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STATION-KEEPING MANEUVER SIMULATION FOR THE KOREASAT SPACECRAFT USING MISSION ANALYSIS SOFTWARE

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ABSTRACT

A series of east/west and north/south station-keeping maneuvers were simulated for the KOREASAT spacecraft which has to be maintained within ±0°.05 at the nominal longitude of 116° E. Weekly and biweekly based station-keeping maneuver plannings were used, and weekend maneuvers were avoided. All of the station-keeping maneuver plannings and executions were performed using KOREASAT Mission Analysis Software on VAX/VMS operating system. Fourteen weeks station-keeping maneuvers were performed and various station-keeping orbital parameters were obtained.

1. INTRODUCTION

The KOREASAT program will provide the satellite communications and the direct broadcasting services over the Korean peninsula. The space segment consists of two Ku-band satellites, and the ground segment consists of two TT&C stations. The satellites will be collocated at 116° East longitude and maintained within ±0°.05 box of the nominal longitude. The periodic station-keeping maneuvers are planned and commanded by Satellite Control Center. KOREASAT Mission Analysis Software (MAS) is used for all of the flight dynamics calculations for the KOREASAT spacecraft. The MAS uses an interactive graphical user interface for the station-keeping maneuver planning. The host machine for the MAS is a Micro VAX series computer running on VAX/VMS operating system.

In this paper, weekly and biweekly based station-keeping maneuver plannings were used, and weekend maneuvers were avoided. The Sun-pointing perigee control method was used for the East/West Station-Keeping (EWSK) maneuver which was done with a seven-day cycle time as well as a fourteen-day cycle time. Slavinskas *et al.* (1988)'s minimum fuel consumption method was applied to the North/South Station-Keeping (NSSK) maneuver with a twenty-eight-day cycle time. All of the station-keeping maneuver plannings and executions were performed using KOREASAT Mission Analysis Software on VAX/VMS operating system. A total of fourteen weeks station- keeping maneuvers were performed and various station-keeping orbital parameters were obtained.

2. EAST/WEST STATION-KEEPING MANEUVER STRATEGY

The KOREASAT spacecraft stationed at 116° E tends to move west toward the stable point near 75° E by the Earth's tesseral harmonics. This means that the semi- major axis of the orbit is increasing and the orbital period is extended. Solar radiation pressure causes eccentricity vector to rotate perpendicular to the Earth-Sun line and with the same sense as the orbital velocity (Kelly *et al.* 1994). The EWSK maneuver burn is tangent to the orbit and adjusts the semi-major axis and eccentricity of the orbit to maintain the spacecraft within the station-keeping box. The station-keeping maneuver strategy should be designed to minimize spacecraft propellant usage and ground operational load. This implies that orbit determination error and maneuver execution error must be allowed when allocating the available east-west deadband. The KOREASAT spacecraft is allocated $0\overset{\circ}{.}1$ of EWSK band. Of this allocation, a guard band of $0\overset{\circ}{.}01$ on each end is allowed for orbit determination error and maneuver execution error, and two $0\overset{\circ}{.}007$ bands for perturbations due to luni-solar gravitational effects (Hubert and Swale 1984). The remaining planning limit of about $0\overset{\circ}{.}066$ must accommodate the diurnal longitude variation due to mean eccentricity, which is governed by solar radiation pressure, and secular drift due to the Earth's triaxiality. The maximum free drift time T is obtained from quadratic expressions of longitude motion due to triaxiality as a function of time (Soop 1983).

$$T = 4\left(\frac{\delta\lambda}{\ddot{\lambda}}\right)^{1/2} \tag{1}$$

where, $\delta\lambda$ denotes half size of the deadband and $\ddot{\lambda}$ denotes the mean drift-rate change, $\ddot{\lambda} = -0.198 \times 10^2 (deg/day^2)$ at 116° E. For the operational purpose of the Satellite Control Center, station-keeping is chosen on a weekly base to avoid weekend maneuver. If we choose a 7-day and a 14-day EWSK cycle, the total deadband is calculated from equation (1) as $0\overset{\circ}{.}012$ and $0\overset{\circ}{.}048$. The remaining $0\overset{\circ}{.}054$ and $0\overset{\circ}{.}018$ will be used for diurnal longitude variation due to the eccentricity. The effect of eccentricity on longitude is approximately described by the following relation:

$$\Delta\lambda_{ecc} = \frac{720}{\pi}\, e_{mean} \tag{2}$$

The mean eccentricity limit, e_{mean} for 7-day EWSK is calculated from equation (2) as 2.356×10^{-4} and 14-day EWSK as 7.854×10^{-5}. The EWSK maneuver band allocations are summarized in Table 1.

