Comparisons of Two Station-keeping Strategies for Ionic Propulsion Systems

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The latest geostationary telecommunication satellites are equipped with ionic propulsion systems for high propellant efficiency. Geostationary satellites experience perturbations due to the earth's geopotential field, solar radiation pressure and the sun and moon gravity attractions. Periodic North/South and East/West station-keeping maneuvers are required to keep the satellite within a control box. The ionic thrusters are used for North/South inclination control maneuvers. Because of the large plasma plumes from the ionic propulsion systems, the thrusters are canted about 45 degrees in the spacecraft (Y, Z) plane in order to minimize the degradation effects on the solar array. Due to the canting angles, the ionic thrusters will produce about equal magnitude of both normal and radial components for each firing during station-keeping maneuvers. Two station-keeping strategies are compared for the ionic propulsion systems. One strategy calls for a combined control of inclination and eccentricity by the ionic thrusters during North/South maneuvers. The other strategy controls the eccentricity during East/West maneuvers. In both cases, a modified East/West control strategy is necessary to manage the eastward longitude drift due to the radial component coupling from the ionic thruster firings. Brief descriptions of the strategies, including a discussion on advantages and disadvantages as well as simulation results, will be presented.

INTRODUCTION

Ionic propulsion systems are equipped on the latest geostationary telecommunication satellites for high propellant efficiency in order to maximize orbital maneuver life (OML) with minimum satellite mass. There are two issues related to the ionic propulsion systems: (1) although the ion thrusters are fuel efficient, they provide low thrust and, thus the maneuver durations tend to be long and frequent maneuvers are required; (2) because of the plumes from the ionic propulsion system, the North/South thrusters are canted about 45 degree in the spacecraft (Y,Z) plane in order to minimize the degradation effects on the solar array. The (Y, Z) plane is defined as the plane perpendicular to the orbital velocity direction with the +Z axis pointing to the Earth. These large cant angles will introduce a large radial component for each maneuver firing.

The radial effects can be cancelled by splitting a North/South maneuver into a pair of a North maneuver followed by a South maneuver 12 hours later. The magnitudes of the maneuvers need to be adjusted to account for the slight differences in the canting angles for the North and South ionic thrusters. In this strategy, the North/South maneuvers are planned to follow the conventional secular mean line (SML) strategy (Ref. 1) where the

North/South maneuvers are performed to cancel only the secular growth of the inclination perturbations due to the Sun and the Moon effects. The in-plane station-keeping to control the eccentricity and longitude drift are performed using conventional East/West maneuver strategies. East/West maneuvers are necessary to correct the orbital eccentricity and longitude drift due to orbital perturbations from the Sun, the Moon and the Earth. Depending on the mission requirements such as control box size and maneuver cycles, the maneuvers will usually consist of either double maneuver pairs for spacecraft with larger area-to-mass ratios or single maneuvers following sun pointing strategy (Ref 3.) for spacecraft with relatively small area-to-mass ratios.

Another approach is to take advantage of the large cant angles of the thrusters and perform the North/South maneuvers to control eccentricity also. This concept was proposed in 1993 (Porte, et al.). This combined inclination and eccentricity control strategy is detailed in this paper. In addition, modifications to the East/West station-keeping strategy necessary to manage the induced positive longitude shift due to the radial component coupling from the ionic thruster firings is also described.

