Analysis of the Effects of Mean Local Node-Crossing Time on the Evolution of Sun-Synchronous Orbits*

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ABSTRACT

This study, an investigation of the effect of mean local node-crossing time on the evolution of Sun-synchronous orbits, was undertaken during Phase-A orbit analysis for the National Oceanic and Atmospheric Administration (NOAA) O,P,Q environmental spacecraft. That analysis added to the growing body of evidence that individual Sun-synchronous missions, at differing node-crossing times, experience nodal drift rates that can differ in both magnitude and direction. A Sun-synchronous orbit is obtained by means of a nodal drift rate approximating the 0.9856-degree-per-day apparent precession of the position of the mean Sun. This drift rate is achieved through the interaction of the orbital semimajor axis and inclination in Earth's geopotential field. Influencing perturbations include atmospheric drag and, most important, the effects of solar gravitation on inclination. The present analysis examines a series of Sun-synchronous orbits with mean local node-crossing times at 1-hour intervals from 6 a.m. to 6 p.m. It considers the fixed geometry of each orbital plane with respect to both the Sun and the diurnal atmospheric bulge, then analyzes the influence of these features upon the evolution of the semimajor axis and inclination and thus upon the rate of the nodal drift in the course of 1 year.

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1. INTRODUCTION

Because of the nonspherical mass distribution of the Earth, satellite orbits between roughly 200 kilometers (km) and 6000 km in altitude experience gravitational perturbations that cause the orbital plane to rotate about the Earth's polar axis. As shown in Figure 1 (from Reference 1), the resulting nodal rotation is negative for direct orbits [inclination (i) < 90 degrees (deg)]. For retrograde orbits (i > 90 deg) the nodal rotation is positive. The rate of the nodal drift can be approximated by:

$$\dot{\Omega} = -2.06474 \times 10^{14} a^{-7/2} \left(1 - e^2\right)^{-2} (\cos i) \qquad (1)$$

where $\dot{\Omega}$ = nodal drift rate (deg/day)

a = semimajor axis (km)

i = inclination (deg)

e = eccentricity

[derived from Equation (3-41), Reference 1]. In a near-circular retrograde orbit, the altitude and inclination may be chosen to produce a nodal drift rate equal to the 0.9856 deg/day precession of the position of the mean Sun. With such a drift rate and without other perturbations, the orbital plane would maintain a fixed geometry with respect to the Sun's position throughout the course of the year. In practice, the altitude and/or inclination are selected to maintain Sun-synchronicity for a specified period within specified bounds. The orientation of a specific Sun-synchronous orbit with respect to the Sun is identified by its mean local time (MLT) of node-crossing: i.e., the local Sun time (LST) of the nodal crossing nearest the Sun.

Figure 2 plots the results of Equation 1, showing mean altitude versus mean inclination for Sun-synchronous orbits from 200 km to 5974 km in altitude. The resulting curve approximates the full range of altitude/inclination (a/i) combinations which, without other perturbations, would produce nodal drift rates equaling the Sun's precession. A/i combinations above and to the left of this Sun-synchronous curve produce nodal drift rates of less than 0.9856 deg/day. The MLT of such an orbit gradually decreases as the node moves westward toward 06:00 LST (6 a.m.). Similarly, an a/i combination below and to the right of the curve produces a drift rate greater than 0.9856 deg/day, with an MLT that gradually increases as the node moves eastward toward 18:00 LST (6 p.m.).

It has been widely observed both in orbit determination and in theoretical studies (Table 1, References 2 and 3) that nodal drift rates can differ significantly from mission to mission, in direction as well as in magnitude. Where the a/i's are similar, the rate differences can occur with differing MLTs. One example comes from early mission planning for the NOAA O,P,Q series of Sun-synchronous environmental spacecraft, scheduled for launch after 2001. These spacecraft are designed to operate in one of two orbits with similar a/i's but differing MLTs (orbit parameters are given in Table 2). Figure 3 [from orbit propagations using the Goddard Mission Analysis System (GMAS)] shows that, when each orbit is targeted to an a/i point lying on the Sun-synchronous curve, the MLT drift of the 08:00 LST morning ("AM") orbit is opposite to that of the 13:45 LST afternoon ("PM") orbit. The mean attitude and inclination for both orbits in Figure 3 are plotted against time in Figures 4 and 5, respectively. The differences in the altitude decay rates of the two orbits is attributed to atmospheric drag effects, which are discussed below. The directional difference in the a/i drift is explained in Figure 5, where the inclination is shown to be increasing in the PM orbit and decreasing in the AM. As demonstrated by K. I. Duck in 1973 (References 2 and 3) and supported by analysis in GMAS (shown in Figures 6a and 6b), the source of this inclination drift is solar gravitation.

