OPERATIONAL VALIDATION OF THE FLIGHT DYNAMICS SYSTEM FOR COMS SATELLITE

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Keywords: *COMS, flight dynamics, station-keeping, orbit determination, wheel off-loading*

Abstract: *As a multi-mission GEO satellite, COMS has three payloads including Ka-band communications, geostationary ocean color imager, and meteorological imager. COMS flight dynamics system provides the general on-station functions such as orbit determination, orbit prediction, event prediction, station-keeping maneuver planning, station-relocation maneuver planning, and fuel accounting. There are some specific flight dynamics functions to operate the Eurostar 3000 spacecraft bus such as wheel off-loading management, oscillator updating management, and on-station attitude reacquisition management. In this paper, operational validation of the major functions in COMS flight dynamics system is presented for the first six month of operations period.*

Keywords: *COMS, flight dynamics, station-keeping, orbit determination, wheel off-loading*

1 Introduction

As a multi-mission GEO satellite, Communications, Ocean, and Meteorological Satellite (COMS) was launched in June 26, 2010 by Ariane 5 launch vehicle. After three apogee engine firing and two station-acquisition maneuvers, COMS satellite was stationed at 128.2° East longitude in July 4, 2010. Since then, the COMS satellite ground control system [1] is used for satellite mission operations including satellite tracking and ranging, telemetry reception and processing, command generation and transmission, satellite mission planning, flight dynamics operations, and satellite simulation.

The COMS satellite has three payloads including Ka-band communications, Geostationary Ocean Color Imager (GOCI), and Meteorological Imager (MI). Although the COMS spacecraft bus is based on the Astrium Eurostar 3000 series, it has only one solar array to the south panel because all of the imaging sensors are located on the north panel. In order to maintain the spacecraft attitude with 5 wheels and 7 thrusters, COMS should perform twice a day Wheel Off-Loading (WOL) thruster firing operations which affect on the satellite orbit [2].

COMS Flight Dynamics System (FDS) provides the general on-station functions such as orbit determination, orbit prediction, event prediction, station-keeping maneuver planning, station-relocation maneuver planning, and fuel accounting. All of orbit related functions in flight dynamics system consider the orbital perturbations due to wheel off-loading operations. There are some specific flight dynamics functions to operate the Eurostar 3000 spacecraft bus such as wheel off-loading management, oscillator updating management, and on-station attitude reacquisition management.

An object oriented analysis and design methodology was applied to the COMS FDS development [3]. Programming language C# within Microsoft .NET framework was used for the implementation of COMS flight dynamics system on Windows based personal computer.

In this paper, operational validation of the major functions in COMS FDS is presented for the first six month of operations period. It is very important because the COMS FDS is newly developed and firstly applied to COMS satellite operations. The another newly developed ground control systems including tracking, telemetry, and command system, real-time operations system, and

mission planning system have been also validated during a first three months of In-Orbit Test (IOT) periods[4].
Orbit determination using single ground station measurement data was performed in everyday considering twice-a-day wheel off-loading maneuver. On-board fuel consumption and velocity increments during the wheel off-loading maneuver were reckoned using thruster related telemetry data. Occasionally ground station antenna bias estimation was carried out using foreign ground station data because there is a geometrical singularity in longitudinal separation between COMS satellite and Daejeon station. Weekly based North-South Station-Keeping (NSSK) and East-West Station-Keeping (EWSK) maneuvers were applied to maintain the satellite within 128.2°±0.05° box. The updating parameters for sidereal day oscillator and tropical year oscillator were calculated in COMS FDS. The updated oscillator parameters were uploaded on-board the spacecraft once a month. Orbital events such as the blinding of the Earth sensor, GOCI, and MI were predicted for satellite operations.

2. Orbit Determination and prediction

The orbit determination and prediction should be carried out everyday for ground based Image Navigation and Registration (INR). The orbit determination performance should satisfy the position error of 4 km in one sigma. The orbit determination should consider twice a day wheel off-loading thruster firing operations for stabilizing the attitude and weekly NSSK and EWSK maneuvers for maintaining the position of the satellite within 128.2°±0.05°. As an example, Table 1 shows the velocity increments by WOL and station-keeping maneuvers.

Table 1. Velocity increments according to the maneuver plan.