ALGORITHM DESCRIPTIONS

In order to avoid singularity of small inclination (i) and eccentricity (e), we will define the following classic set of non-singular elements to describe the orbital parameters for the geostationary satellites:

$$
\begin{aligned}
& a = semi-major \;\; axis \\
& e_c = e\cos(\omega+\Omega) \\
& e_s = e\sin(\omega+\Omega) \\
& w_c = \sin(i)\cos(\Omega) \\
& w_s = \sin(i)\sin(\Omega) \\
& \lambda = \omega+\Omega+M \equiv mean\,orbital\,longitude
\end{aligned}
$$

Where:
$\omega \equiv$ argument of perigee
$\Omega \equiv$ the right ascension of the ascending node
$M \equiv$ mean anomaly

The relationships between radial, tangential and normal components of impulsive maneuvers ($\Delta v_r, \Delta v_s, \Delta v_w$) and the non-singular orbital elements can be written as[1] :

(2)
$$\Delta e_c = \frac{2\cos(\Lambda)}{na}\Delta v_s + \frac{\sin(\Lambda)}{na}\Delta v_r$$
$$\Delta e_s = \frac{2\sin(\Lambda)}{na}\Delta v_s - \frac{\cos(\Lambda)}{na}\Delta v_r$$
$$\Delta w_c = \frac{\cos(\Lambda)}{na}\Delta v_w$$
$$\Delta w_s = \frac{\sin(\Lambda)}{na}\Delta v_w$$
$$\Delta\lambda = -\frac{2}{na}\Delta v_r$$
$$\Delta a = \frac{2}{n}\Delta v_s$$

Here n is the orbital mean motion, and Λ is the maneuver centroid time described in terms of Sidereal time:

$$\Lambda \equiv \Omega + \omega + \nu$$
$$= \lambda + (\nu - M)$$

where ν is true anomaly.

From the above expressions, one notices that the radial and normal components of the impulsive maneuvers affect the inclination and eccentricity elements. In addition, a radial impulsive maneuver also produces a shift in longitude.

Without loss of generality, one can write the linear perturbation of the 6 non-singular elements as:

$$elem(t) = \langle \text{sec}ular\ mean \rangle + short\ period$$

Based on (1) the secular mean terms for eccentricity and inclination vectors can be written as:

(3)
$$\langle e_c \rangle = e_{c_0} + e_{c_t}(t - t_0) + H_{e_c}\cos(\lambda_h)$$
$$\langle es \rangle = e_{s_0} + e_{s_t}(t - t_0) + H_{e_s}\sin(\lambda_h)$$

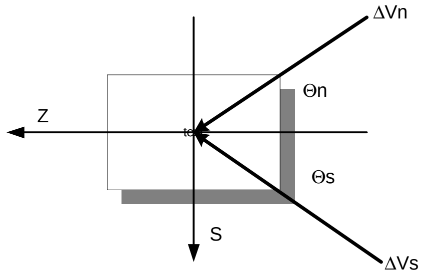
(4)
$$\Delta e_c \approx \langle \Delta e_c \rangle = \left(e_{c_t} - H_{e_c}\sin(\lambda_h)\,\dot{\lambda}_h\right)\ \Delta t$$
$$\Delta e_s \approx \langle \Delta e_s \rangle = \left(e_{s_l} + H_{e_s}\cos(\lambda_h)\,\dot{\lambda}_h\right)\ \Delta t$$

(5)
$$\langle w_c \rangle = w_{c_0} + w_{c_t}(t - t_0)$$
$$\langle w_s \rangle = w_{s_0} + w_{s_t}(t - t_0)$$

(6)
$$\Delta w_c \approx \langle \Delta w_c \rangle = w_{c_t} \Delta t$$
$$\Delta w_s \approx \langle \Delta w_s \rangle = w_{s_t} \Delta t$$

where:
$\Delta t \equiv t - t_0$ is the time duration for a station-keeping cycle.
e_{c_l} and e_{s_l} are the eccentricity secular rate due to the moon's orbit.
H_{e_c} and H_{e_s} are the solar radiation force coefficients proportional to the area-to-mass ratio of the satellite.
λ_h is the mean celestial longitude of the Sun.
ω_{c_l} and ω_{s_l} are the inclination secular rate due to the moon's gravity perturbations.

