COMS THRUSTER SET SELECTION FOR WHEEL OFFLOADING

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ABSTRACT: This paper discusses wheel offloading approaches of COMS which has a single side solar array system for the accommodation of the optical payloads. First of all, in an effort to reduce fuel consumption and reflect practical implementation point of view, thruster sets for wheel offloading are proposed based on numerical analyses taking into account the COMS configuration. In this analysis, it is assumed that the wheel offloading is conducted twice a day. Secondly, in order to evaluate the effectiveness of the proposed thruster sets, orbit simulations have been conducted for several wheel offloading approaches and compared.

KEY WORDS: COMS, Geostationary Satellite, Momentum Dumping, Wheel Offloading

1. INTRODUCTION

Communication, Ocean and Meteorological Satellite (COMS) satellite is in schedule to be launched in 2008. The COMS contract to develop the COMS satellite and to provide support for system activities has been awarded by KARI to ASTRIUM France. The joint project group is composed of KARI and ASTRIUM engineers. This paper discusses about COMS operational aspect in terms of wheel offloading thruster set selection.

Generally, geostationary meteorological satellite like GOES has single sided solar panel system in order to be provided with better thermal environment for meteo-optical payload. The sun light reflected from solar panel can cause thermal problem to optical sensor which performance is very sensitive to temperature.

Unfortunately, in case of single sided solar panel system, the momentum accumulation is inevitable owing to unsymmetrical solar pressure incidence, which in turn will cause attitude error. GOES system has solved this problem by accommodating a solar sail boom system which is designed to remove torque bias resulted from solar pressure[NASA, 1996;NASA, 1997]. Solar sail boom is designed to have long and thin shape in order to minimize radiation effect and in order to maximize compensation torque induced by solar pressure. This system has advantage in making attitude control system simple. However it is not easy to implement a reliable deploy mechanism.

The COMS is designed to accommodate active wheel offloading system handling accumulated momentum bias, in place of solar sailing boom, as shown in figure 1. This approach is expected to make the hardware design simple in comparison with a satellite with solar sail boom. The main disadvantage of this system is that the accumulation of the momentum will increase momentum wheel speed as function of time. At certain time the momentum wheel will be saturated, which means complete loss of the satellite attitude. In order to overcome this phenomenon, we need to confine wheel speed in its operation range which can be done by periodical thrusters firing in the manner of producing torque compensating momentum bias. Generally, this compensation activity is called wheel offloading. Wheel offloading consumes additional fuel which consequently reduces satellite mission life or increases launch mass. Therefore detailed analysis on wheel offloading fuel consumption should be done.

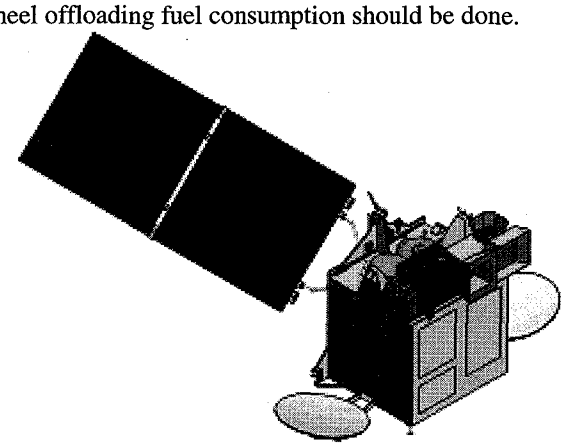

Figure 1. COMS configuration

[Park, 2005] proposed a wheel offloading approaches and compared the amount of fuel consumed for several cases under consideration of COMS geometry. The approach proposed by [Park, 2005] is performing the wheel offloading at (-Y) axis of ECI in order to make incidental north direction velocity change act on north/south stationkeeping in positive manner.

This paper improves the results of [Park, 2005] in the light of realization. In case of the approach discussed in reference [Park, 2005], wheel offloading time should be delayed 3 minutes every day, and in turn it will cause some constraints on the optical payload operation. In order to handle this problem, this paper evaluates a modified wheel offloading method allowing fixed execution time. Thruster sets for wheel offloading depending on season are proposed and amount of fuel to be consumed is analyzed through simulation.