Time (UTC) YYYY/MM/DD hh:mm:ss.sss	Type	Radial (m/s)	Along-track (m/s)	Cross-track (m/s)
2010/8/daily 06:45:00.000	WOL	-0.00136	0.00157	0.00762
2010/8/daily 15:21:00.000	WOL	-0.00054	0.00062	0.00301
2010/8/03 12:04:01.310	NSSK	-0.02507	0.00184	0.89358
2010/8/05 16:31:12.600	EWSK	0.00555	-0.05943	0.01664

During the six months of In-Orbit Test (IOT) period, a batch of ranging data from Dongara in Australia had been additionally used for estimating the azimuth bias of Daejeon station antenna in Korea. Due to the geometrical singularity between the COMS satellite longitude of 128.2° and Daejeon station longitude of 127.354°, the azimuth bias of Daejeon antenna could not be estimated when using single station range and angle measurements [5]. The estimated azimuth bias is directly added to azimuth measurement in Daejeon station. Table 2 shows the locations of Daejeon and Dongara station. The range noises of Daejeon and Dongara stations are 10 m and angle noises of Daejeon station are 0.011° in Root-Mean-Square (RMS) level.

Table 2. Daejeon and Dongara stations measurement noises and biases

Station	Longitude	Latitude	Range (m)		Azimuth (deg)		Elevation (deg)	
			Noise	Bias	Noise	Bias	Noise	Bias
Daejeon	127.354° E	36.379°N	10	20	0.011	0.115*	0.011	0.004
Dongara	115.349° E	29.046°N	10	-	N/A	N/A	N/A	N/A

*Estimated value

We prepared range and angle data from Daejeon and range data from Dongara for the date of August 1 to 8, 2010. The azimuth bias of Daejeon antenna was estimated with eight-day data set. The data set includes one NSSK, one EWSK, and 16 WOL maneuvers. We estimates satellite position, velocity, velocity increments for SK, and azimuth bias in orbit determination. Figure 1 shows the estimated azimuth bias of Daejeon station using Dongara station range data. The azimuth bias is roughly 0.115° average with 0.0017° standard deviation. The azimuth bias, 0.115° is added to real azimuth observation tracked by Daejeon station antenna. Figure 1 presents estimated antenna bias during the orbit determination.

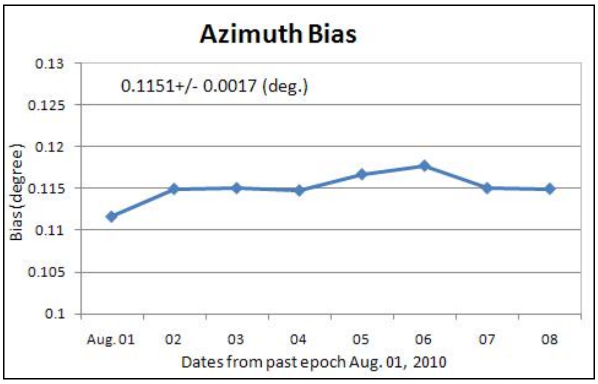

Figure 1. COMS satellite azimuth bias estimation by orbit determination

COMS OD uses high fidelity dynamic model. We consider Earth gravity, solar radiation pressure, and Luni-Solar perturbations. Earth gravity model uses EGM96 [6] six by six in degree and order. Batch-Least-Square-Estimator (BLSE) is used to adjust COMS orbit every day. COMS satellite position, velocity, the coefficient of solar radiation pressure, and velocity increments for SK are estimated. The estimation of the velocity increments are only performed for the date of August 3 and 5, 2010 for the OD performance in this paper (Table 1). In case of the WOL velocity increment, we use planned velocity values instead of the estimated velocity values. Figure 2 - 3 shows measurement residuals for range, azimuth, and elevation for Daejeon site of August 2, 2010, respectively.