Consider the following ion thruster alignments:



In this case we can write the radial and normal impulsive maneuver components as:

(7)
$$\Delta v_{w_s} = \Delta v_s \sin(\theta_s)$$
$$\Delta v_{r_s} = -\Delta v_s \cos(\theta_s)$$

$$\Delta v_{w_n} = -\Delta v_n \sin(\theta_n)$$
$$\Delta v_{r_n} = -\Delta v_n \cos(\theta_n)$$

The objective for correcting for inclination and eccentricity perturbations over a station-keeping cycle Δt is to determine the North and South maneuver magnitudes and maneuver centroid times ($\Delta v_n, \Delta v_s, \Lambda_n, \Lambda_s$) such that the following conditions hold:

$$
\begin{aligned}
\delta w_c &\equiv \Delta w_{c_{man}} + \Delta w_{c_{perturbation}} = 0 \\
&= \frac{\cos(\Lambda_n)}{na}\Delta v_{w_n} + \frac{\cos(\Lambda_s)}{na}\Delta v_{w_s} + \Delta w_c \qquad (8) \\
&\approx \frac{1}{na}\left[-\cos(\Lambda_n)\Delta v_n \sin(\theta_n) + \cos(\Lambda_s)\Delta v_s \sin(\theta_s)\right] + w_{c_t}\Delta t \quad = 0
\end{aligned}
$$

$$
\begin{aligned}
\delta w_s &\equiv \Delta w_{s_{man}} + \Delta w_{s_{perturbation}} = 0 \\
&= \frac{\sin(\Lambda_n)}{na}\Delta v_{w_n} + \frac{\sin(\Lambda_s)}{na}\Delta v_{w_s} + \Delta w_s \qquad (9) \\
&\approx \frac{1}{na}\left[-\sin(\Lambda_n)\Delta v_n \sin(\theta_n) + \sin(\Lambda_s)\Delta v_s \sin(\theta_s)\right] + w_{s_t}\Delta t \quad = 0
\end{aligned}
$$

$$
\begin{aligned}
\delta e_c &\equiv \Delta e_{c_{man}} + \Delta e_{c_{perturbation}} = 0 \\
&= \frac{\sin(\Lambda_n)}{na}\Delta v_{r_n} + \frac{\sin(\Lambda_s)}{na}\Delta v_{r_s} + \Delta e_c \qquad (10) \\
&\approx \frac{-1}{na}\left[\sin(\Lambda_n)\Delta v_n \cos(\theta_n) + \sin(\Lambda_s)\Delta v_s \cos(\theta_s)\right] + [e_{c_t} - H_{e_s}\sin(\lambda_h)\dot{\lambda}_h]\Delta t = 0
\end{aligned}
$$

$$
\begin{aligned}
\delta e_s &\equiv \Delta e_{s_{man}} + \Delta e_{s_{perturbation}} = 0 \\
&= \frac{-\cos(\Lambda_n)}{na}\Delta v_{r_n} + \frac{-\cos(\Lambda_s)}{na}\Delta v_{r_s} + \Delta e_s \qquad (11) \\
&\approx \frac{1}{na}\left[\cos(\Lambda_n)\Delta v_n \cos(\theta_n) + \cos(\Lambda_s)\Delta v_s \cos(\theta_s)\right] + [e_{s_t} + H_{e_s}\cos(\lambda_h)\dot{\lambda}_h]\Delta t = 0
\end{aligned}
$$

The short period perturbations were neglected in these equations. The short period perturbations have periods less than 24 hours, and the amplitude for inclination due to these terms is less that 0.03 degrees. Figure 1 shows the simulation of inclination perturbations.

