Station-keeping strategies for satellite constellation

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STATION-KEEPING STRATEGIES FOR SATELLITE CONSTELLATION

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This paper firstly introduces the concepts on control box and control reference for absolute and relative station-keeping, how to determine the control reference, and the uniform control flow for different station-keeping strategies. And then, studies the different station-keeping control-laws for Walker constellation, including different orbital regions. The demonstration experiments concerning different station-keeping strategies are carried out with initial orbit element errors and control tolerance based on Constellation Station Keeping Kit (CSKK), which is recently designed and developed at BACC for satellte constellation operation demonstration.

INTRODUCTION

A single satellite played an important role in the early application of satellite. But, as the range of the satellite application is extended, more and more mission can't be accomplished only by a single satellite. So, the constellations composed by more than one satellite become prevalent, which are the first scheme for many flying missions. However, constellation system is great and complicated, which involves two major aspects, configuration design and management strategy. Many steps should be considered in the constellation management strategy, including deployment strategy, station-keeping strategy, reconfiguration strategy, and reinforcement strategy. Because deployment strategy, reconfiguration strategy, and reinforcement strategy are similar to configuration design, and configuration design has been introduced in other paper [1], this paper focuses on the research about station-keeping strategies, which is vital to Chinese future constellation missions, especially for Beijing Aerospace Control Center (BACC).

Lamy and S. Pascal [2] studied station-keeping strategy for circular symmetrical satellite constellation on the basis of relative station-keeping theory, and P. Brodsky and S. Chen [3] also done the similar research. R. E. Glickman [4] presented Timed-Destination approach to constellation formation-keeping. Y. Ulybyshev [5] described the strategy using Linear-Quadratic controller. E. Lasserre and F. Dufour [6] studied homogeneous satellite constellation station-keeping problem making use of linear programming solution. Some literature [7,8,9,10,11,12] studied station-keeping strategies for highly elliptical orbit (HEO) satellite constellation, for the merit of regional coverage. G. Rondinelli and A. Cramarossa's [10,11,12] researches foucused on TUNDRA orbit, and

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Kechichian J. A. [13] analyzed orbit plane control strategies for inclined geosynchronous satellite constellation. D. du Toit [14] presented the orbit phase control approach in the same orbit plane using atmospheric drag. Microcosm [15] provided autonomous on-board orbit control by precision autonomous navigation components (PAN), and orbit control kit component (OCK), which can be adopted to satellite constellation. The station-keeping strategies for satellite constellation at work are referential to this research, such as ORBCOMM [16], GPS [17], MACROSAT [18], and so on.

To begin, it is critical to understand the distinction between absolute station-keeping, which maintains each satellite in a predefined mathematical box relative to the Earth or inertial space and relative station-keeping, which maintains only the relative positions of the satellites with respect to each other and not the absolute positions. There are some advantages and disadvantages of absolute vs. relative station-keeping, but the advantages may be changed to disadvantages on the basis of the initial errors and precision demand.

This paper firstly introduces the concepts on control box and control reference for absolute and relative station-keeping, how to determine the control reference, and the uniform control flow for different station-keeping strategies. And then, studies the different station-keeping control-laws for Walker constellation, including different orbital regions. The demonstration experiments concerning different station-keeping strategies are carried out with initial orbit element errors and control tolerance based on Constellation Station Keeping Kit (CSKK), which is recently designed and developed recently at BACC for satellte constellation operation demonstration.

STATION-KEEPING CONTROL BOX AND CONTROL REFERENCE

The aim of station-keeping is to maintain the satellite in a control box, the green box as shown in Fig. 1, which is determined by the control tolerance. In practice, we only concern the In-track control and Cross-track control, so the control box can be described as Fig.2. ε_u is the In-track control tolerance, and ε_Ω is the Cross-track control tolerance [19].