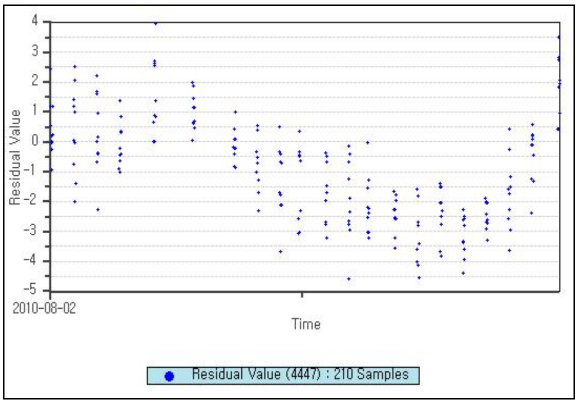

Figure 2. Range residuals of Daejeon station for the date Aug. 2, 2010

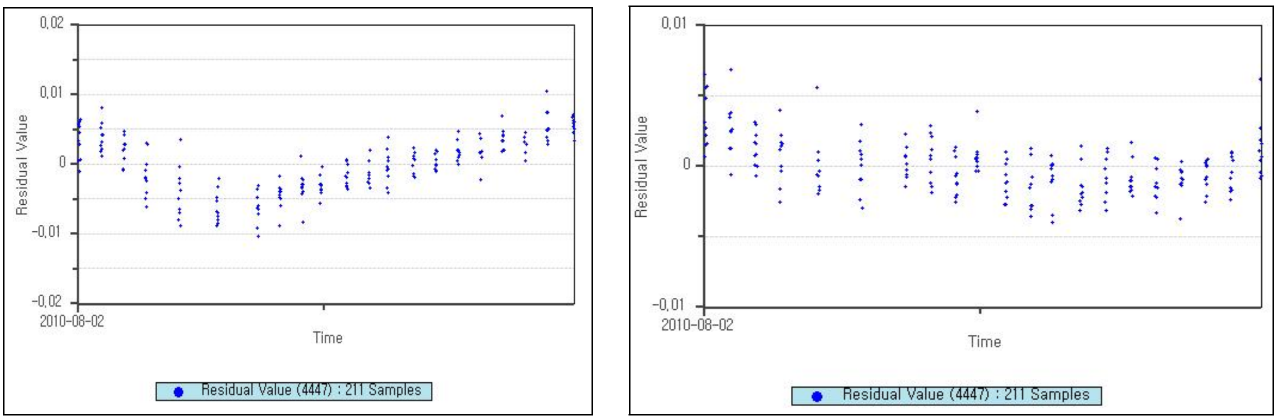

Figure 3. Azimuth and elevation residuals of Daejeon station for the date of Aug. 2, 2010

Figure 4 shows range residuals for OD result using the Daejeon and Dongara site measurement. In this figure two range data are used to determine the orbit for August 2, 2010. Blue dot of 72 samples indicates Dongara station ranging residuals (triangle mark column) and green dot is the residuals of Daejeon site.

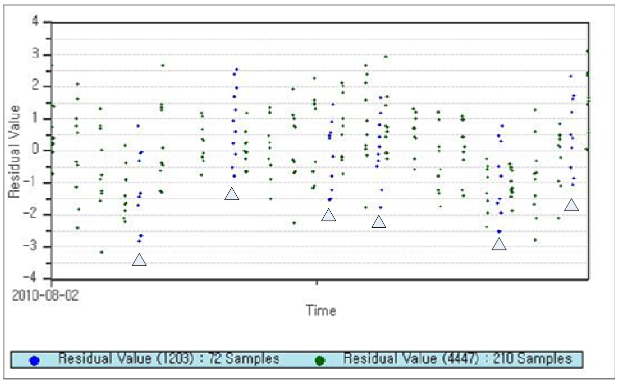

Figure 4. Range residuals of two stations for the date of Aug. 2, 2010 (Blue dot-triangle: Dongara station, Green dot: Daejeon station)

Table 3 summarizes the measurement residuals of the OD results using single (Daejeon) station and two stations for each day. Each range residual shows less than 5 m in RMS for both single and two stations. The average azimuth and elevation residuals show 0.0046° and 0.0024° respectively.

Table 3. RMS for measurement residuals (Aug. 1-8, 2010).

	Single station (Daejeon) OD				Two stations OD		
Arc	Samples of Daejeon	RNG(m)	Az.(deg)	El.(deg)	Samples of Dongara	Dongara RNG(m)	Daejeon RNG(m)
Aug. 01	181	2.07	0.0067	0.0026	51	1.06	1.48
Aug. 02	211	1.75	0.0041	0.0020	72	1.40	1.11
Aug. 03	211	1.38	0.0039	0.0026	51	1.29	1.07
Aug. 04	201	2.79	0.0052	0.0028	45	2.55	2.49
Aug. 05	251	2.82	0.0035	0.0022	48	2.92	2.71
Aug. 06	231	1.94	0.0031	0.0020	61	1.73	1.60
Aug. 07	211	2.45	0.0052	0.0024	51	1.65	1.64
Aug. 08	201	3.16	0.0050	0.0026	52	1.12	1.08
Average	**-**	**2.30**	**0.0046**	**0.0024**	**-**	**1.72**	**1.65**

Table 4 summarizes orbit errors in each direction between single station and two stations OD, between single station OD and OP, and between two stations OD and OP for the date of Aug. 1-8, 2010. While single station OD result used roughly 200 samples, two stations OD was performed using 50-70 samples. The two stations OD is more stable with respect to the orbit propagation. However, orbit differences in each direction are less than 4 km RMS in one-sigma. So, the single station orbit determination meets the performance requirement.