2. PERTURBATIONS IN SUN-SYNCHRONOUS ORBITS

Because of the fixed geometry with respect to the Sun, Sun-synchronous orbits are subject to the cumulative effects of solar gravitation. This force, which is greater on the Sunward side of the orbit, produces a small resultant (orbit-averaged) torque that acts on the angular momentum vector, thereby changing the inclination as shown diagrammatically in Figure 7 (adapted from Reference 4) and analytically (from GMAS outputs) in Figures 6a and 6b. As can be readily deduced from Figure 7, the torque is opposite in direction for MLTs on opposite sides of local noon, whether ascending or descending nodal crossings are involved. According to Duck's analysis, maximum inclination drift rates should occur at 09:00 and 15:00 LST, with minimum drifts at 06:00, 12:00, and 18:00 LST. Since there is no fixed geometry with respect to the Moon, lunar gravitation produces no cumulative torque on the orbit but does cause the oscillation in the rate of the inclination drift seen in Figures 5 and 6a.

As in all near-Earth orbits, the altitude is subject to decay due to atmospheric drag. Due to the fixed geometry, however, Sun-synchronous orbits decay at differing rates depending on the orientation of the orbit plane to the diurnal bulge in Earth's atmosphere. Daily heating of the atmosphere results in a bulge of warmed air which lies about 2 hours east of the Sun line. Thus, Sun-synchronous spacecraft with MLTs near 14:00 LST pass through increased densities at each node crossing on the Sunward side. This causes the difference in decay rates in Figure 4.

3. EFFECT OF NODE-CROSSING TIME ON NODAL DRIFT

To examine systematically the effect of node-crossing time, a series of 1-year orbit propagations was generated in GMAS using the Goddard Space Flight Center (GSFC) Flight Dynamics Division (FDD) mainframe computing system. The GMAS force model [calibrated on observed Television Infrared Observation Satellite (TIROS) data] included the following: the Goddard Earth Model (GEM9) geopotential field model with a 21 × 21 matrix, atmospheric drag modeling based on modified Harris-Priester atmospheric density tables with July 1, 1991, Schatten $+2\sigma$ solar flux prediction data, and solar and lunar gravitational perturbations. The Averaged Variation of Parameters (AVGVOP) propagator was used with a 1-day step size. Identical initial Brouwer mean element sets (Table 3) were used in each run, with the exception of the right ascensions of the ascending node (RAANs, Table 4), which were chosen as necessary for MLTs at 1-hour intervals from 06:00 to 18:00 LST. The 800-km altitude and 98.603-deg inclination were taken from Figure 2, with other elements from a NOAA O,P,Q, AM orbit and an epoch of January 1, 1999. Rates of change of the mean altitude and inclination over the year were calculated from the GMAS output and plotted for analysis using the Quattro Pro commercial spreadsheet package running on an IBM PC.

The resulting 1-year drift rates in inclination and altitude are plotted against MLT in Figures 8a and 8b, respectively. As K. I. Duck predicted (References 2 and 3), the direction of inclination drift is negative at morning MLTs and positive at afternoon MLTs, with maximum rates at 09:00 and 15:00 LST and near-zero drift at 06:00, 12:00, and 18:00 LST. The rates at intermediate MLTs show an orderly progression between the predicted means and extremes, suggesting that, with appropriate altitudes, the long-term result of the Sun's gravitational torque would be to align Sun-synchronous orbits perpendicular to the Sun vector. This variation of the drift rates across the day also accords well with the 08:00 and 13:45 LST NOAA O,P,Q inclination changes seen in Figure 5. The drift rates at 08:00 and 14:00 LST are indeed opposite in direction, with the same near-maximum magnitudes. As expected, the maximum altitude decay rate was at 14:00 LST, with the minimum rate 6 hours earlier at 08:00 LST, when the spacecraft would encounter the lowest atmospheric densities. Again, this agrees with the altitude decay rates seen in the PM and AM NOAA O,P,Q orbits (Figure 4).