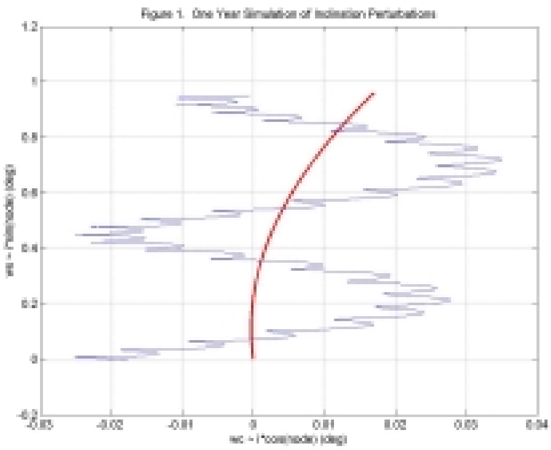


Figure 1. One Year Simulation of Inclination Perturbations

In this figure the secular mean perturbation is shown in "Bold" and the full perturbation terms are shown in "Light". One can see the errors committed by neglecting the short perturbation terms are less that 0.03 degree in inclination.

Considering equations (8) – (11), let us define the following variables:

$$A = \cos(\Lambda_n)\Delta v_n$$
$$B = \cos(\Lambda_s)\Delta v_s$$
$$C = \sin(\Lambda_n)\Delta v_n$$
$$D = \sin(\Lambda_s)\Delta v_s$$

One can then simplify the above equations into the following:

$$\frac{1}{na}\begin{bmatrix} -\sin(\theta_n) & \sin(\theta_s) & 0 & 0 \\ \cos(\theta_n) & \cos(\theta_s) & 0 & 0 \\ 0 & 0 & -\cos(\theta_n) & -\cos(\theta_s) \\ 0 & 0 & -\sin(\theta_n) & \sin(\theta_s) \end{bmatrix}\begin{bmatrix} A \\ B \\ C \\ D \end{bmatrix} \approx \begin{bmatrix} -w_{c_t} \\ -[e_{s_t} + H_{e_s}\cos(\lambda_h)\dot{\lambda}_h] \\ -[e_{c_t} - H_{e_c}\sin(\lambda_h)\dot{\lambda}_h] \\ -w_{s_t} \end{bmatrix}\Delta t$$

Solutions for A,B,C and D can be easily obtained by simply solving for two 2x2 matrix equations.
After obtaining solutions for A,B,C and D one can compute the maneuver parameters ($\Delta v_n, \Delta v_s, \Lambda_n, \Lambda_s$) using the following relationships:

$$\Delta v_n = \sqrt{A^2 + C^2}$$
$$\tan(\Lambda_n) = \frac{C}{A}$$

$$\Delta v_s = \sqrt{B^2 + D^2}$$
$$\tan(\Lambda_s) = \frac{D}{B}$$

Note that the resultant radial component of the inclination maneuvers also produces a shift in longitude according to equation (2). In order to manage this effect we will shift the mean station-keeping longitude and apply an offset to the natural drift rate over a station-keeping cycle Δt. The longitude drift offset can be computed based on the following equation:

$$\delta\lambda \equiv \frac{-2}{na}\Delta v_r + \Delta\dot{\lambda}\,\Delta t = 0$$

Solving for $\Delta\dot{\lambda}$ we obtain:

$$\Delta\dot{\lambda} = +\frac{2}{na}\frac{\Delta v_r}{\Delta t} \quad (\,^{o}/\text{day})$$

Note that for this configuration, Δv_r component is always negative thus producing a positive or an eastward shift on the longitude. This requires a negative offset to the drift rate in order to cancel this radial component effect.

RESULTS AND DISCUSSIONS

Simulations were performed using this combined inclination and eccentricity control strategy over a 15-year duration. The parameters used for the simulation are shown in Table 1.

Table 1. Simulation Parameters

Thruster alignments	45 degrees
Station-keeping (SK) Cycle	7 days
ISK maneuvers frequency	Daily N/S maneuver pair for 4 days
Station-keeping longitude	359.0 degrees E
Area-to-mass ratio	0.043 m^2/kg

Figures 2a and 2b display the results of the inclination in the form of phase plane (w_c,w_s) and polar plot presentation (inc,node).