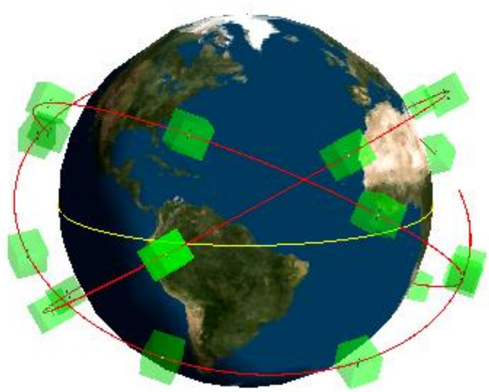

Figure 1. The Control Box Concept for Satellite Constellation

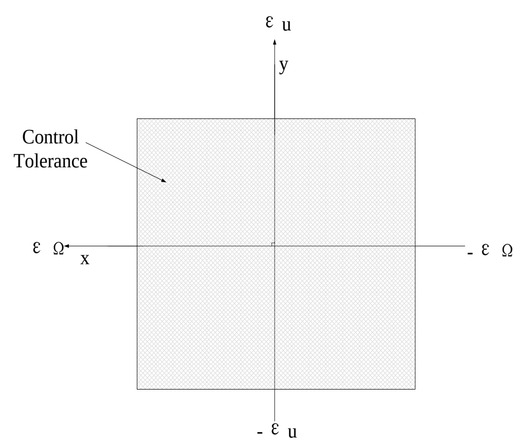

Figure 2. The Control Tolerance for In-track control and Cross-track control

The uniform In-track control flow as shown in Fig. 3, on the basis of the orbit determination result, $u_{measured}$, and control reference, $u_{reference}$, in the on-board computer memory, the control law can give the ΔV_u. The uniform In-track control flow as shown in Fig. 4, on the basis of the orbit determination result, $\Omega_{measured}$, and control reference, $\Omega_{reference}$, in the on-board computer memory, the control law can also give the ΔV_h .

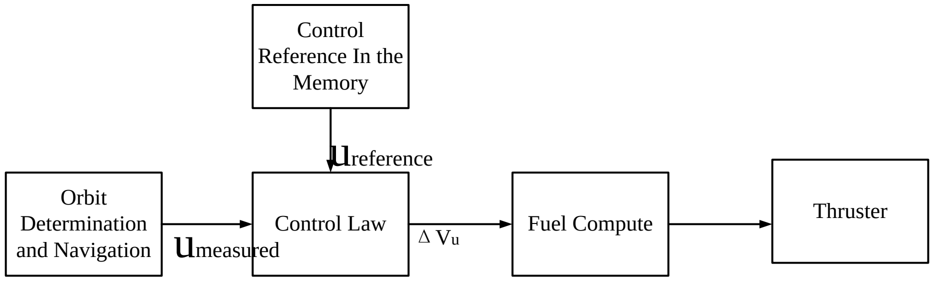

Figure 3. The Uniform In-track Control Flow

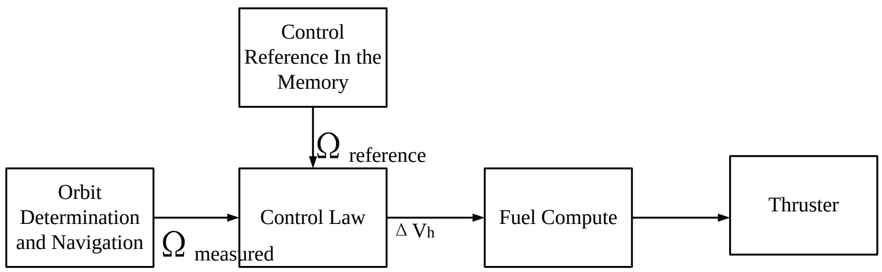

Figure 4. The Uniform Cross-track Control Flow

The control reference for absolute station-keeping strategy can be easily determined by truncating the geopotential model order adopted in the orbit propagator. The control reference for relative station-keeping strategy should be determined using several constellation satellites. With regard to Walker constellation configuration, the ith orbit plane and kth satellite can be defined as,