Figure 8c shows the combined changes in a/i for each MLT. As expected, the lines for the 06:00 (6 a.m.), 12:00 (noon), and 18:00 (6 p.m.) LST MLTs lie near the center of the plot, indicating little inclination change. The curves for the morning (6 to 11 a.m) MLTs curve to the left, showing decreasing inclinations, and the curves for afternoon (1 to 6 p.m.) MLTs curve right, showing increasing inclinations. The lengths of the curves, indicating the change in altitude, decrease from 06:00 to 08:00 LST, then increase to a maximum at 14:00 (2 p.m.) LST, after which they begin decreasing again. Figure 8d shows the inclination drifts in a 1200-km Sun-synchronous orbit where altitude decay is no longer a factor.

It is evident from Equation (1) that the initial nodal drift rate at each MLT is dependent upon both altitude and inclination. Subsequent nodal drift rates at each MLT are controlled chiefly by the altitude and inclination drift rates in effect at that MLT, as described above. A third factor in the determination of the long-term MLT drift at a given MLT is the solar flux level, determined by the phase of the 11-year solar cycle, which affects the rate of altitude decay at lower altitudes. To test this effect, an additional series of GMAS runs was performed using the original elements (Table 3) with the MLT-specific RAANs (Table 4), but changing the epoch to 2006 and the solar flux data to -2σ, effectively changing the solar flux level from near maximum to near minimum. As shown in Figure 9a, this change has little effect on inclination drift. However, the effect on altitude decay (Figure 9b) is more significant. Figure 10 shows the effect on MLT drift for the NOAA O,P,Q PM orbit due to flux differences between the maximum and minimum phases of the solar cycle.

4. COMBINED EFFECTS OF INCLINATION, ALTITUDE, AND NODE-CROSSING TIME ON NODAL DRIFT

How, then, do altitude decay and inclination drift rates vary across the day for Sun-synchronous orbits at varying a/i combinations? Further GMAS propagation runs, modeled as described above, were executed for selected a/i combinations from Table 1 and/or Figure 2. Again, the MLT-specific RAANs were taken from Table 4 and the remaining elements from Table 3. The epoch in all cases was January 1, 1999, with $+2\sigma$ solar flux data. The resulting altitude and inclination drift rates are shown in Figures 11a and 11b, respectively. The disparity in the inclination drift rates at 500 km is due to rapid altitude decay at that altitude. Figure 11c shows the resulting MLT drift rates at 14:30 LST for 500-, 800-, and 1200-km Sun-synchronous orbits.

Note the inclination drift rate (from Table 1) indicated in Figure 11a by the numeral 1, a value of 0.053 deg/year as calculated in GMAS. This value agrees very well with K. I. Duck's 1973 prediction of 0.0552 deg/year inclination drift for a 3:00 p.m. (15:00 LST) orbit at this altitude (References 2 and 3). [The inclination for the GMAS runs at this altitude was estimated using Equation (1).] Other key data points from Table 1 are also indicated by item number on Figure 11a.

5. MISSION PLANNING ISSUES

Though the drift rates in Figure 8c, 11a, and 11b will vary with the solar cycle, as has been shown, they can be used together with the methods described in References 5 and 8 to guide the initial design of Sun-synchronous orbits. For one example, altitude-sensitive missions would do well to avoid the 13:00 to 15:00 LST MLT range. For another, the low inclination drift rates at MLTs near 06:00, 12:00, and 18:00 LST (Figure 11a) suggest that long-duration missions might operate more efficiently at near-noon or near-terminator node crossings. Figure 12b confirms this for orbits in the 800 km altitude range, showing how closely the 12:00 LST (noon) A/I drift tracks the Sun-synchronous line. However, with the low altitude decay rates in 1200 km orbits (Figure 12a), even a small inclination drift moves the A/I curve away from the Sun line very quickly. With the high altitude decay rates in 500 km orbits (Figure 12c) no MLT will hold the A/I drift near the Sun line, but a comparison of Figures 12b and 12c suggests that, for altitudes in the 600 to 750 km range, a morning MLT might be found which would hold the A/I drift curve very near the Sun-line. This would allow a very stable node-crossing MLT for an extended period. Where the science or operational requirements of a mission make these choices impossible, an understanding of the direction and rate of a/i drift at a given MLT, altitude, and/or inclination can lead very quickly to a Sun-synchronous or biased-Sun-synchronous targeting scenario to meet the general MLT constraints. With such a scenario in hand, relatively few GMAS propagation runs are needed to optimize the a/i targets for a detailed plan to meet mission constraints over a given phase of the solar flux cycle. As an example of such a plan, the biased Sun-synchronous orbit plan for NOAA O,P,Q (complete with a mid-life maneuver for the PM orbit) is given in Figures 13a through 13c. Figure 13a shows the 5-year a/i drift; the resulting MLT drifts in the PM and AM orbits are shown in Figures 13b and 13c, respectively.

