Semiautonomous Stationkeeping of Geosynchronous Satellites

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A feasibility study on semiautonomous stationkeeping of geosynchronous satellites has been performed. The concept is to make the stationkeeping maneuvers autonomously for a period of six months based on predetermined longitude variation and maneuver sequences. Because this strategy does not require a sophisticated, fully autonomous navigation package, the impact on the cost and reliability of the mission is minimized. Results of this analysis indicate that the feasibility of this concept depends on longitude control tolerance and stationkeeping maneuver uncertainty. This report also discusses the potential of using the solar array current variations during Earth eclipses for removing the longitude prediction error.

Introduction

ONCE a satellite is placed into a geosynchronous orbit, it tends to drift away from its nominal position because of natural perturbations and injection errors. Hence the orbit must be corrected periodically in order to keep the satellite at its nominal position within a specified tolerance. The stationkeeping of current geosynchronous satellites depends heavily on ground station support. Those ground stations are not only expensive to maintain and operate, they are also vulnerable to enemy attack. The increased number of geosynchronous satellites in the future will significantly increase the work load of the ground stations. Therefore, the need for autonomous or semiautonomous stationkeeping to reduce the dependence on ground support has become very important.

In the past twenty years, various studies and investigations on the subject of autonomous spacecraft navigation have been made by many researchers.[1-24] A recent study on fully autonomous stationkeeping of future communication satellites was carried out by Vendy and Plummer.[16] Their study requires optical sensors for Earth, sun, and Polaris viewing to obtain the navigational information. The target accuracy for autonomous stationkeeping is ±0.1 deg in both longitude and latitude. The orbit determination concept involves the satellite attitude. The orbit parameters are computed once per orbit by a least squares curve fit, and then a classical stationkeeping strategy is used to maintain the orbit. Orbit corrections can be accomplished by a high- or low-thrust propulsion system. Autonomous stationkeeping is demonstrated for five days.

A more recent paper by Eckstein et al.[24] follows a slightly more sophisticated approach using an attitude-independent orbit determination concept and an optimal orbit correction strategy especially designed for low-thrust electric propulsion. The navigational data from the sun, Earth, and Polaris sensors are evaluated by an epoch element filter which combines the batch least square and sequential filter algorithms. Based on one year's autonomous stationkeeping simulation, Eckstein concluded that stationkeeping accuracies of the order ±0.1 deg are feasible with certain assumptions on the sensor bias magnitude.

The two approaches discussed above have demonstrated through computer simulations the feasibility of a fully autonomous stationkeeping system for maintaining the geosynchronous orbits. However, before any fully autonomous stationkeeping system becomes operational, some lengthy tests and on-orbit demonstrations have to be made in order to establish its accuracy and reliability. Furthermore, the impact on a given mission due to the increased weight and cost of this system should also be studied.

From a practical point of view, it is legitimate to study the feasibility of a semiautonomous system first. The period of autonomous satellite operation is assumed to be six months. This approach is aimed at reducing the ground station work load and expense with minimum impact on the cost and reliability of the mission. The purpose of this study is to examine the feasibility of semiautonomous stationkeeping of geosynchronous satellites. Two types of control requirements were analyzed: a ±1.0 deg longitude tolerance and a ±0.1 deg longitude and latitude tolerance.

Concept and Assumptions

The concept of semiautonomous stationkeeping is to accurately predict the orbit variations and required stationkeeping maneuvers based on ground observations and orbit determinations at the start of each autonomous stationkeeping period. The times and magnitude of the required maneuvers during that period are transmitted to the spacecraft and stored in an onboard computer. At the proper time, the spacecraft performs the stationkeeping maneuver autonomously according to the preprogrammed sequence, and thus keeps the orbit within the tolerance limit. The period of autonomous stationkeeping is aimed at six months. The above concept is to achieve the following goals:

1) Reduce ground station work load and expense.