Table 4. Differences among OD using single, two stations, and OP (Aug. 1-8, 2010).

Units (km)	Radial	Along-track	Cross-track	3D
Single station OD - Two stations OD	0.141	1.061	1.379	1.746
Single station OD - OP	0.140	1.412	1.321	1.938
Two stations OD - OP	0.182	1.066	0.114	1.087

3. Station-Keeping Maneuver and wheel off-loading

3.1 Station-Keeping maneuver

Weekly based NSSK and EWSK maneuvers have been performed every Tuesday and Thursday respectively in order to maintain COMS within 128.2°±0.05° longitude and latitude box. The reason performing EWSK two days after NSSK is to compensate tangential side effect caused by NSSK [7]. COMS FDS provides three kinds of NSSK strategy such as Minimum Fuel Target (MFT) [8], Maximum Compensation Target (MCT), Track Back Chord Target (TBCT) and two kinds of EWSK strategy such as one-burn and two-burn. In normal operation, we used to apply MFT/one-burn strategy for NSSK/EWSK maneuver to minimize consumed fuel. If one-burn strategy couldn't control eccentricity and semi-major axis efficiently, two-burn strategy was applied. Figure 5 shows the station keeping maneuver window and Table 5 shows the number of EWSK/NSSK maneuver and Del-V required from July 10 to December 31, 2010. Totals of 25 times EWSK and 24 times NSSK have been performed and in case of EWSK, three times two-burn maneuver has been carried out. The parameters about EWSK/NSSK were stored in maneuver stack and updated after fuel accounting.