$$\left.\begin{aligned} a_{jk} &= a \\ e_{jk} &= 0 \\ i_{jk} &= i \\ \Omega_{jk} &= \Omega_0 + j*2\pi/P \\ \omega_{jk} &= 0 \\ u_{jk}(t) &= u_{00}(t) + j*F*2\pi/T + k*2\pi/S \end{aligned}\right\} \quad \begin{aligned} (\ j &= 0, 1, 2, \cdots, P-1 \\ k &= 0, 1, 2, \cdots, S-1\ ) \end{aligned} \tag{1}$$

where a is the semi-major axis, i the orbit inclination angle, e the eccentricity, ω the argument of perigee, Ω_0 the right ascension of the ascending node (RAAN) of the first orbit plane, u_{00} the argument of latitude, P the number of orbit planes, F the phase factor of Walker constellation, S the satellite number in constellation plane. We set Ω_0=0° and u_{00}=0° , because the configuration of Walker constellation is symmetric and e=0, ω =0° .

The relative control reference for Walker constellation can be obtained:

$$\left.\begin{aligned} a^*_{jk} &= a^* \\ e^*_{jk} &= 0 \\ i^*_{jk} &= i^* \\ \Omega^*_{jk} &= \Omega^*_0 + j * 2\pi / P \\ u^*_{jk}(t) &= u^*_{00}(t) + j * F * 2\pi / T + k * 2\pi / S \end{aligned}\right\} \quad \begin{aligned} (\ j &= 0, 1, 2, \cdots, P-1 \\ k &= 0, 1, 2, \cdots, S-1\ ) \end{aligned} \tag{2}$$

where “*” means the control reference. E_{jk} stands for the orbit elements (a_{jk} , i_{jk} , Ω_{jk} , u_{jk}). In order to get the reference, need to minimize Q_E, which can be defined as,

$$Q_E = \sum_{j=0}^{P-1} \sum_{k=0}^{S-1} \lambda_{jk} (E_{jk} - E^*_{jk})^2 \tag{3}$$

where λ_{jk} is the weight value. To solve the derivative of Eq. (3), we can obtain:

$$\left.\begin{aligned} a^* &= \sum_{j=0}^{P-1} \sum_{k=0}^{S-1} \lambda_{jk} a_{jk} \\ i^* &= \sum_{j=0}^{P-1} \sum_{k=0}^{S-1} \lambda_{jk} i_{jk} \\ \Omega^*_0 &= \sum_{j=0}^{P-1} \sum_{k=0}^{S-1} \lambda_{jk} (\Omega_{jk} - j * 2\pi / P) \\ u^*_{00}(t) &= \sum_{j=0}^{P-1} \sum_{k=0}^{S-1} \lambda_{jk} (u_{jk}(t) - j * F * 2\pi / T - k * 2\pi / S) \end{aligned}\right\} \tag{4}$$

The control reference for every satellite in the constellation can be obtained using Eq. (2), and then, the orbit element difference can be defined as,

$$\Delta E_{jk} = E_{jk} - E^*_{jk} \tag{5}$$

STATION-KEEPING STRATEGIES

Once the control reference for absolute and relative station-keeping strategies is determined, the transfer time and fuel cost can be obtained by the control laws for different orbit types as follows:

(A) MEO (Altitude: 1500~10000km）

In this orbital region, the atmospheric drag can be ignored, the In-track control law is shown as Fig. 5. Maintain the satellite in a control box, if it drifts to one side of the box, "hitting" it with a thruster, letting it drift across the box and back, and then hitting it again. If you want to change the drift rate of argument of latitude, $\Delta\dot{u}$, to set the satellite drift across the box during d days, the change to the semi-major axis is defined as,

$$\Delta a = \frac{2a^2}{3}\sqrt{\frac{a}{\mu}}(\Delta\dot{u} + \Delta\dot{u}_{define}) \tag{6}$$