2) Reduce or eliminate dependence on fixed overseas ground stations, and thus become less vulnerable to station failure or enemy attack.

3) Retain good spacecraft reliability by not adding a sophisticated, fully autonomous package to the spacecraft.

4) Provide the foundation for an effective implementation of a fully autonomous spacecraft maintenance system at a later date.

The feasibility of the concept of semiautonomous stationkeeping depends primarily on the accuracies of orbit prediction, maneuver execution, and the clock onboard the spacecraft. Results of a recent study[25] show that the longitude of one of the communication satellites can be predicted over a span of six months with an error less than 0.02 deg. The assumed maneuver error is about 10%; however, this error can be removed almost entirely with an accelerometer onboard. The onboard clock is needed for timing the maneuver sequences with an accuracy of about ±1.0 s during the

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autonomous period. A clock with moderate stability ($\Delta f/f \approx 5\times10^{-8}$) is adequate. The following accuracies are assumed for this feasibility study.

The accuracy of orbit prediction for six months:
longitude = 0.02 deg
latitude = 0.002 deg

The accuracy of stationkeeping maneuvers:
current capability = 10% uncertainty
with accelerometer = 0% uncertainty

The accuracy of onboard clock:
± 1.0 s for six months

For spacecraft with three-axis stabilization, the effect due to the momentum wheel unloading may be significant and should be calibrated. This effect is not included in this analysis because it is spacecraft dependent.

To further illustrate the concept, Fig. 1 schematically depicts an example of semiautonomous longitude stationkeeping. The solid curve is a predetermined or predicted longitude variation with prescheduled maneuvers to keep the longitude within limits. The broken curves indicate the estimated worst-case deviations due to errors in orbit prediction and maneuver execution. When the uncertainty of the predicted longitude is nearly the size of the tolerance limit, autonomous stationkeeping can no longer continue. The region next to the upper and lower limits allows for diurnal longitude variations due to the eccentricity of the orbit.

Analysis

The longitude drift of a geosynchronous orbit is primarily caused by the gravitational acceleration due to tesseral harmonics of the Earth; that is, $J_{22}, J_{32}, \ldots$, etc. The acceleration is a function of longitude. When the longitude variation is small (±1.0 deg), the "scallop"-shaped motion shown in Fig. 1 can be approximated by a quadratic profile as in Ref. 26.

$$\Delta\lambda = \Delta n_0 (t-t_0) + \frac{\epsilon}{2}(t-t_0)^2 \tag{1}$$

where

$\Delta\lambda = \lambda - \lambda_0$ = longitude variation from an epoch value λ_0
t = time
Δn_0 = constant longitude drift rate at t_0
ϵ = constant acceleration at λ_0 due to tesseral harmonics
t_0 = epoch time, may be the start of an autonomous period or the time of a maneuver

For circular orbits, the above relation can be expressed in terms of the ΔV applied at t_0 as

$$\Delta\lambda = -\frac{3}{2}\frac{\Delta V}{a}(t-t_0) + \frac{\epsilon}{2}(t-t_0)^2 \tag{2}$$

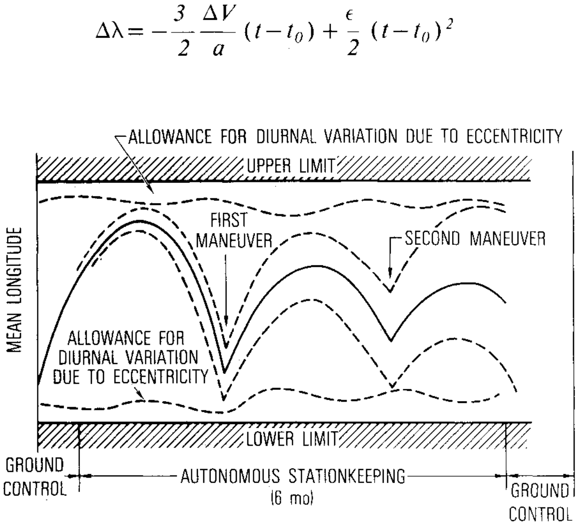

Fig. 1 Schematic illustration of semiautonomous longitude stationkeeping.