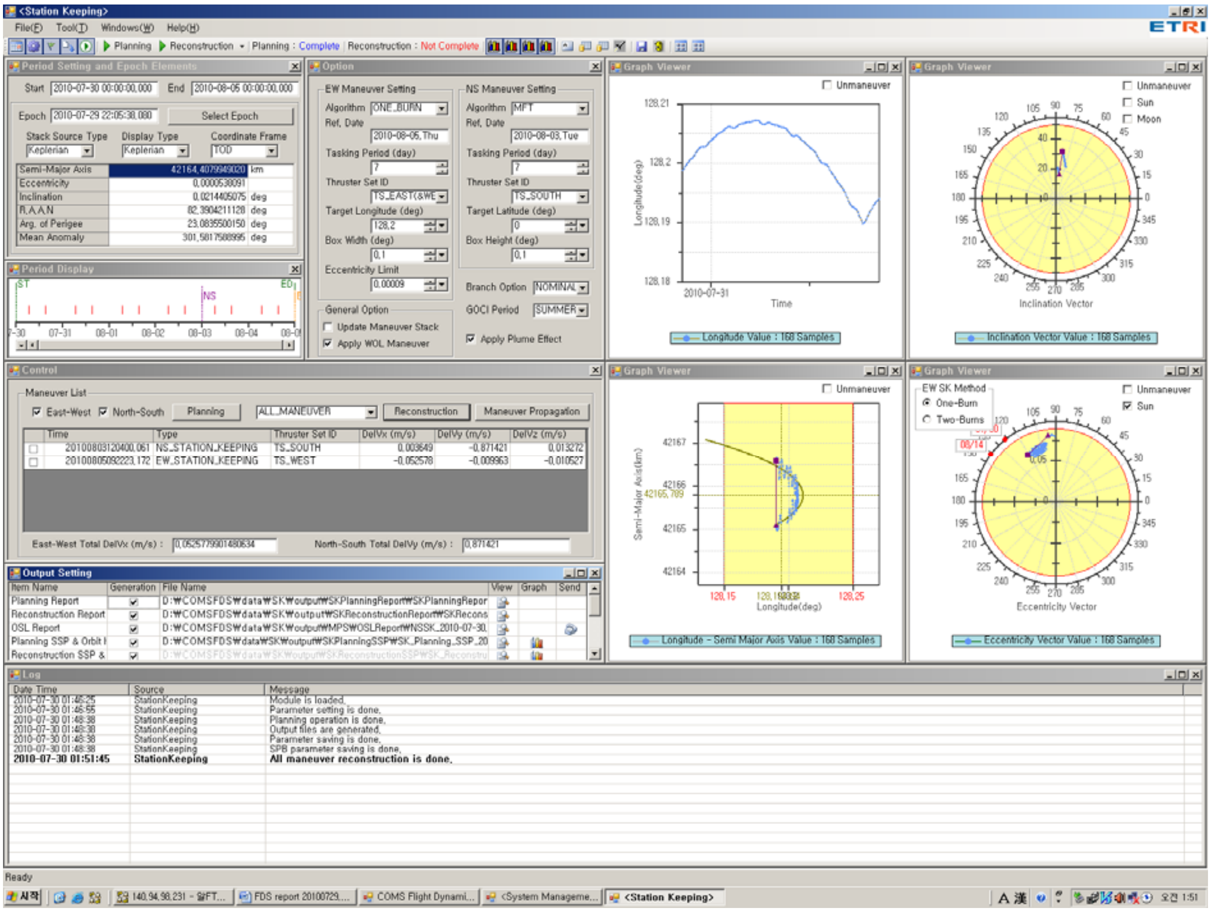

Figure 5. COMS station keeping window

Table 5. Total Del-V of station keeping maneuver

Maneuver	The number of maneuver	Total Del-V (m/s)			Strategy
		Radial	Along-track	Cross-track	
EWSK	25	0.1482	-1.06342	0.3643	One-burn :22 Two-burn :3
NSSK	24	-0.6496	-0.0403	21.4760	MFT

3.2 Wheel Off-Loading

COMS satellite has single solar panel in south panel to avoid thermal effect on GOCI and MI payload in north panel. To cancel excessive torque generated by single solar panel, COMS should perform twice-a-day WOL operations using thruster firing. A seasonal WOL times, and Del-Vs were defined considering effective use of thrusters and fuel optimization as shown in Table 6. The parameters about WOL maneuver were stored in WOL maneuver stack and updated after fuel accounting.

Table 6. Seasonal wheel off-loading time and Del-V

WOL Season	WOL time (UTC)	Del-V (m/s)		
		Radial	Along-track	Cross-track
Period 1 (03/22 - 7/23)	15:21 00:45	1.82e-3 -9.83e-4	-7.75e-5 -8.05e-4	6.51e-3 4.93e-3
Transition (7/24)	15:21 06:45	1.82e-3 -1.36e-3	-7.75e-5 1.57e-3	6.51e-3 7.62e-3
Period 2 (07/25 - 11/23)	15:21 06:45	1.08e-3 -1.36e-3	-4.61e-5 1.57e-3	3.87e-3 7.62e-3
Transition (11/24)	00:45 06:45	-1.93e-3 -5.39e-4	-1.58e-3 6.20e-4	9.67e-3 3.01e-3
Period 3 (11/25 - 3/20)	00:45 06:45	-1.93e-3 -5.39e-4	-1.58e-3 6.20e-4	9.67e-3 3.01e-3
Transition (3/21)	15:21 00:45	1.08e-3 -9.83e-4	-4.61e-5 -8.05e-4	3.87e-3 4.93e-3

After performing the WOL operations in every day, thruster related telemetry was processed in fuel accounting function of COMS FDS. The actual thruster operations were reconstructed based on the telemetry data and thruster modeling. Table 7 presents predicted and reconstructed Del-V for WOL operations from Oct. 5, 2010 to Jan. 26, 2011. The predicted Del-Vs are based on the COMS spacecraft design. There are some differences of Del-V in each orbital direction. The differences are due to the discrepancy between the spacecraft model in design phase and actual environment in space. The WOL maneuver stack data file will be updated based on the actual values for the next year.

Table 7. Predicted and reconstructed Del-V for WOL (2010/10/5 – 2011/1/26)

	Radial (m/sec)	Along-track (m/sec)	Cross-track (m/sec)
Predicted	0.278368	0.220355	1.377950
Reconstructed	0.388379	0.250296	1.893558
Difference	0.110011	0.029941	0.515608
Percentage	39.52	13.59	37.42

3.3 Fuel Accounting

Remaining fuel of COMS has been estimated using two strategies such as Pressure, Volume, and Temperature (PVT) method and Thruster-On-Time (TOT) method. Both methods estimate remaining fuel using telemetry data transmitted from the satellite. PVT method uses temperature and pressure of the fuel tank while, TOT method uses pulse of the thruster firing. In normal operation, we used to apply TOT method for fuel accounting after NSSK, EWSK, and WOL operations.