where,

$$\Delta\dot{u}_{define} = \frac{2*\pi/180*\Delta u}{86400*d} \tag{7}$$

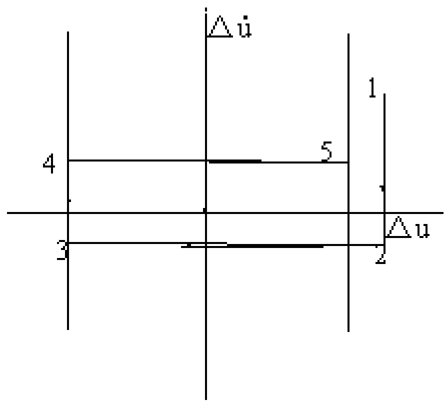

Figure 5. The In-track Control Law without atmospheric drag

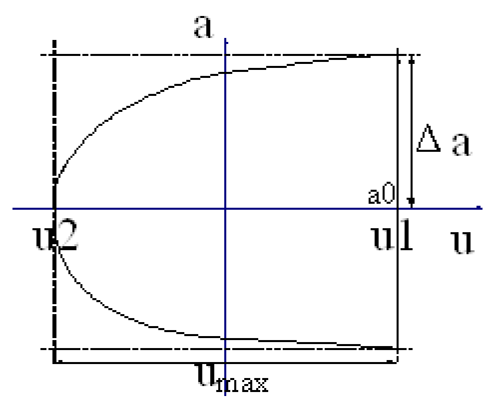

Figure 6. The relation between argument of latitude and semi-major axis with atmospheric drag

Similarly, change the orbit inclination angle to change the drift rate of right ascension of the ascending node, and the change is defined as,

$$\Delta i = -\frac{2}{3J_2 \sin i}\left(\frac{a}{R_E}\right)^2 \sqrt{\frac{a^3}{\mu}} \cdot \Delta\dot{\Omega}_* \tag{8}$$

where $\Delta\dot{\Omega}_*$ is the targeted drift rate which can be defined similar to In-track control.

(B) LEO (Altitude: 700~1500km）

In this orbital region, the atmospheric drag can not be ignored. During the time set, t, the change to argument of latitude due to Δa is defined as,

$$\Delta u_1 = \Delta n.t = \sqrt{\mu}.(a^{\frac{-3}{2}})'.\Delta a.t = -\frac{3}{2}.\sqrt{\mu}.a^{\frac{-5}{2}}.\Delta a.t = -\frac{3}{2}.\frac{a}{n}.\Delta a.t \tag{9}$$

and the change due to the atmospheric drag is,

$$\Delta u_2 = -\frac{3}{4}.\frac{n}{a}.\dot{a}.t^2 \tag{10}$$

where,

$$\frac{da}{dt} = -(\frac{c_d.\rho.S}{m}).\frac{na^2}{(1-e^2)^{\frac{3}{2}}}.(1+e^2+2e.\cos f)^{\frac{3}{2}} \tag{11}$$

And then, the total change is,

$$\Delta u = \Delta u_1 + \Delta u_2 = -\frac{3}{2}.\frac{a}{n}.\Delta a.t - \frac{3}{4}.\frac{n}{a}.\dot{a}.t^2 = -\frac{3}{2}.\frac{a}{n}.(\Delta a + \frac{\dot{a}}{2}.t).t \tag{12}$$

The In-track control law is shown as Fig. 6. Impose the change, Δa, on a_0 at u_1, the satellite drifts to u_2, and then it goes to u_1 due to the drag. The time from u_1 to u_2 is,

$$t_{max} = -\frac{\Delta a}{\dot{a}} \tag{13}$$

u_{max} and Δa can be obtained:

$$u_{max} = -\frac{3}{2}.\frac{a}{n}.(\Delta a + \frac{\dot{a}}{2}.(-\frac{\Delta a}{\dot{a}})).(-\frac{\Delta a}{\dot{a}}) = \frac{3}{4}.\frac{a}{n}.\frac{\Delta a^2}{\dot{a}}$$

$$\Delta a = \sqrt{\frac{4.u_{max}.a.\dot{a}}{3.n}} \tag{14}$$

(C) MEO (Altitude: 15000~25000km）

In this orbital region, due to the lunar and solar perturbation force influences on orbit inclination angle are different from different Ω, and the coupling of argument of latitude with Ω, the orbit elements should be maintained respectively with classical station-keeping strategies for single satellite.