Table 1. EWSK maneuver band allocation.

Band Allocations(deg.)	7-Day EWSK	14-Day EWSK
Guard Band for OD and Maneuver Execution Errors	0.02	0.02
Guard Band for Luni-Solar Perturbations	0.014	0.014
Allocation for Drift and N/S Coupling	0.012	0.048
Allocation for Eccentricity Due to Solar Pressure	0.054	0.018
Mean Eccentricity Limit	2.356×10^{-4}	7.854×10^{-5}

For the sake of fuel efficiency and operational simplicity, it is always desirable to control eccentricity simultaneously with longitudinal drift. The method used in Sun-pointing perigee strategy is to target the beginning-of-cycle and end-of-cycle mean eccentricities to equal limit, and the average direction of perigee over the cycle to equal the average right ascension of the Sun (Kamel & Wagner 1982). To change the drift rate of a satellite, the velocity must be changed. In order to change the location of the synchronous longitude of the satellite, a single tangential burn changes the semi-major axis and the eccentricity of the orbit. The change of semi- major axis means the change of the drift rate of the longitude.

The EWSK maneuver planner comprises of a Drift Maneuver Planner and an Eccentricity Maneuver Planner. The Drift Planner is a display of the pre- and post-maneuver ephemerides in the longitude- drift phase plane. The Eccentricity Planner displays the pre- and post-maneuver ephemerides in the eccentricity h-k space. Here, h and k are defined by the following relations.

$$\vec{e} = \begin{bmatrix} h \\ k \end{bmatrix} = e \begin{bmatrix} \cos(\Omega + \omega) \\ \sin(\Omega + \omega) \end{bmatrix} = e \begin{bmatrix} \cos\tilde{\omega} \\ \sin\tilde{\omega} \end{bmatrix} \tag{3}$$

where, $\vec{e}$ denotes eccentricity vector, and Ω, ω and $\tilde{\omega}$ denotes right ascension of ascending node, argument of perigee, and longitude of perigee, respectively. The size and time of day of the burn are controlled by mouse manipulation of the burn vectors in either the drift or the eccentricity space. Maneuvers performed near the crossing of the semi-latus rectum will maximize the rotation of the eccentricity vector while minimizing the change in its magnitude (Brock *et al.* 1990). On the other hand, maneuvers performed near the line of apsides, will maximize the change in magnitude, and minimize the rotation. Figure 1 and Figure 2 show the Drift Planner and the Eccentricity Planner, respectively.

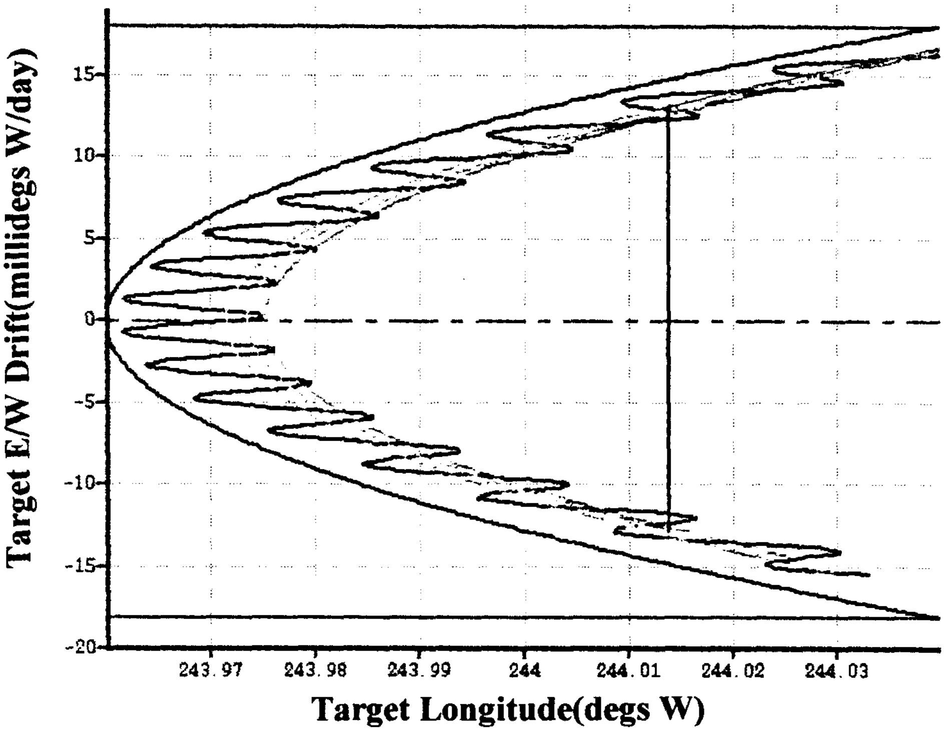

Figure 1. Drift Planner for East/West Station-Keeping Maneuver.