2. WHEEL OFFLOADING ANALYSIS

2.1 Momentum Accumulation from Solar Pressure

As shown in figure 2, ECI and orbit coordinate are adopted for analysis of the wheel offloading.

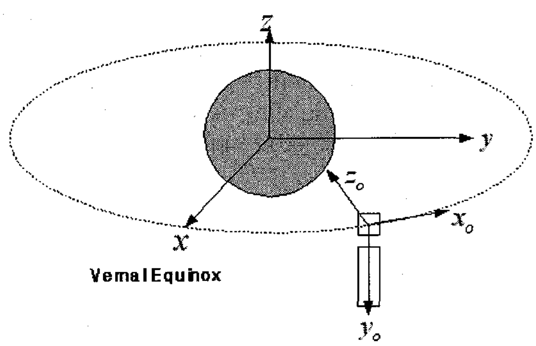

Figure 2. Coordinate Definition

External force induced by solar pressure and acting on solar array is as follows[Pocha, 1987];

$$F_{sp} = GA\left(\frac{1+R}{2}\right) \quad (1)$$
$$G = 9.1\times 10^{-6}\,Nm^2$$

where G is solar pressure constant, A is the area of satellite perpendicular to sun light. R represents specular reflectivity. As the body of the satellite is almost symmetrical in shape, the torque resulted from sun light illuminating satellite body is negligible. The daily amount of momentum accumulated(ΔM_d) is formulated as follows;

$$\Delta M_d = \int_0^{24h} dF_{sp}\,dt \quad (2)$$

Based on COMS configuration and equation (2), we can easily prove the COMS momentum accumulation to be $25Nm/day$. Basically, this amount of momentum shall be compensated every day through wheel offloading in order to maintain satellite attitude in reasonable range.

2.2 Wheel Offloading

In order to compensate accumulated momentum, it shall be formulated in form of a vector in 3-demensional space. And we need to select thrusters to be used taking into account the momentum vector generated by each thruster. And this information should be combined to produce the amount of impulse to be produced by selected thrusters.

The amount of momentum accumulated is as follows in ECI;

$$\Delta M_o = d\times F = \Delta M_d \frac{d\times S}{|d\times S|} \quad (3)$$

$$d = \begin{bmatrix} 0 \\ 0 \\ -d \end{bmatrix}$$

where S indicates Sun vector in ECI frame, d is a vector heading from spacecraft center of mass to solar penal center of area.

Regarding the torque induced by thruster in ECI coordinate, it can be shown as follows in terms of torque component in spacecraft body coordinate;

$$M_t = TF_x\left(\frac{\pi}{2}\right)TF_z\left(-\Omega-\frac{\pi}{2}\right) TF_x(-i)TF_z(-M-\omega)M_{tb} \quad (4)$$

where, TF_x and TF_z indicate Euler coordinate transformation matrixes with respect to x and z axis respectively. And M is mean anomaly, i is inclination, ω is argument of perigee, and Ω is right ascension of ascending node.

If we assume that i is approximately zero, as is the case of geostationary satellite, equation (4) is simplified as follows;

$$M_t = TF_x\left(\frac{\pi}{2}\right)TF_z\left(-\theta-\frac{\pi}{2}\right)M_{tb} \quad (5)$$
$$\theta = \Omega + \omega + M$$

Compensation of the accumulated momentum shall meet the condition expressed as follows;

$$M_t = TF_x\left(\frac{\pi}{2}\right)TF_z\left(-\theta-\frac{\pi}{2}\right)M_{tb} = -\Delta M_o \quad (6)$$

Again, this equation can be reformulated into useful form after simple algebraic manipulation

$$M_{tb} = \begin{bmatrix} \sin\theta & 0 & +\cos\theta \\ \cos\theta & 0 & -\sin\theta \\ 0 & -1 & 0 \end{bmatrix}\Delta M_o \quad (7)$$

COMS has three thrusters mounted on south panel and producing torque shown in figure 3 on their 1 second firing.