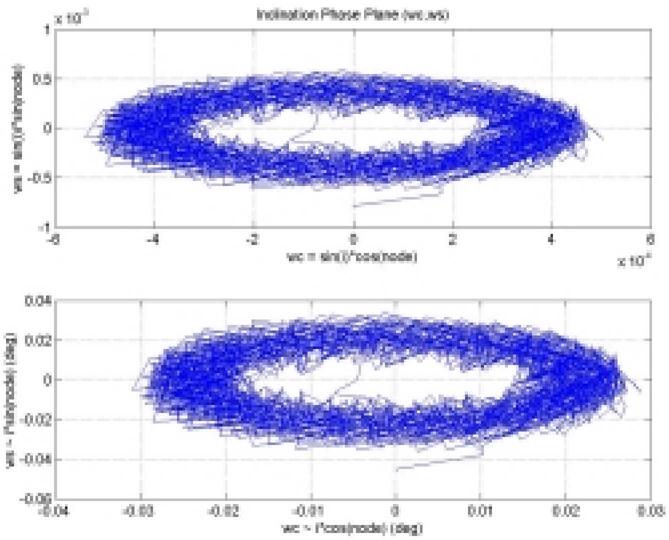


Figure 2a. Inclination Phase Plane for 15-year ISK Simulation

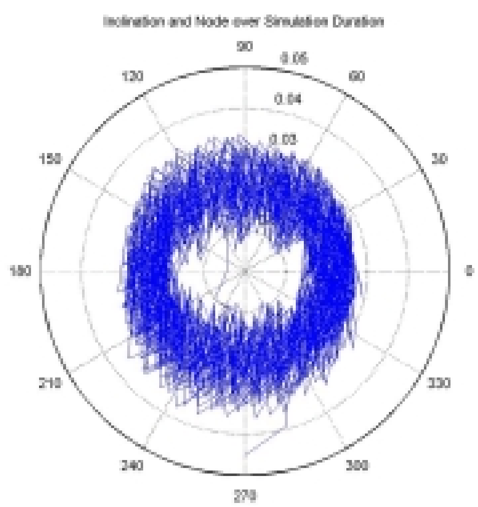


Figure 2b. Inclination and Ascending Node for 15-year ISK Simulation

In these Figures it is shown that one can maintain the inclination to about 0.03 degrees limit circle if careful choice of initial orbital parameters is chosen so that the inclination vector is centered at (0,0). Periodic re-centering may be necessary due to thruster performance dispersions. The re-centering maneuvers can be performed together with the scheduled station-keeping maneuvers. The re-centering maneuvers in most cases will be performed in small steps because of the constraints on the ionic thruster firing duration. In the case shown in Figures 2a and 2b, the re-centering maneuvers are performed over 3 station-keeping cycles. As can be seen in Figure 2b, the initial conditions used for the simulation are inclination = 0.045^o and ascending node = 270^o.

The average annual delta-v requirement for the combined inclination and eccentricity maneuvers (ISK) is 65.9 m/sec while the theoretical optimal annual delta-v requirements for inclination corrections along secular mean line (SML) is 65.2 m/sec for the same period. The difference between the two strategies is about 1% which is equivalent to about 1 month for a satellite with 13 years of design life. The slightly lower efficiency for the ISK strategy over the SML strategy is due to the offsets applied to the inclination maneuver centroid times in order to correct for the eccentricity perturbations. Figure 3 shows the time history of the ISK N maneuver centroid angles (“Light”) versus the SML optimal centroid angles (“Bold”).