where ΔV is the circumferential velocity increment at t_0, and a is the semimajor axis of the orbit. The magnitude of the ΔV is such that the absolute value of the longitude drift rate after the maneuver is equal to that just before the maneuver. With the above relation and an orbit propagator,[25] the feasibility of semiautonomous stationkeeping can be understood through simulations with assumed accuracies of orbit prediction and maneuvers. Two different levels of stationkeeping tolerance limit were examined: 1) the longitude is controlled to within ±1.0 deg from a nominal value; and 2) both the longitude and the latitude are controlled to within ±0.1 deg. The ±1.0 deg requirement is typical of current geosynchronous satellites such as the Fleet Satellite Communications (FLTSATCOM) system. The ±0.1 deg limit is for future communication satellites like the Phase III of the Defense Satellite Communications System (DSCS III).

The ±1.0-Deg Tolerance Limit

The variation of the mean longitude of a geosynchronous satellite with stationkeeping controls can be illustrated by an example shown in Fig. 2. The satellite is stationkept at 337°E longitude with ±1.0 deg tolerance limit. This simulation from GEOSYN, an orbit propagator,[25] shows that the time between stationkeeping maneuvers is about 160 days. Thus, there will be one maneuver needed during six months.

The magnitude and frequency of stationkeeping maneuvers depend on the longitude. Figure 3 shows the average intervals in days between maneuvers as a function of longitude. Each solid circle in Fig. 3 is the average of a five-year simulation;

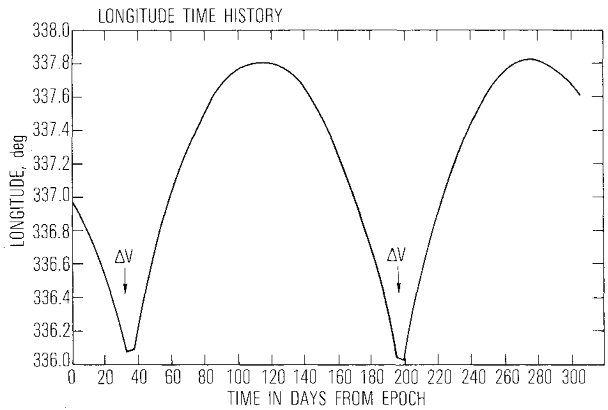

Fig. 2 Simulated longitude control with ± 1.0 deg limit (FLTSATCOM).

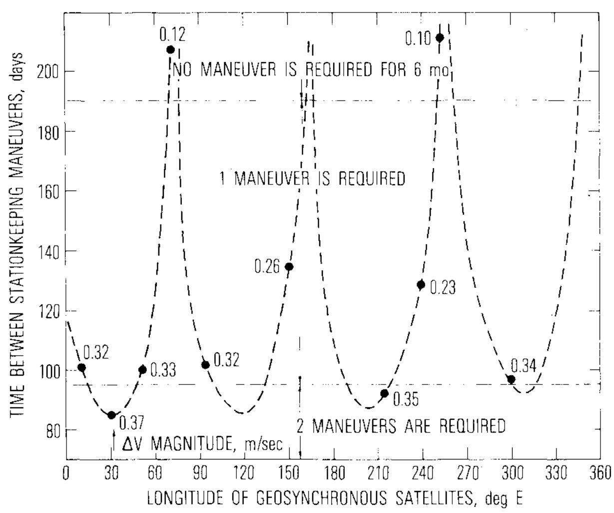

Fig. 3 Stationkeeping (±1.0 deg) frequency and ΔV magnitude (m/s).

the values indicate the magnitude of each maneuver in meters per second. It is interesting to see that when the longitude is near one of the four particular values—76, 164, 258, and 349°E (Ref. 27)—no maneuver is needed within six months. The shortest interval, 85 days, occurs when the longitude is near 34, 119, 208, and 306 deg. The uneven distribution of these four longitudes (not 90 deg apart) is a result of the combined effects of the four tesseral harmonics (J_{22}, J_{31}, J_{32}, J_{33}) included in the computation. For these longitude regions, two maneuvers are required within six months to keep the longitude within limits.