Figure 6 shows FDS report for TOT fuel accounting. Number of pulses for each used thrusters in COMS satellite were counted to estimate the used fuel and oxidizer. The Delta-Vs for each

direction were also estimated using the thruster modeling. The fuel used during the EWSK maneuver was about 0.03246 kg. Thruster number 5A was used to reduce the orbital speed of the COMS satellite.
Figure 7 presents remaining fuel and oxidizer from July 10 to December 31, 2010. The fuel and oxidizer consumptions during the NSSK maneuvers are shown as downward steps.
Figure 8 depicts consumed fuel and oxidizer for each NSSK, EWSK, and WOL operations. The major source of fuel usage is NSSK maneuver. We can see two part EWSK maneuvers in the figure. The fuel usage of twice-a-day WOL operations is very tiny as shown in Figure 8.
Table 8 shows COMS satellite mass changes during six months of IOT periods. About 14.452 kg of fuel and oxidizer are used.

```
TOT Fuel Accounting Report

Report Generation Time : 2010/07/30 00:39: 9.076

Fuel Accounting Type: Nominal Case (SKM)
Input Data File:
01      D:\COMSFDS\data\FA\input\ROS\TOTTelemetry\FDS_TOT_20100729000000.TLM.2.0

Satellite initial mass : 1519.25993 (kg)
Satellite dry mass : 1164.20000 (kg)
Satellite initial fuel mass : 135.22032 (kg)
Satellite initial oxidizer mass : 219.83960 (kg)

From:     2010/07/29 16:29:28.000
To:       2010/07/29 16:31:52.000
Duration(sec):     144.000

Apply the updated maneuver time to stack : False
Updated firing time : 2010-07-29 16:29:52.000
Updated impulse time : 2010-07-29 16:30:52.000

Thruster        Variation          Mass Consumption (kg)         Delta V (m/s)
ID         FCVSUM        FCVON     Oxidizer   Fuel        x          y          z
1A      0.000 -> 0.245  2362 -> 2383  0.00056  0.00035  -0.00001247  -0.00168687  -0.00045182
2A      0.000 -> 0.069  2124 -> 2130  0.00016  0.00010   0.00009777  -0.00047261   0.00008981
3A      0.000 -> 0.414  1560 -> 1592  0.00094  0.00060  -0.00059225  -0.00282396   0.00054044
4A      0.000 -> 0.000  1902 -> 1902  0.00000  0.00000   0.00000000   0.00000000   0.00000000
5A      0.000 -> 6.950   181 -> 206   0.01567  0.01000  -0.04566195  -0.00758213  -0.01194080
6A      0.000 -> 1.034   336 -> 372   0.00235  0.00149   0.00000000   0.00000000   0.00728934
7A      0.000 -> 0.065  1695 -> 1701  0.00015  0.00009   0.00000000   0.00000000   0.00046143
1B      0.000 -> 0.000     0 -> 0     0.00000  0.00000   0.00000000   0.00000000   0.00000000
2B      0.000 -> 0.000     0 -> 0     0.00000  0.00000   0.00000000   0.00000000   0.00000000
3B      0.000 -> 0.000     0 -> 0     0.00000  0.00000   0.00000000   0.00000000   0.00000000
4B      0.000 -> 0.000     0 -> 0     0.00000  0.00000   0.00000000   0.00000000   0.00000000
5B      0.000 -> 0.000     0 -> 0     0.00000  0.00000   0.00000000   0.00000000   0.00000000
6B      0.000 -> 0.000     0 -> 0     0.00000  0.00000   0.00000000   0.00000000   0.00000000
7B      0.000 -> 0.000     0 -> 0     0.00000  0.00000   0.00000000   0.00000000   0.00000000
Total      ------------     --------  0.01984  0.01263  -0.04616890  -0.01256556  -0.00401160

Satellite final mass : 1519.22746 (kg)
Satellite dry mass : 1164.20000 (kg)
Satellite final fuel mass : 135.20770 (kg)
Satellite final oxidizer mass : 219.81977 (kg)
Total consumption mass : 0.03246 (kg)
```