In the Drift Planner, the maximum allowable drift change is determined from the current magnitude of the net eccentricity change. In the Eccentricity Planner, the minimum allowable eccentricity change is determined from the current magnitude of the net drift change. Two part maneuvers are necessary if the desired change in eccentricity is not achievable with a single burn. In this event both east face thruster and west face thruster are used for two part maneuvers.

3. NORTH/SOUTH STATION-KEEPING MANEUVER STRATEGY

The perturbations caused by the Sun and the Moon are predominantly out-of-plane effects causing a change in the inclination and in the right ascension of the ascending node (Pocha 1987). The NSSK maneuver burn is normal to the orbit and adjusts the inclination of the orbit to control the daily latitudinal excursions of the spacecraft. Because of the high fuel consumption needed for NSSK maneuvers, compared with EWSK, it is particularly important to optimize the maneuvers. The maneuver burns are actually planned

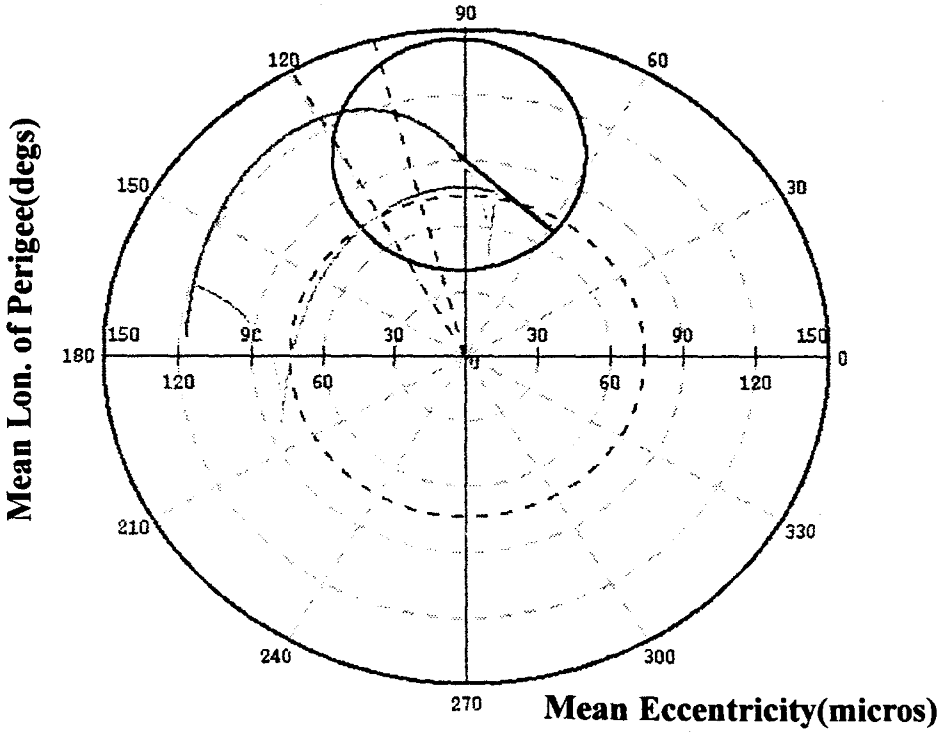

Figure 2. Eccentricity Planner for East/West Station-Keeping Maneuver.

in a graphical display. The North-South Planner is the NSSK maneuver planner display as shown in Figure 3. The North-South Planner is a display of the pre- and post-maneuver ephemerides in the inclination p-q space. The size and epoch of the inclination maneuver are controlled by mouse manipulation of the burn vector. Here, p and q are defined as the following relations.