NUMBERICAL SIMULATIONS

We will carry out demonstration experiments on the basis of appointed reference orbit, initial orbit element errors, and control tolerance using CSSK shown as Fig. 7. Three experiments are chosen to deal with station-keeping, and the input parameters are listed in Table 1, including appointed reference orbit, initial orbit element errors, and control tolerance.

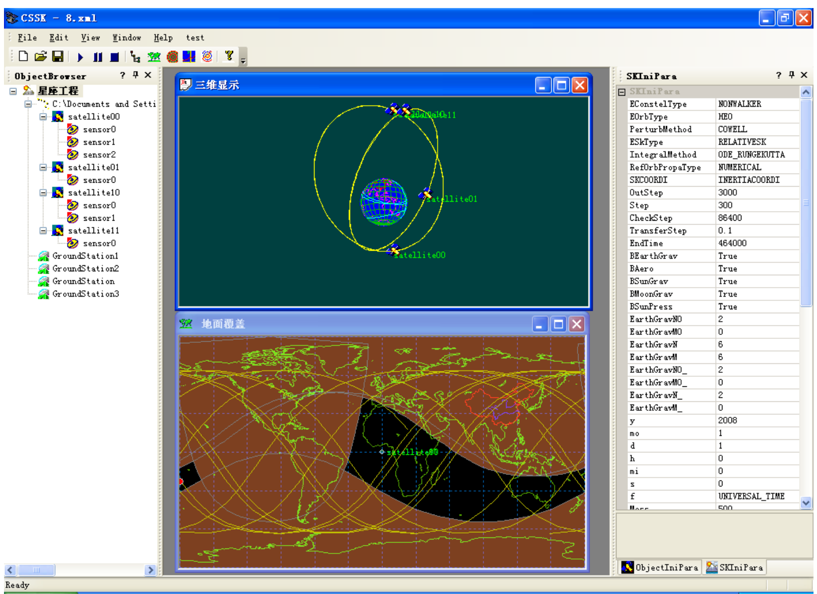

Figure 7. The CSSK Interface

Table 1. Initial parameters for experiments.

Case1: Altitude: 1500~10000km						
Constellation configuration	a (km)	e	i (°)	ω (°)	Ω (°)	θ (°)
	10000	0	60	0	0	0 180

T/P/F 4/2/0					180	0 180
Initial orbit element errors	Δa (m)	Δe	Δi (°)	ΔOMG (°)	Δomg (°)	$\Delta \theta$ (°)
	400	0.0002	0.01	0.1	0.2	0.2
Control tolerance	Δa (m)	Δe	Δi (°)	ΔOMG (°)	Δu (°)	
	2000	0.001	0.4°	0.5°	1.0°	
Case2: Altitude: 700~1500km						
Constellation configuration T/P/F 4/2/0	a (km)	e	i (°)	ω (°)	Ω (°)	θ (°)
	7200	0	60	0	0	0 180
					180	0 180
Initial orbit element errors	Δa (m)	Δe	Δi (°)	ΔOMG (°)	Δomg (°)	$\Delta \theta$ (°)
	400	——	0.01	0.1	0.2	0.2
Control tolerance	Δa (m)	Δe	Δi (°)	ΔOMG (°)	Δu (°)	
	2000	——	0.2	0.5	1.0	
Case3: Altitude: 15000~25000km						
Constellation configuration T/P/F 4/2/0	a (km)	e	i (°)	ω (°)	Ω (°)	θ (°)
	22000	0	60	0	0	0 180
					180	0 180
Initial orbit element errors	Δa (m)	Δe	Δi (°)	ΔOMG (°)	Δomg (°)	$\Delta \theta$ (°)
	400	0.0002	0.01	0.1	0.4	0.4
Control tolerance	Δa (m)	Δe	Δi (°)	ΔOMG (°)	Δu (°)	
	2000	0.001	0.05	0.5	2.0	

The reference orbit only involves J6*6, and the simulated ture orbit involves gravity field, atmospheric drag, solar radiation pressure, accelerations due to 3rd body. The simulation begins at 01 Jan. 2012 12:00:00.000, and ends at 01 Jan. 2014 12:00:00.000, using C++ implementation in a PC with P4 2.66 GHz. The results for the experiments are listed in Table 2 for absolute and relative station-keeping. Fig.8~Fig13 show the effect of station-keeping.