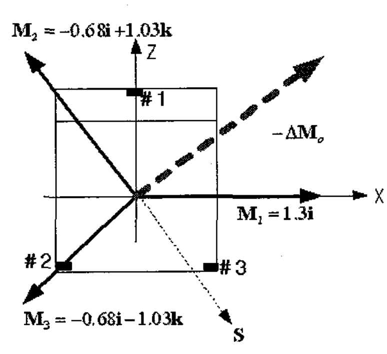

Figure 3. Thruster Location and Momentum Vectors of COMS

When several thrusters are operated simultaneously, the resultant torque is the vector sum of torques of all fired thrusters.

$$M_{tb} = \sum_i M_{tbi} \tag{8}$$

We can perform wheel offloading in any orbital location or time by applying two or three thruster together with adjusted firing duration for each thruster. However if we want to apply only one thruster, the wheel offloading is possible only when the condition of bellow equation (9) is satisfied.

$$\theta = \tan^{-1}\left(\frac{\Delta M_{ox} M_{tbx} - \Delta M_{oz} M_{tby}}{\Delta M_{oz} M_{tbx} + \Delta M_{ox} M_{tby}} \right) \tag{9}$$

In COMS case, the condition of equation (9) is met three times a day, because the COMS has three thrusters usable for wheel offloading purpose.

3. WHEEL OFFLOADING TIME SELECTION

3.1 Strategy I: Fixed Time Wheel Offloading

Perturbation induced by wheel offloading degrades performance of the optical payload. That explains why the optical payload shall be stopped or neglected during wheel offloading. In COMS case, payload operation schedule is repeated in daily base. Therefore fixed time wheel offloading approach has some advantages in payload operation point of view.

According to [Park, 2005], in case of COMS, wheel offloading in three time slot shown in figure 4 gaurantees minimum fuel usage for wheel offloading. The time slots are 00:00, 08:17 and 15:49. Simply these three time slots are the time when equation (9) is met, in which case momentum arm is maximized. On the other hands, at around 04:00 and 20:00, the wheel offloading consumes maximum amount of fuel and two thrusters shall be used together in order to produce torque heading to proper direction intended.

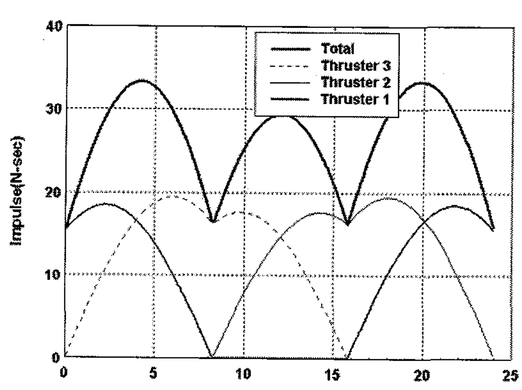

Figure 4. Impulse Requirement vs. Wheel Offloading Time

3.2 Strategy II: Wheel Offloading at (-Y) Axis of ECI

[Park, 2005] also had proposed wheel offloading at (-Y) axis of ECI. As widely known, north/south stationkeeping is periodically performed in order to maintain the orbit inclination as nearer as possible to the equatorial plane. The north/south stationkeeping is performed every 7 days or 14 days depending on situation and removes inclination change induced by Sun and moon gravitational forces. The velocity change for north/south stationkeeping is planned to head to north or south direction and its magnitude is as follows;

$$\Delta V_{NS} = 2V_s \sin\frac{|\Delta i|}{2} \tag{10}$$

where, V_s is tangential spacecraft velocity, Δi is inclination change required to compensate inclination change. In average, north/south station keeping is performed in (-Y) axis. Therefore [Park, 2005] discussed performing wheel offloading at (-Y) axis in order to make velocity change resulted from wheel offloading act in positive way to north/south stationkeeping. By using this approach, we can reduce fuel usage necessary for north/south stationkeeping. In this approach, more than two thrusters shall be selected for wheel offloading at same time.

3.3 Strategy III: Combined Approach

In case of Strategy II, as mentioned earlier, wheel offloading time shall be changed day by day, which is a disadvantage in payload operation point of view. In an effort to handle this problem, COMS will adopt an approach combining and compromising above mentioned two strategies: Strategy I and Strategy II.