$$\vec{i} = \begin{bmatrix} p \\ q \end{bmatrix} = 2\tan\left(\frac{i}{2}\right)\begin{bmatrix} \cos\Omega \\ \sin\Omega \end{bmatrix} \cong i\begin{bmatrix} \cos\Omega \\ \sin\Omega \end{bmatrix}, \; i \to 0 \tag{4}$$

where, $\vec{i}$ denotes inclination vector

In NSSK maneuver, the timing of the burn determines the magnitude of the scalar inclination and the right ascension of the ascending node of the resulting orbit. Three optional strategies are provided for the NSSK maneuver planning. In the maximum compensation strategy, the NSSK burn is applied at the ascending node so that the maximal reduction in inclination is obtained. The track-back chord strategy calculates a burn vector such that the

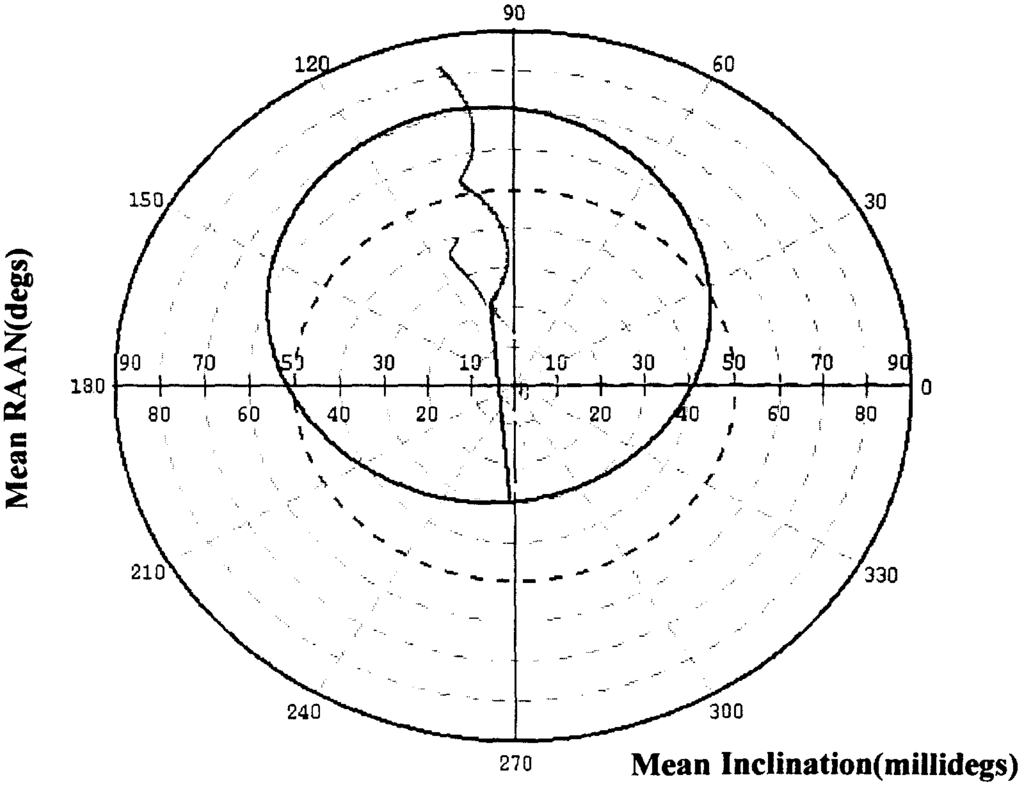

Figure 3. Inclination Planner for North/South Station-Keeping Maneuver.

chord of the next maneuver cycle passes through the origin. The minimum fuel strategy does not compensate the cyclic changes in inclination orthogonal to the secular drift to minimize the fuel used for inclination station-keeping. This approach reduces the cyclic contributions and avoids the 2.3 to 4.0 % fuel penalty altogether (Slavinskas *et al.* 1988). The minimum fuel initialization is used for the initialization of the inclination, before applying minimum fuel strategy. Four EHTs (Electro-thermal Hydrazine Thrusters) and four REAs (Rocket Engine Assemblies) are located in the north face panel of the KOREASAT spacecraft for NSSK maneuver.

4. SIMULATION

A total of fourteen EWSK maneuvers and four NSSK maneuvers have been performed using 7-day EWSK/28-day NSSK cycle during fourteen weeks simulation periods. In contrast, a total of seven EWSK maneuvers and four NSSK maneuvers have been carried out using 14-day EWSK/28-day NSSK cycle during the same periods. The last two NSSK maneuvers have been carried out every 14-day interval due to the electrical power limitations for using EHT during the eclipse season. Thursday was fixed for EWSK maneuvers and Tuesday for NSSK maneuvers. Two-day's separation between NSSK and EWSK was required for compensating east/west drift caused by NSSK maneuver.