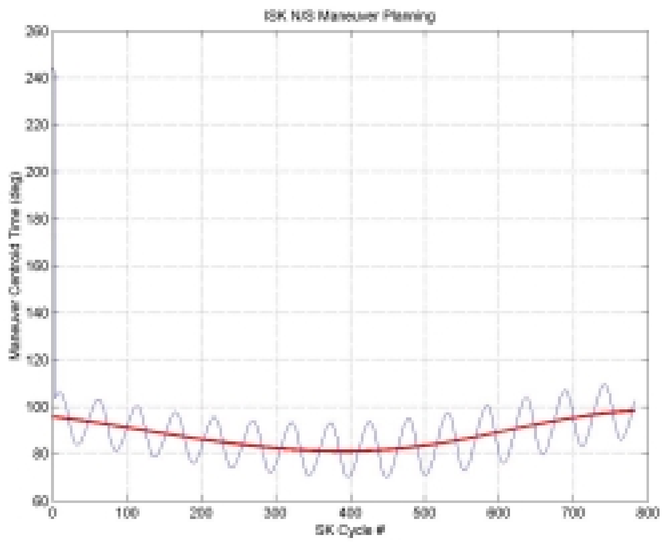


Figure 3. Maneuver Centroid Angles for 15-year ISK Simulation

In Figure 4 we show the comparisons of the ISK North (“Bold”) and South (“Light’) maneuver delta-v magnitudes and the maneuver centroid angles with SML optimal strategy. The differences are results of the ISK strategy for combine inclination and eccentricity control. The larger differences shown in Figures 3 and 4 at the beginning three station-keeping cycles are due to the re-centering maneuvers.

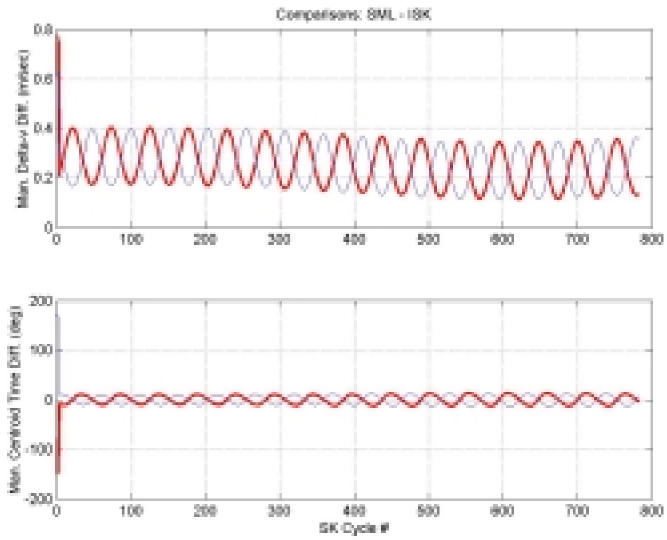


Figure 4. N/S Delta-V and Maneuver Centroids Comparisons for 15-year ISK Simulation

The corrections to the eccentricity perturbations were achieved due to the canting angles of the thrusters. Figure 5 shows the eccentricity evolutions in the eccentricity phase plane over the span of the 15-year simulation.