Table 2. Results for experiments.

Case1: Altitude: 1500~10000km				
SatID	absolute station-keeping		relative station-keeping	
	Thrust number	Thrust consumption (kg)	Thrust number	Thrust consumption (kg)
1	15	0.6548	8	0.5918
2	16	4.1618	7	4.3236
3	19	1.2398	10	1.1274
4	17	1.1870	8	1.1060

Case2: Altitude: 700~1500km				
SatID	absolute station-keeping		relative station-keeping	
	Thrust number	Thrust consumption (kg)	Thrust number	Thrust consumption (kg)
1	10	0.1887	13	4.3826
2	12	4.1035	10	0.1782
3	12	4.1416	12	1.7801
4	9	1.6468	11	0.2186

Case3: Altitude: 15000~25000km		
SatID	absolute station-keeping	
	Thrust number	Thrust consumption (kg)
1	28	10.8558
2	26	10.8605
3	24	0.2304
4	24	0.2332

The thrust number of absolute station-keeping is more than relative station-keeping clearly for case1, but the difference of thrust consumption between absolute and relative station-keeping is not remarkable.

The difference of thrust number between absolute and relative station-keeping for case2 is not remarkable because of the drift character of argument of latitude due to atmospheric drag. And there is no clear law on the thrust consumption.

We only use absolute station-keeping for case3, because the accelerations due to 3rd body are different from different Ω, and the acceleration of high order gravity field is low.