To illustrate this strategy, a simulation of semiautonomous stationkeeping was performed at 30°E longitude. After a few iterations, a nominal longitude variation with two maneuvers was determined and shown in Fig. 4 by the solid curve. The two broken curves show the worst deviations due to orbit prediction errors and a 10% error in maneuver execution. Results indicate that even at the most unfavorable longitude, the variation can be controlled within the ±1.0 deg limit in an autonomous mode for a period of six months. Therefore, one can conclude that semiautonomous stationkeeping with the ±1.0 deg tolerance limit for a period of six months is feasible.

The ±0.1-Deg Tolerance Limit

As the longitude tolerance limit is changed from ±1.0 deg to ±0.1 deg, the task of autonomous stationkeeping becomes several times more difficult and challenging. The time between maneuvers decreases substantially and is plotted as a function of longitude in Fig. 5. Most longitudes require more than three maneuvers during the six-month period. In some regions, six or more maneuvers are needed. Now the uncertainty in longitude prediction and the diurnal variation due to eccentricity account for a significant portion of the tolerance band. The diurnal longitude variation has an amplitude of $\pm 2e$ rad, where e is the eccentricity. Therefore, the eccentricity should be maintained at a very low value. Based on the physical properties of the DSCS III spacecraft, eccentricity may be controlled to a constant value of about 0.00036 by utilizing the solar radiation pressure effect.[28] The resulting diurnal variation in longitude due to eccentricity is about 0.04 deg. Combining this amplitude with the 0.02-deg prediction error, the tolerance limit for the mean longitude at the end of six months is reduced to ±0.04 deg in order to meet the ±0.1 deg requirement. Figure 6 simulates the variation at a longitude of 30 deg with the above tolerance. The frequency of maneuvers is increased because of the reduced tolerance limit. This simulation indicates that semiautonomous stationkeeping appears feasible if the 10% maneuver error is removed by an onboard accelerometer and the longitude prediction error grows linearly to 0.02 deg. The 10% maneuver uncertainty may be tolerated within certain longitude regions (15% of all longitudes) where only two maneuvers are needed in six months.

The north-south stationkeeping (±0.1 deg) is easier to accomplish than the east-west stationkeeping because the former has no diurnal variation due to eccentricity and because the prediction error in the north-south direction is smaller than that in the east-west (in-track) direction. The latitude or the orbit inclination is controlled by applying ΔV normal to the orbit plane at the ascending or descending node. The amount of ΔV is determined from the desired inclination correction with the following equation:

$$\Delta V = 2V \sin\frac{\Delta\theta}{2} \qquad (3)$$

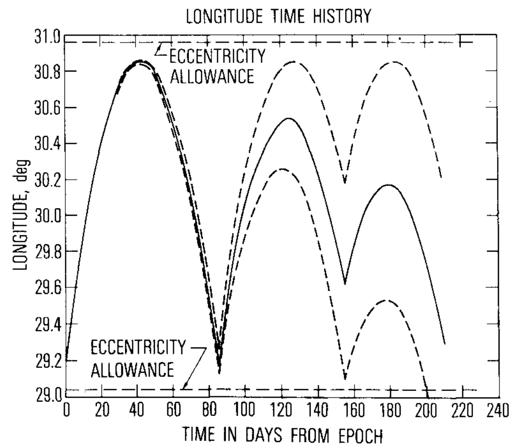

Fig. 4 Longitude variations and simulated stationkeeping maneuvers (±1.0 deg tolerance).