6. SUMMARY

The evolution of the MLT of node-crossing of Sun-synchronous orbits depends upon drifts in the orbital inclination and altitude, which arise from perturbations due to solar gravitation and atmospheric drag. As shown in Figures 8c, 11a, and 11b, the rates of these drifts vary with the node-crossing time as well as with the initial altitude and inclination. Though the drift rates will vary to some extent with the solar cycle, these figures can be used according to methods described in References 5 and 8 to simplify early mission planning for any Sun-synchronous orbit.

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3. K. I. Duck, GSFC Memorandum 733:73, "Inclination Biases for Sun Synchronous Spacecraft," April 1973
4. D. Folta to W. Barnes, "Analysis of Earth Observing System Zenith Angles, Sun Angles, Mean Local Time, and Ground Track," private communication, December 12, 1990
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3. B. Kampos, NASA CR-1008, "General Perturbation Theory," April 1968

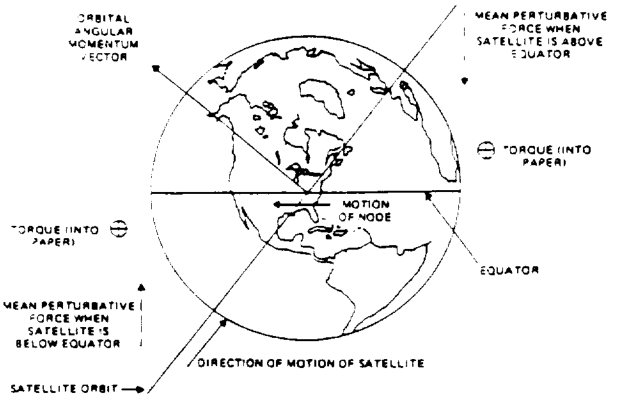

Figure 1. Regression of Nodes Due to the Earth's Oblateness

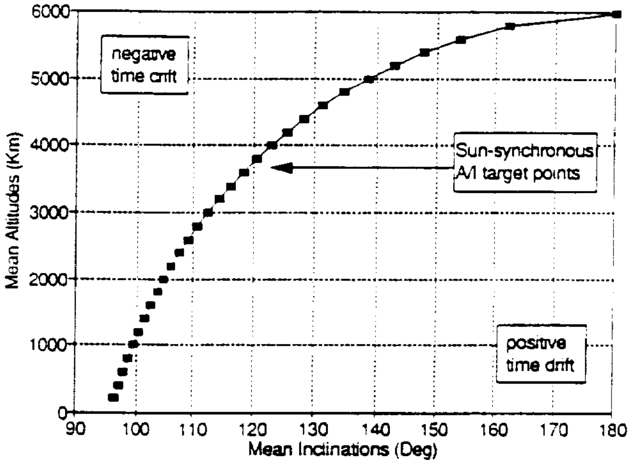

Figure 2. Altitude and Inclination Required for Sun-Synchronous Orbits, 200 to 5974 km

Table 1. Observed and Theoretical Data on the Evolution of MLT Drift Rates as a Function of MLT

ITEM	SPACECRAFT/COMMENT	REF	TYPE OF DATA	ALTITUDE (KM)	INCLINATION (DEG)	MLT (LST)	INCLINATION DRIFT (DEG/YEAR)
1	DUCK ANALYSIS	2	THEORETICAL	1684.0	102.9850*	15:00	0.0552
	ESSA-8	2	OBSERVED			09:00	−0.0540
	TIROS-M	2	OBSERVED			15:00	0.0560
2	EOS-PM	5, 6	THEORETICAL	708.3	98.1355	13:30	0.0310
3	LANDSAT-4**	7	OBSERVED	699.6	98.2320	09:31	−0.0430
4	LANDSAT-5**	7	OBSERVED	699.7	98.2890	09:32	−0.0480
5	COBE (POSTVENTING)**	7	OBSERVED	881.0	99.0210	06:11	−0.0080