Figure 6. COMS fuel accounting report

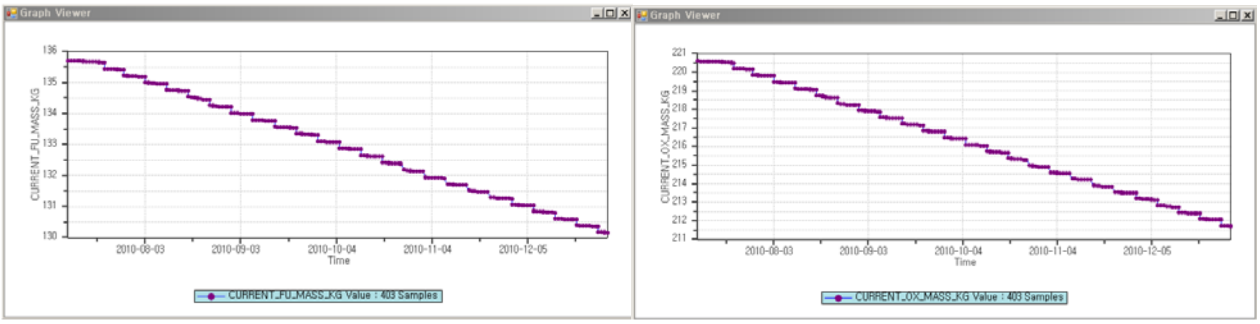

Figure 7. Remaining mass of fuel and oxidizer
(Left: time history of remaining fuel mass, Left: time history of remaining oxidizer mass)

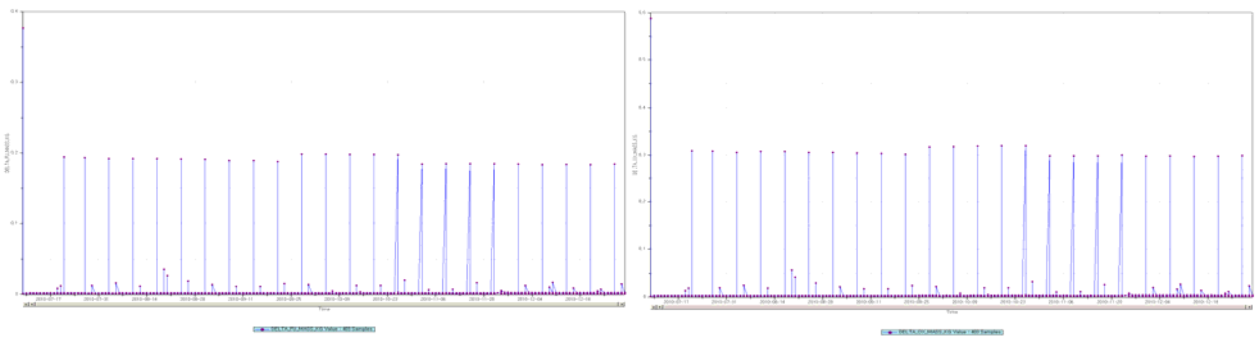

Figure 8. Consumed mass of fuel and oxidizer
(Left: time history of consumed fuel mass, Left: time history of consumed oxidizer mass)

Table 8. COMS total mass

Time	Dry mass (kg)	Fuel (kg)	Oxidizer (kg)	Total mass (kg)
2010/07/09 00:00:00	1164.200	135.700	220.600	1520.500
2011/01/01 00:00:00	1164.200	130.150	211.698	1506.048
Consumed mass	-	5.550	8.902	14.452

4. Oscillator Updating and Event Prediction

4.1 Oscillator Updating

In normal operation, sidereal day oscillator and tropical year oscillator should be updated in every month. The first oscillator updating was performed on July 5 by EADS Astrium after hand over the satellite. After that, six times of oscillator updating were carried out successfully by KARI. The parameters of oscillator updating were stored in oscillator updating stack in COMS FDS. Table 9 presents updated sidereal oscillator and tropical oscillator for every month. Although the unit of actual uploading command parameter is rad/sec., the unit of deg/day and deg/year are used for easy understanding in Table 9. The reference oscillator values are also shown in the bottom of the Table 9. All of the oscillator updating operations were carried out smoothly.

Table 9. Updated value of sidereal and tropical oscillator

No.	Updating time UTC	Updated sidereal oscillator (deg/day)	Updated tropical oscillator (deg/year)
1	2010/07/24 09:20:00	360.9786679	359.8958870
2	2010/08/25 06:20:00	360.9789770	359.9186084
3	2010/09/13 07:20:00	360.9774153	360.0628712
4	2010/10/11 05:40:00	360.9769394	360.0774206
5	2010/11/08 05:10:00	360.9769897	360.0421503
6	2011/12/08 09:30:00	360.9769989	359.9249584
	Reference Value	360.9856420	360.0001775

4.2 Event Prediction

Event prediction provides sun eclipse time, MI/GOCI sensor intrusion time, ground antenna sun outage time, node crossing time, apogee/perigee crossing time, and station keeping box limit. In normal operation, event prediction has been performed every day. Among them, one of the important events was sun interference of the ground antenna which was occurred near vernal and autumnal equinox. Table 10 shows the time and duration of predicted and realized sun interference. Predicted dates of sun outage for Daejeon station antenna were Oct. 7 - 9, 2010. The realized start times were somewhat earlier than the prediction and the duration of the interference were also longer than expected. There was telemetry loss for a few seconds in Oct. 7 and 8, 2010. The affected antenna Field Of View (FOV) should be enlarged based on the realized sun interferences.

