society, Korea Society for Aeronautical and Space Sciences, American Institute of Aeronautics and Astronautics, and American Astronautical Society.

Byoung-Sun Lee received the BS, MS, and PhD degrees in astronomy and space sciences from Yonsei University, Seoul, Korea in 1986, 1988, and 2001, respectively. He joined ETRI in 1989, where he was involved in developing the KOREASAT project. From 1992 to 1994, he was a visiting engineer with Lockheed-Martin Astrospace, USA and Martra-Marconi Space, UK for the KOREASAT project. From 1995 to 1999, he participated in the KOMPSAT-1 Ground Mission Control project as a senior member of research staff for Mission Analysis and Planning Subsystem. From 2000 to 2005, he worked on the KOMPSAT-2 Ground Mission Control project as a principal member of research staff. Since 2006, he has worked for the KOMPSAT-3, KOMPSAT-5, and COMS-1 Ground Mission Control projects as a principal member of research staff. His research interests are tracking and orbit determination of satellites and station-keeping maneuvers of the collocated geostationary satellites. He is a member of the American Astronautical Society, the Korean Space Science Society, Korea Society for Aeronautical and Space Sciences, and ICASE. He is a member of the editorial board of the Journal of Astronomy and Space Sciences.

Hae-Yeon Kim received the BS and MS degrees in astronomy and space sciences from Yonsei University, Seoul, Korea. She joined ETRI in 2005 and has been involved in the COMS-1 Ground Mission Control project. Her research interests are astrodynamics, satellite ground control, and station-keeping maneuvers of geostationary satellites. She is a member of the Korean Space Science Society and Korea Society for Aeronautical and Space Sciences.

Haedong Kim received the BS and MS degrees in aerospace engineering from Seoul National University, Seoul, Korea in 1989 and 1991, respectively, and the PhD degree in aeronautics and astronautics from Purdue University, IN, USA, in 2001. He is currently an assistant professor of the Department of Aerospace engineering at Sejong University, Seoul, Korea. His main research interests are computational fluid dynamics, helicopter flight simulation, numerical method, spacecraft dynamics, and MEMS gyro. He is a member of the Korea Society for Aeronautical and Space Sciences and American Institute of Aeronautics and Astronautics.

Jaehoon Kim received the PhD degree in computer engineering from Chungbuk National University, Cheongju, Korea in 2001. He joined ETRI in 1983, where he was involved in developing the Intelligent Network and KOREASAT projects. From 1992 to 1994, he was an OJT engineer in Martra-Marconi Space in the UK for the KOREASAT Project. From 1995 to 1999, he participated in the KOMPSAT-1 Ground Mission Control project as a principle member of engineering staff in system engineering. From 2000 to 2005, he participated in the KOMPSAT-2 Ground Mission Control project as the team leader. He is now working for the COMS-1, KOMPSAT-3, and KOMPSAT-5 Ground Mission Control projects as the team leader. His research interests are security in satellite communications, fault diagnosis of satellites using AI technologies, and system modeling using objected-oriented technologies.