*ESTIMATED USING EQUATION 1
**NO LONGER FULLY SUN-SYNCHRONOUS

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Table 2. NOAA O,P, Q Mission Parameters

PARAMETER	AFTERNOON ORBIT	MORNING ORBIT
NODE-CROSSING TIME	13:45 LST	8:00 LST
MLT CONSTRAINT	± 10 MIN	± 10 MIN
TARGET ELEMENTS:		
MEAN ALTITUDE	824 KM	844 KM
MEAN INCLINATION:		
SUN-SYNCHRONOUS	98.616°*	98.833°**
BIASED SUN-SYNC	98.581°*	98.868°**

*For January 1, 1999
**For January 1, 2006

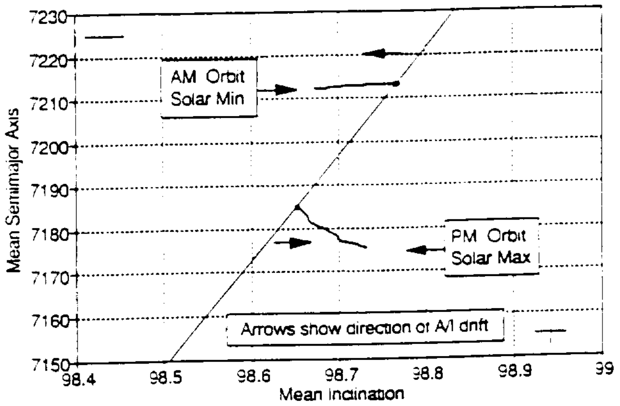


Figure 3. Evolution of SMA and Inclination for NOAA O,P,Q Afternoon and Morning Orbits