Table 10. Predicted/Real ground antenna sun interference (Oct. 2010)

	Predicted Start MM/DD hh:mm:ss	Duration (sec.)	Realized Start MM/DD hh:mm:ss	Duration (sec.)	TM Link	TM Loss hh:mm:ss
1	10/07 03:13:22	162	10/07 03:11:00	420	Loss	03:17:03~03:17:07
2	10/08 03:12:25	241	10/08 03:10:00	480	Loss	03:16:46~03:16:52
3	10/09 03:12:54	150	10/09 03:10:00	480	OK	-

Event predictions for blinding of the Infra-Red Earth Sensors (IRES) on board the COMS satellite due the Sun and Moon were also carried out. There were IRES sensors blinding events during a week of Aug. 25, 2010.

Figure 9 depicts actual Sun and Moon position in the IRES FOV. The affected FOVs of the IRES for Sun and Moon are also shown in Figure 9. The circle in the center presents Earth disk shown in COMS orbital position. The COMS FDS provides the time and elevation angle of the Sun and Moon when the mouse is pointed to the objects. Table 11 presents IRES blinding events during a week of Aug. 25, 2010.

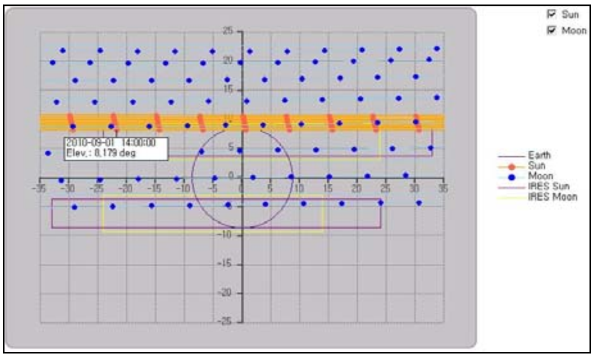

Figure 9. IRES Blinding due to the Sun and Moon

Table 11. IRES blinding report

	Start	End	Sensor	Intrusion	Moon disk (%)
1	2010/08/25 01:51:40	2010/08/25 04:45:52	IR_ST_M	MOON	95.6
2	2010/08/27 03:57:21	2010/08/27 06:51:39	IR_NT_M	MOON	83.1
3	2010/08/28 04:38:29	2010/08/28 07:33:00	IR_NT_M	MOON	77.0
4	2010/08/30 13:51:10	2010/08/30 17:40:42	IR_NT_S	SUN	N/A
5	2010/08/31 13:50:28	2010/08/31 17:40:34	IR_NT_S	SUN	N/A
6	2010/09/01 13:50:09	2010/09/01 17:40:15	IR_NT_S	SUN	N/A

Figure 10 presents Sun eclipse due to the Earth from Aug. 30 to Oct. 15, 2010. The Sun eclipse due to the Earth are predicted on-board the satellite using sidereal and tropical oscillators. The figure was used as reference for satellite operations.

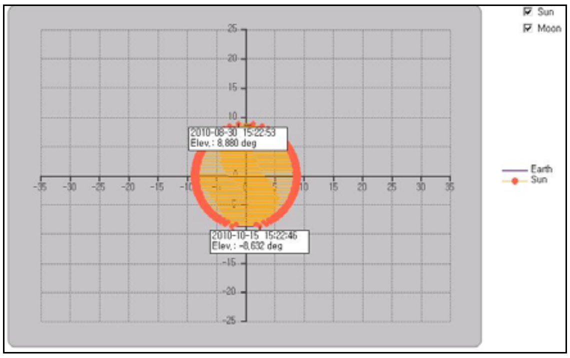

Figure 10. Sun eclipse due to the Earth

5. Conclusions

A newly developed COMS Flight Dynamics System (FDS) has been successfully validated during a six months of In-Orbit Test (IOT) operations. Major FDS functions including orbit determination and prediction, station-keeping maneuver and fuel accounting, twice-a-day thruster based Wheel Off-Loading (WOL) operations, monthly sidereal and tropical oscillator updating operations, and event predictions have been operated with performance factors. The COMS satellite will be in normal mission operations in February, 2011. A full year of FDS operations will be required for validating all the functions in COMS FDS. In the mean time, COMS FDS will be continuously upgraded for the better functions and performances.

6. References

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