Figure 4 and Figure 5 show the longitude history during the 14 weeks. EWSK maneuver point is not clearly shown in Figure 4 due to the diurnal variation caused by eccentricity. On the other hand, Figure 5 shows the distinct figure of drift and diurnal variation. Figure 6 and Figure 7 show the eccentricity history for the same period. In Figure 6, the magnitude of eccentricity is well below the eccentricity limit after continuing EWSK maneuvers. On the other hand, the magnitude of eccentricity is somewhat above the eccentricity limit in Figure 7. In this case, two-burn strategy may be applied to reduce the magnitude of eccentricity. Figure 8 shows latitude history for the simulation periods. Figure 9 shows the inclination vs right ascension of ascending node. Since the minimum fuel strategy has been applied to the NSSK maneuver, the inclination is not always approached to zero.

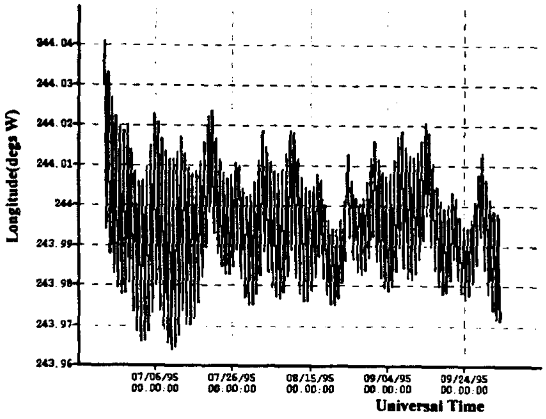

Figure 4. Longitude history for the 7-day EWSK cycle.

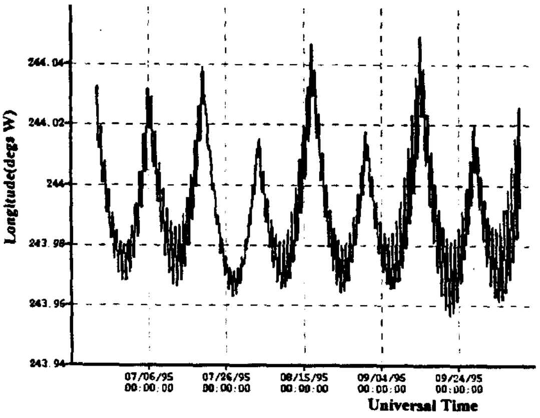

Figure 5. Longitude history for the 14-day EWSK cycle.

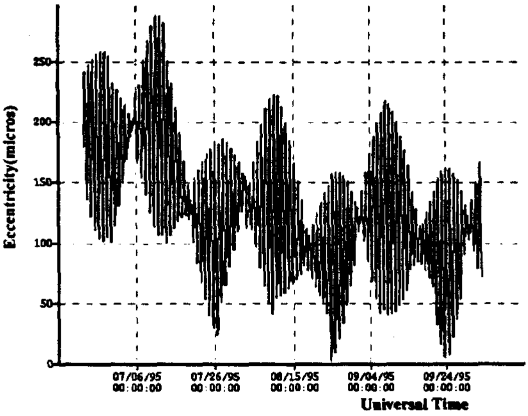

Figure 6. Eccentricity history for the 7-day EWSK cycle.

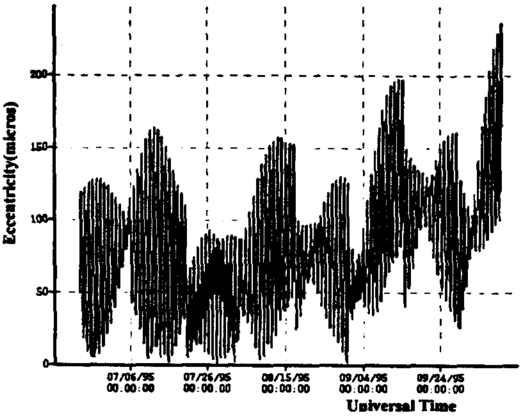

Figure 7. Eccentricity history for the 14-day EWSK cycle.