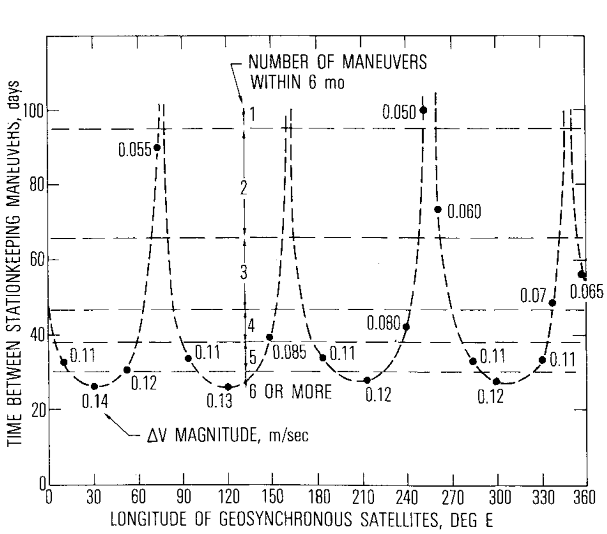

Fig. 5 DSCS III stationkeeping (±0.1 deg) frequency and ΔV magnitude (m/s).

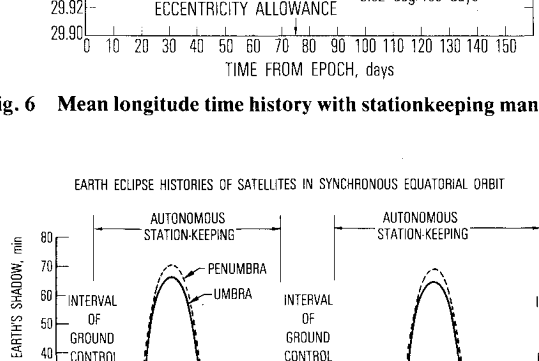

Fig. 6 Mean longitude time history with stationkeeping maneuvers.

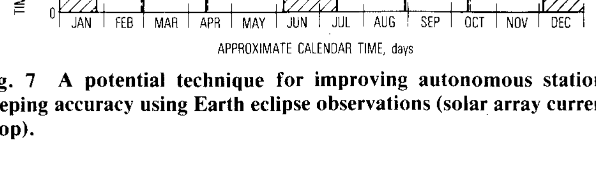

Fig. 7 A potential technique for improving autonomous stationkeeping accuracy using Earth eclipse observations (solar array current drop).

where V is the circumferential velocity at the point of correction and $\Delta\theta$ is the total plane change. For a ± 0.1-deg stationkeeping requirement, the total plane change $\Delta\theta$ is equal to 0.2 deg. The perturbations in orbit inclination are due to the lunisolar attractions. The ΔV is applied to obtain a desirable value of ascending node (≈ 270 deg). The lunisolar perturbations gradually decrease the inclination to zero and then slowly increase the inclination to the stationkeeping limit when the next maneuver is executed. The time between maneuvers for a ± 0.1 deg north-south stationkeeping ranges from 60 to 100 days.[25] Therefore, only one or two maneuvers are needed during a six-month period.

Calibrating Longitude with Eclipsing Information

The eclipse season of geosynchronous orbits occurs every six months with a duration of about six weeks as shown in Fig. 7. The electrical power drop during an eclipse may provide accurate longitude information through the timing of the center of the shadow. Figures 8 and 9 show the observed variations in solar array current during two lunar eclipses (partial) of a DSCS II satellite. The reason for studying the lunar eclipse data first is that the data are not affected by the refraction of the sun's rays through the atmosphere. The smooth and well-behaved observations (circles) reveal the potential accuracy of determining the center of the moon's shadow. Preliminary studies of Earth eclipsing data from geosynchronous satellites indicate the feasibility of timing the center of the umbra cone to within 1 s. If the center of the shadow cone can be timed to within 1 s, the longitude of the satellite can be calibrated with an accuracy of about 0.004 deg. Thus, the error in longitude prediction can be largely removed during eclipse seasons.