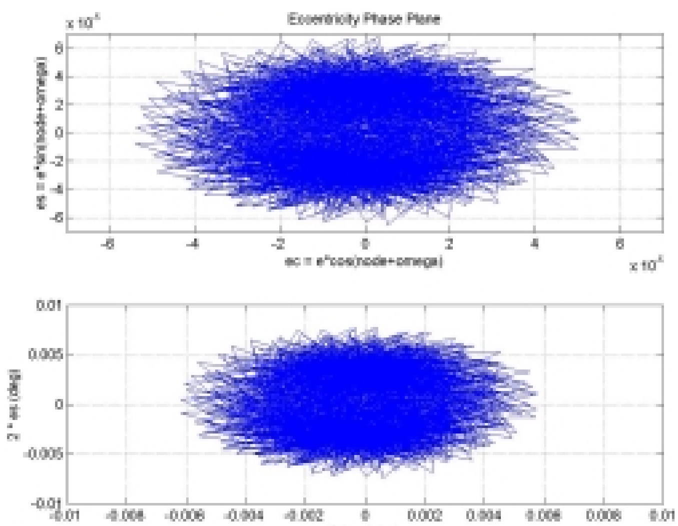


Figure 5. Ecc. Phase Plane for 15-year ISK Simulation

The figure shows that the combined inclination and eccentricity strategy controls the eccentricity to within 6.0E-5 or 0.01 degree in the daily librations. The required delta-v for controlling eccentricity to this size using convention East/West maneuver pairs could be as large as 0.6 m/sec/year for the case considered in this simulation. Note that the delta-v requirement for longitude drift control is also about 0.66 m/sec/year at the longitude considered in this case.

The average radial component for the 15 year ISK simulation is about –0.893 m/sec which results in an eastward shift of 0.033 degree. In order to maintain a station-keeping cycle of 7 days and a mean longitude at 359.0E the drift rate offset requirement is about -0.00476858 ^{o}/day and the mean longitude offset requirement is -0.00709 degree.

Figure 6 shows the longitude phase plane for a typical 7-day station-keeping cycle. The "Bold" represents the theoretical cycle. The "Light" shows the longitude due to radial components from the ionic thruster firings. One can see that if no offsets are applied the longitude shifted to the east after each cycle.

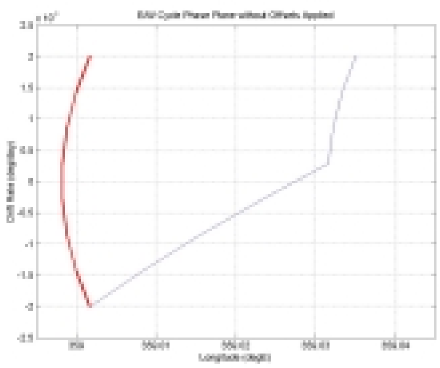


Figure 6. Longitude Phase Plane with no Offsets Applied

Figure 7 shows the longitude phase plane for a typical 7-day station-keeping cycle. The "Bold" represents the theoretical cycle. The "Light" represents the ISK simulation with the mean longitude and drift rate offsets applied. After applying the mean longitude offset the excursions in longitude is centered around 359.0 degree E and the drift rate offset compensated the radial components from the ionic thruster firings.

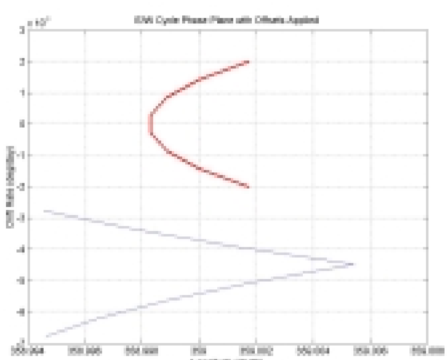


Figure 7. Longitude Phase Plane with Offsets Applied

CONCLUSION

The results show that with slight changes in the maneuver durations and centroid times it is possible to control the growth of eccentricity during the North/South maneuvers by taking advantage of the large thruster canting angles. We have also shown that the combined inclination and eccentricity strategy is the strategy choice if we need to keep eccentricity small due to mission requirements and other spacecraft constraints. In the simulation we showed that only an additional 1.0% of propellant for North/South maneuver is required in order to keep the eccentricity to within 6.0E-05. However, with a more relaxed mission requirements, and if the spacecraft area-to-mass ratio is relatively small and the eccentricity can be controlled using the single-maneuver sun-pointing East/West station-keeping strategy, the conventional secular-mean-line strategy for the North/South maneuvers would be more efficient. In general, tighter eccentricity controls are preferred to provide extra margins for orbital uncertainties and maneuver misperformances.

In addition, regardless of the choice of strategy for the North/South maneuvers, one must also consider the longitude shift due to the radial coupling from the North/South maneuvers. This longitude shift can be accounted for using a bias in the station-keeping semi-major axis resulting in an adjustment to the longitude drift corrections.

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