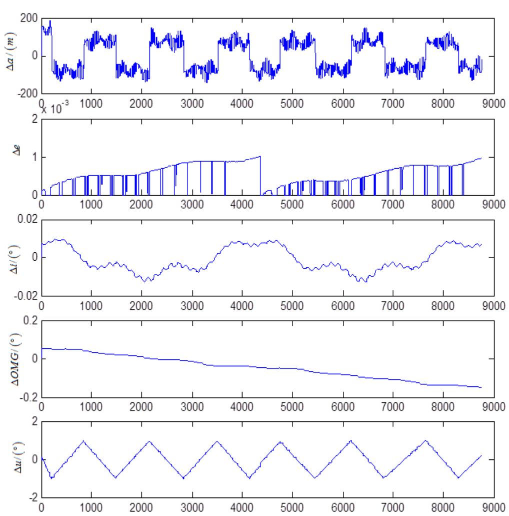

Figure 8. Case1 absolute station-keeping for SatID:1

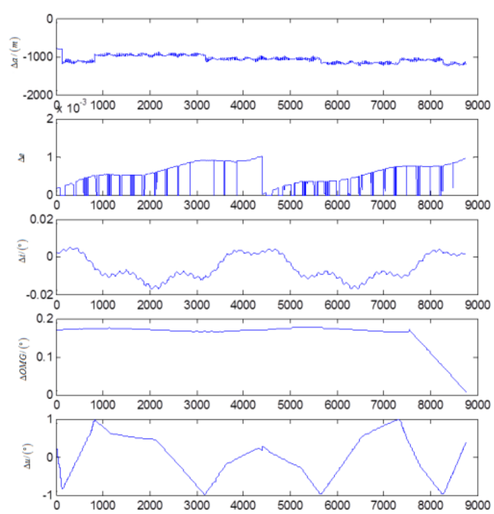

Figure 9. Case1 relative station-keeping for SatID:1

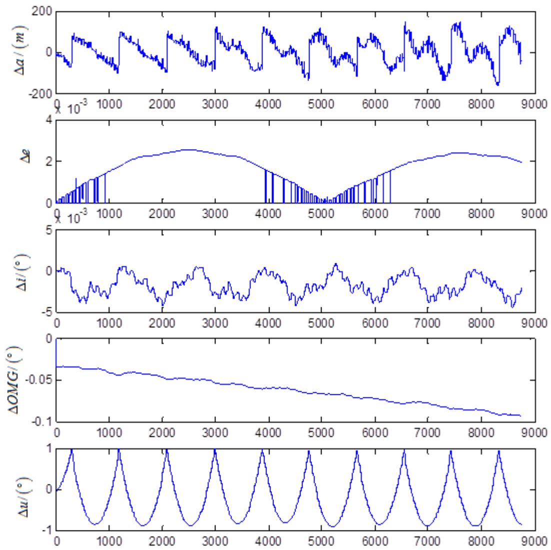

Figure 10. Case2 absolute station-keeping for SatID:1

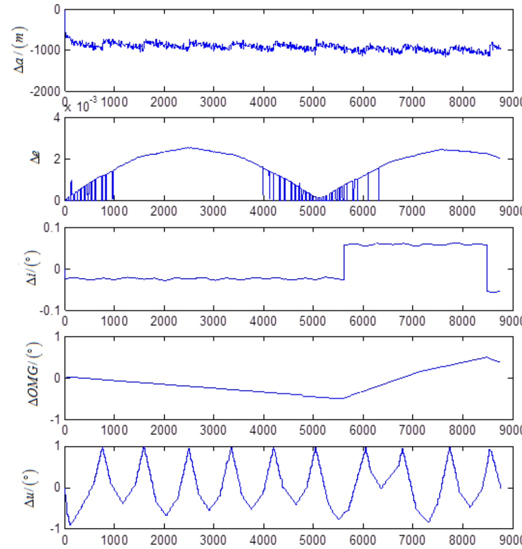

Figure 11. Case2 relative station-keeping for SatID:1

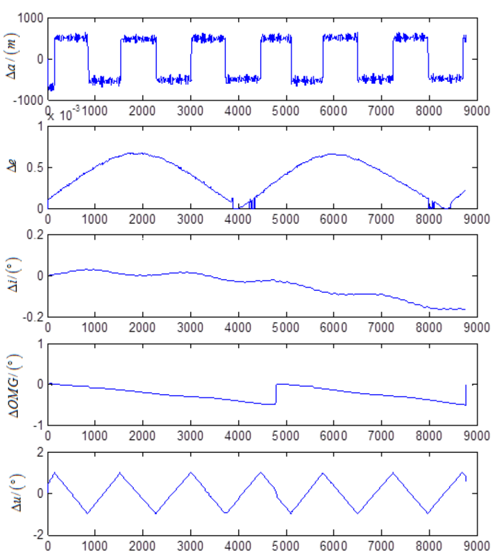

Figure 12. Case3 absolute station-keeping for SatID:1

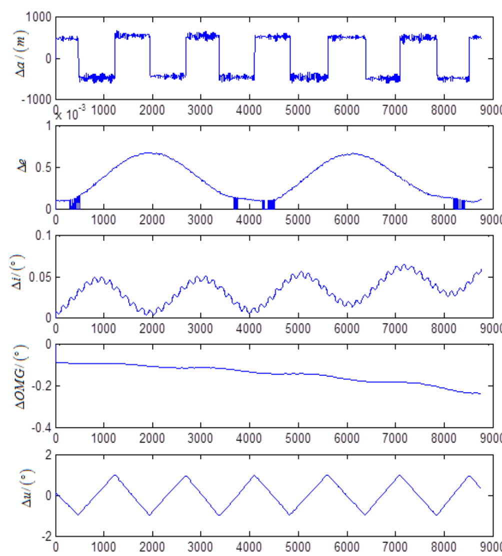

Figure 13. Case2 absolute station-keeping for SatID:3

CONCLUSION

Based on the concepts on control box and control reference for absolute and relative station-keeping, the Constellation Station Keeping Kit (CSKK) is designed and developed recently at BACC for satellite constellation operation demonstration. The numerical simulation has proved the feasibility of different station-keeping strategies and builds up a good basis for satellite constellation mission design.

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