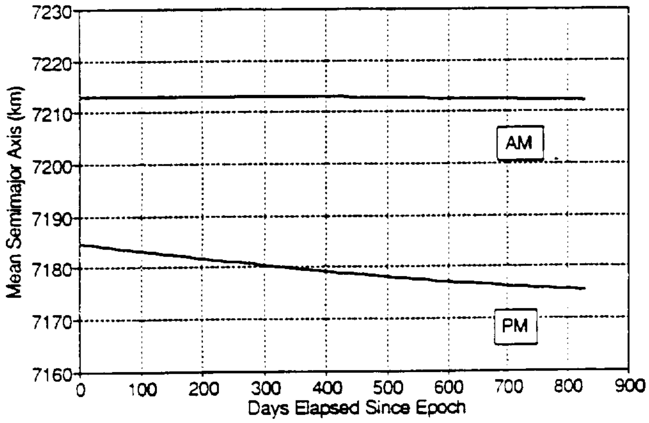


Figure 4. Semimajor Axis Decay for NOAA O,P,Q Afternoon and Morning Orbits

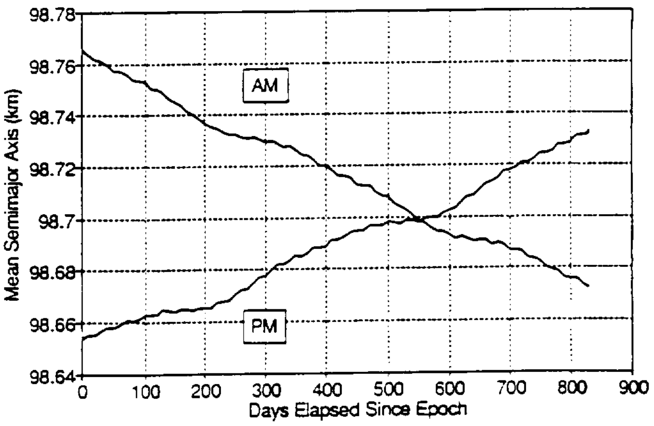


Figure 5. Inclination Drift for NOAA O,P,Q Afternoon and Morning Orbits

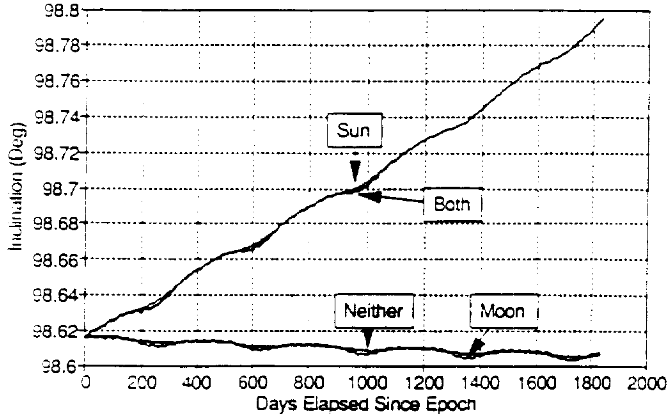


Figure 6a. Effect of Solar and Lunar Gravitation Perturbations on the Inclination of the NOAA O,P,Q Afternoon Orbit

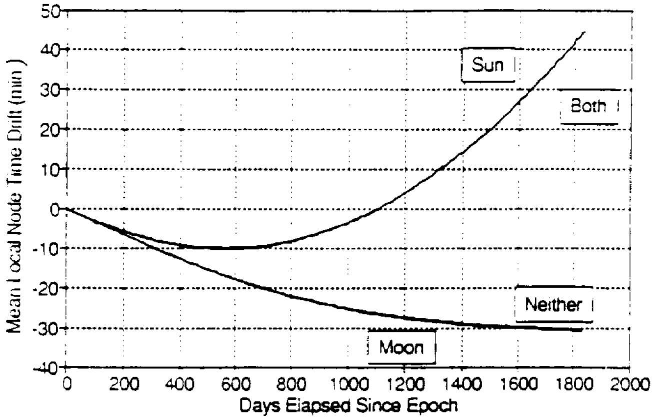
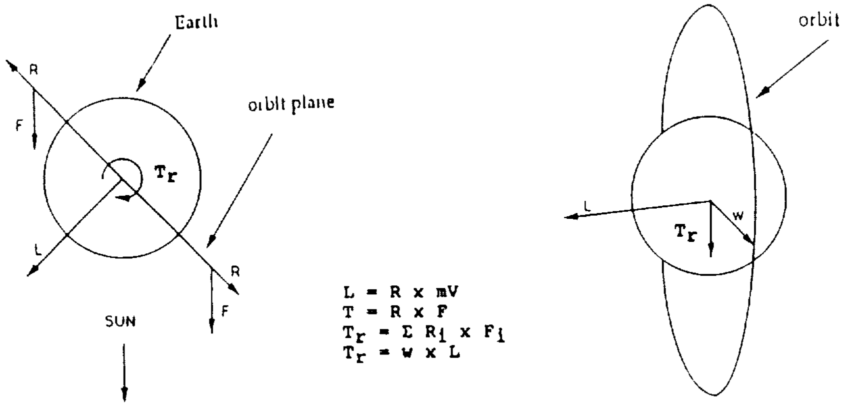


Figure 6b. Effect of Solar and Lunar Gravitation Perturbations on MLT Drift in the NOAA O,P,Q Afternoon Orbit



$L = R \times mV$
$T = R \times F$
$T_r = \Sigma R_i \times F_i$
$T_r = w \times L$

Where:
L = Angular momentum vector
R = Spacecraft position vector
V = Spacecraft velocity vector
F = Force due to solar gravitiation

T = Instantaneous torque due to solar gravitation
T_r = Resultant (orbit averaged) solar gravitation torque
w = Resultant torque precession vector

Figure 7. Torques Due to Solar Gravitation

Table 3. Mean Elements Used In GMAS Runs

SEMIMAJOR AXIS	7178.14
ECCENTRICITY	0.00114
INCLINATION	98.603°
RIGHT ASCENSION OF ASCENDING NODE	SEE TABLE 4
ARGUMENT OF PERIGEE	90.0
MEAN ANOMALY	270.0

Table 4. RAANS Used In GMAS Runs

MLT	RAAN
06:00	190.196
07:00	205.196
08:00	220.196
09:00	235.196
10:00	250.196
11:00	265.196
12:00	280.196
13:00	295.195
14:00	310.196
15:00	325.196
16:00	340.196
17:00	355.196
18:00	10.196