Like strategy I, wheel offloading is performed at fixed time of a day: 2 times a day with combination of 00:00 or 09:17 or 15:49. And thruster selection which is exactly equivalent to wheel offloading slot selection, is made in manner to place wheel offloading position as nearer as possible to (-Y) axis. This approach provides us benefit of maximum length momentum arm, fixed wheel offloading time(strategy I) and reduction in north/south station keeping fuel usage(strategy II). In COMS case, wheel offloading is performed twice a day, for 10 minutes each.

4. SIMULATION AND DISCUSSION

In order to evaluate amount of fuel consumed for above mention three wheel offloading approaches, orbit simulation has been done. Figure 5 shows overall flow of the simulation. For given ΔV requirement, equivalent fuel mass can be obtained from the famous rocket equation shown bellow[Pritchard, 1993].

$$\Delta m = m_{sc}\left[1 - \exp\left(-\frac{\Delta V}{g I_{sp}}\right)\right] \tag{11}$$

where, I_{sp} indicates specific impulse of the selected thruster. In this simulation, I_{sp} is assumed to be 263sec which is typical value for COMS case.

Orbit propagator using on 4th-order Runge-Kutta, 4x4 geopotential perturbation model, Sun and moon gravitational perturbation, and solar pressure is used. Simulations are done for 7 years duration starting from January 1, 2008. Operational longitude is assumed to be 116 deg.E. Table 1 shows expected torque of each thruster.

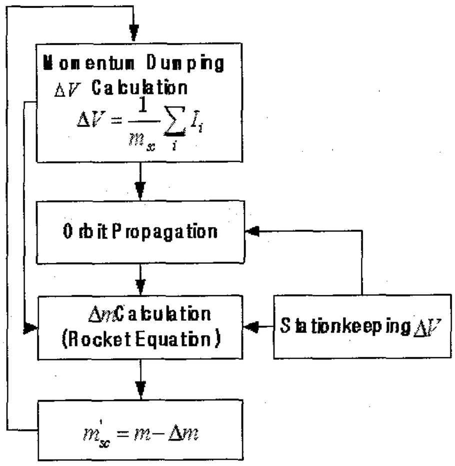

Figure 5. Simulation Flowchart

Figure 6 shows expected angular position of the wheel offloading over a year obtained from equation (6). As mentioned before, selected wheel offloading position is the position where the effective momentum arm of the thruster is maximized. The optimal thrusters set are obtained by selecting thruster nearest to (-Y) axis at given time from figure 6. In COMS case, wheel offloading is performed twice a day. So we can obtain thruster set shown in Table 2. It is noticed that selected thrusters set depends on season.

Figure 7 shows inclination vector trajectory induced by thruster firing under zero perturbing force with a set of thruster shown in Table 2. It can be shown that inclination vector moves toward (-Y) direction. Figure 8 shows the inclination vector trajectory for two cases: with wheel offloading and without wheel offloading. From figure 8, we can notice that wheel offloading with selected thruster set reduces inclination vector changes.

Figure 9 shows wheel offloading time and north/south stationkeeping time together, in order to compare them. As intended, the mean time of two wheel offloading is very close to north/south stationkeeping time.

Table 3 and 4 compare the velocity change and fuel requirements in terms of north/south stationkeeping, east/west stationkeeping and momentum dumping. According to these results, strategy III consumes less fuel than strategy II, contrary to our expectation. This result can be explained as: It is clear that using strategy III gives us benefit of reducing north/south stationkeeping fuel consumption. But the amount of fuel increased owing to reduced effective momentum arm is more than that. In case of strategy III, we cannot perform wheel offloading at optimal position described by equation (9).