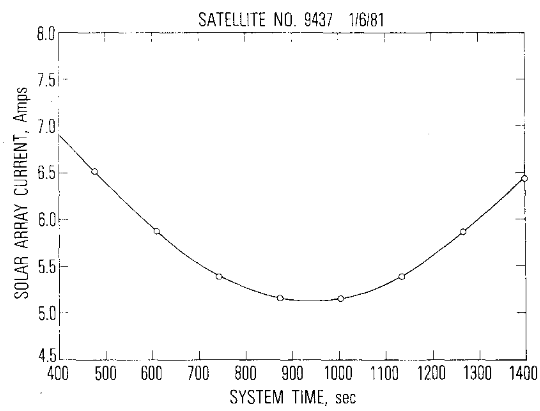

Fig. 8 Observed solar array current variation on Jan. 6, 1981 during a partial lunar eclipse (DSCS II).

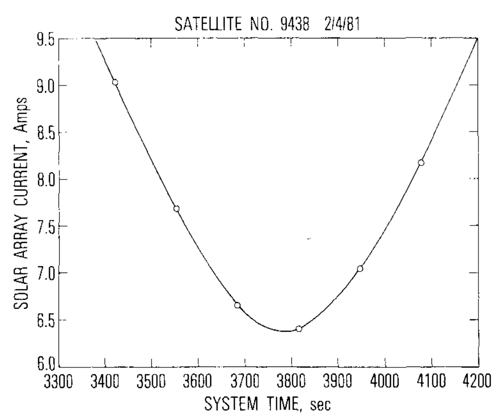

Fig. 9 Observed solar array current variation on Feb.4, 1981 during a partial lunar eclipse (DSCS II).

A proposed strategy of semiautonomous stationkeeping is illustrated in Fig. 7. If the ground control is resumed in June and December of each year, the solar array current variation during eclipses may yield accurate longitude information near the midpoint of the six-month autonomous period. As a result, the prediction error can be significantly reduced, and this technique thus enhances the feasibility of semiautonomous stationkeeping.

Conclusions

The results of this preliminary analysis led to the following conclusions:

1) When the longitude tolerance is ± 1.0 deg (such as for the Fleet satellite Communications System), semiautonomous stationkeeping with a 10% maneuver uncertainty is feasible for a period of six months.

2) For a requirement type such as for the Phase III of the Defense Satellite Communications System (DSCS III), the feasibility of keeping the longitude within ± 0.1 deg depends largely on the longitude. Within certain longitude regions (15% of all longitudes), the number of maneuvers is less than three and autonomous stationkeeping is feasible under the assumption of low eccentricity. In other longitude regions, the number of required maneuvers is three or greater, and the feasibility of six-month semiautonomous stationkeeping depends on the additional assumptions that the 10% maneuver error is removed by an onboard accelerometer and that the longitude error grows linearly with time to 0.02 deg.

3) North-south stationkeeping with a ± 0.1-deg tolerance is easier to accomplish than east-west stationkeeping. With an accelerometer to remove the maneuver uncertainty, semiautonomous stationkeeping in the north-south direction is feasible.

In addition to reducing work load and vulnerability of ground stations, this semiautonomous stationkeeping strategy has two major advantages. First, it retains good reliability by avoiding sophisticated onboard sensors and navigation software. Second, the development and implementation costs should be considerably less than going to a fully autonomous system. It provides the foundation for an effective implementation of a fully autonomous spacecraft maintenance system.

Preliminary studies of Earth eclipsing data from geosynchronous satellites indicate the feasibility of timing the center of the umbra cone to within 1 s.

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