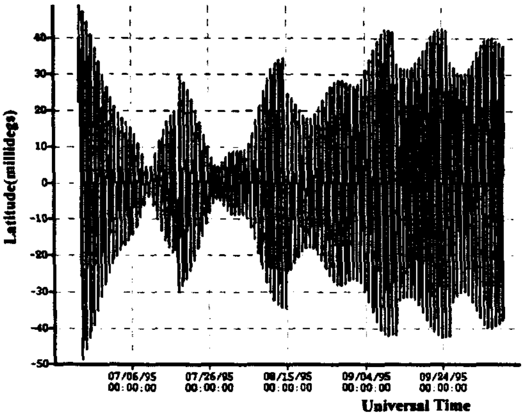

Figure 8. Latitude history for the 28-day NSSK cycle.

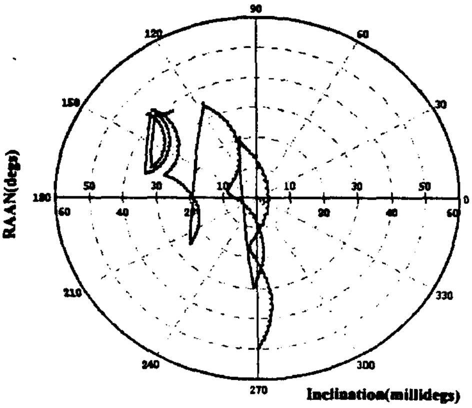

Figure 9. Inclination vs. right ascension of ascending node history for the 28-day NSSK cycle.

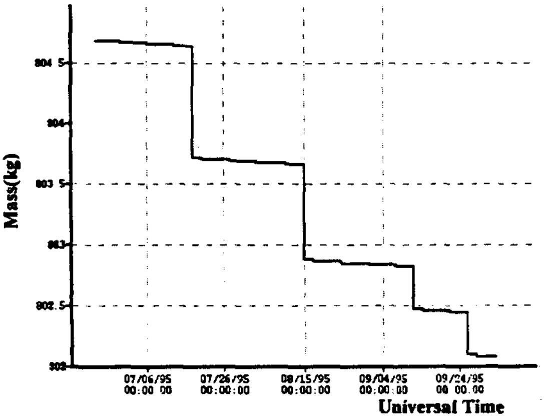

Figure 10. Mass history for 7-day EWSK/ 28-day NSSK cycle.

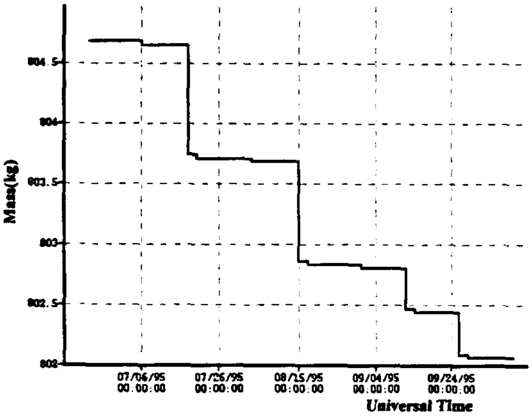

Figure 11. Mass history for 14-day EWSK/ 28-day NSSK cycle.

The KOREASAT spacecraft mass histories during the simulation periods are shown in Figure 10 and Figure 11. In these Figures, the big vertical lines represent the fuel consumption during NSSK maneuvers and the small bits of vertical lines represent the fuel consumption during EWSK maneuvers. Apparently, NSSK maneuvers are primary cause of fuel consumption. There is no big difference between the two Figures except frequent EWSK maneuvers found in Figure 10. Small amount of fuel penalties introduced by frequent maneuvers are expected in the real satellite operations.

5. CONCLUSION

A total of fourteen weeks station-keeping maneuver simulations for the KOREASAT spacecraft were performed using KOREASAT Mission Analysis Software. A seven-day and a fourteen-day cycles were used for EWSK maneuver and a twenty-eight-day cycle was used for NSSK maneuver. Each station-keeping maneuver was made at a fixed date of a week so that the weekend maneuver was avoided. A simultaneous longitude and eccentricity control were accomplished using Sun-pointing perigee strategy. Both seven-day and fourteen-day EWSK cycles found to be applicable to maintain KOREASAT spacecraft within $\pm 0.^{\circ}05$ band. Tight eccentricity control was required when fourteen-day EWSK cycle is used. In this case, two-part eccentricity maneuver may be performed occasionally. For collocation maneuver strategy, seven-day EWSK/fourteen-day NSSK cycle is preferable. Independent simulation study of the collocated spacecraft station-keeping maneuver is needed. Since NSSK maneuver strategy is more critical for the fuel consumption, quantitative NSSK maneuver analyses are required such as track-back chord method, maximum compensation method, and minimum fuel method.

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