Table 1. Torque of each thruster

Thruster ID	M_x	M_y	M_z
1	1.3	0.0	0.0
2	-0.68	0.0	1.03
3	-0.68	0.0	-1.03

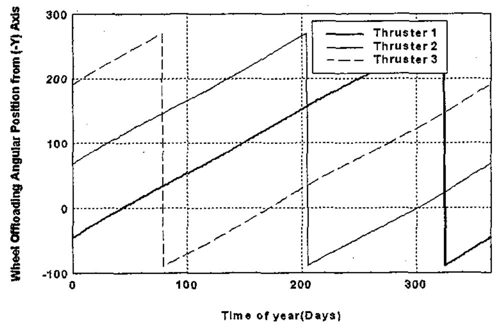

Figure 6. Wheel Offloading Position for Each Thruster

Table 2. Thruster Selection for wheel offloading

Days	Thruster Selection
10/22~2/17	2, 3
2/18~6/19	3, 1
6/20~10/22	1, 2

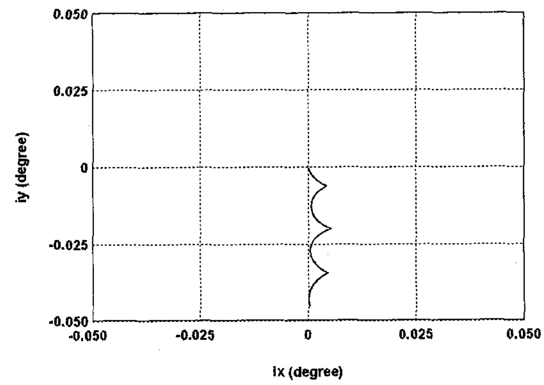

Figure 7. Inclination vector evolution by wheel offloading

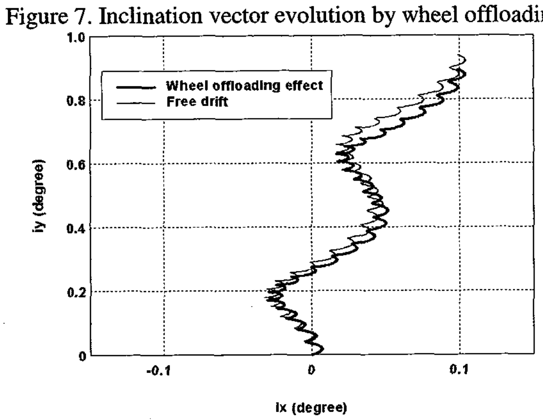

Figure 8. Inclination vector evolution

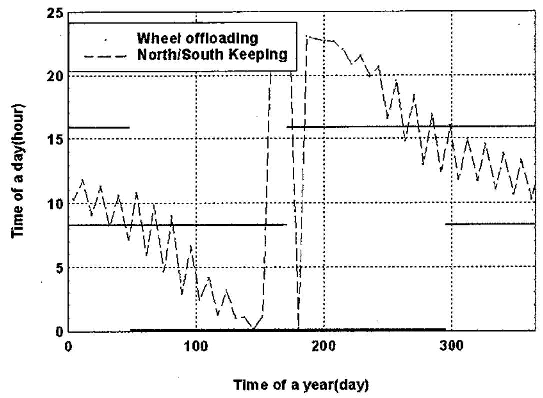

Figure 9. North/south stationkeeping and momentum dumping time

Table 3. ΔV requirements

MD Time		No MD	(-y) Axis	Mid-night	Two Selection
ΔV (m/sec)	NSSK	350.79	319.88	352.71	334.70
	EWSK	30.50	30.09	30.52	30.33
	MD	0.0	69.33	42.618	44.18
	Total	381.29	419.3	425.85	409.21

Table 4. Fuel consumption

MD Time		No MD	(-y) Axis	Mid-night	Two Selection
Fuel Used (kg)	NSSK	168.26	153.39	168.04	159.80
	EWSK	14.50	14.66	14.44	14.34
	MD	0.0	33.08	20.25	20.97
	Total	182.76	201.13	202.73	195.11

5. CONCLUSIONS

This paper discusses wheel offloading of the COMS which has single sided solar panel system and is in schedule to be launched around end of 2008. The analysis is focused on selection of the wheel offloading thruster set for the minimization of the fuel consumption.

By means of simulation, it has been proved that the proposed thruster set guarantees better performance than other approaches discussed in this paper including the approach of performing wheel offloading at (-Y) axis of ECI coordinate, not only in fuel consumption aspect but also in implementation point of view in real operation environment. Even though the technical discussion addressed in this paper is based on COMS satellite, it is applicable to any other satellite with single sided solar panel system which is expected to be much more popular in near future.

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