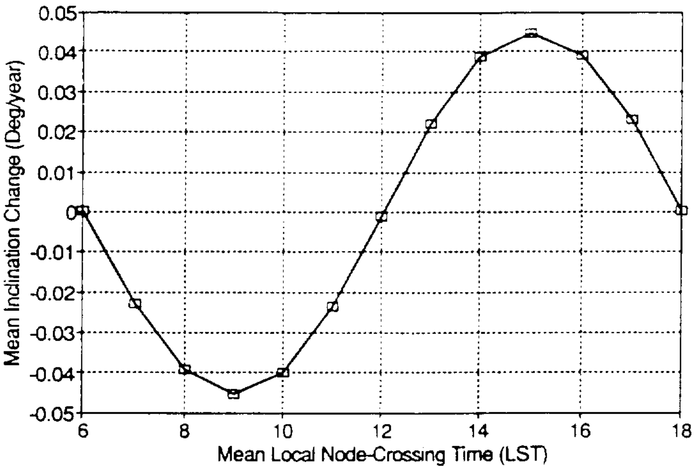


Figure 8a. Effect of Initial MLT on Inclination Drift: Mean Altitude = 800 km, Mean Inclination = 98.603 deg

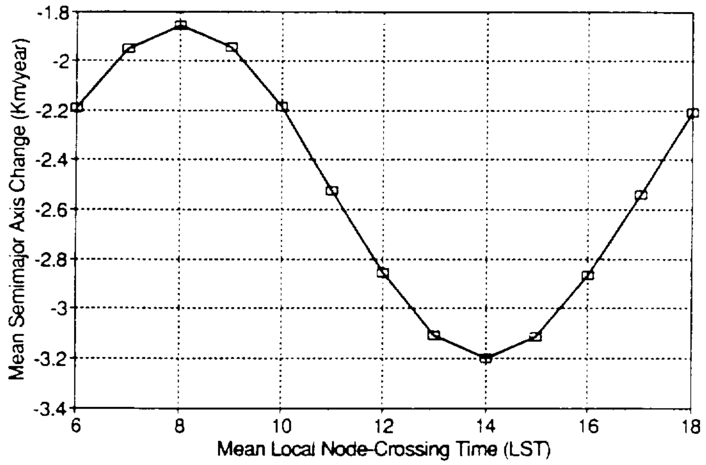


Figure 8b. Effect of Initial MLT on Altitude Decay Rate: Mean Altitude = 800 km, Mean Inclination = 98.603 deg

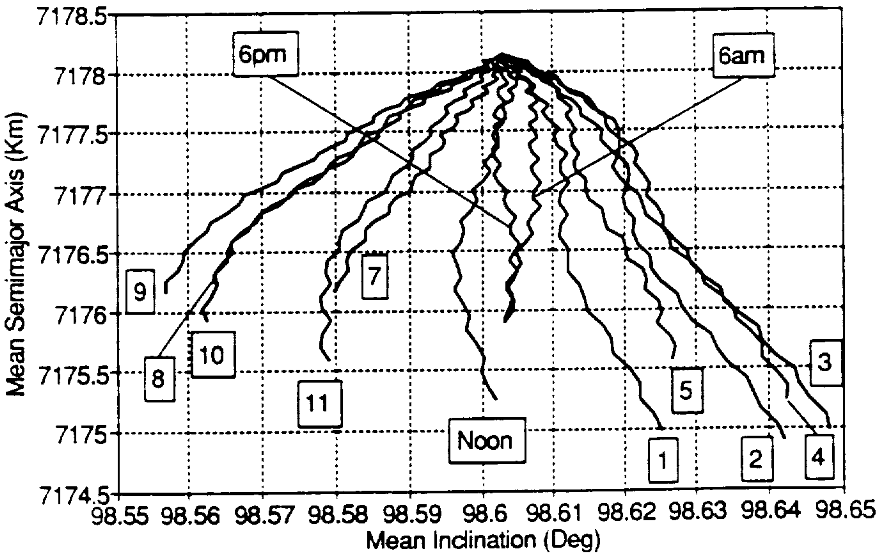


Figure 8c. **Effect of Initial MLT on Altitude Decay and Inclination Drift: Mean Altitude = 800 km, Mean Inclination = 98.603 deg**

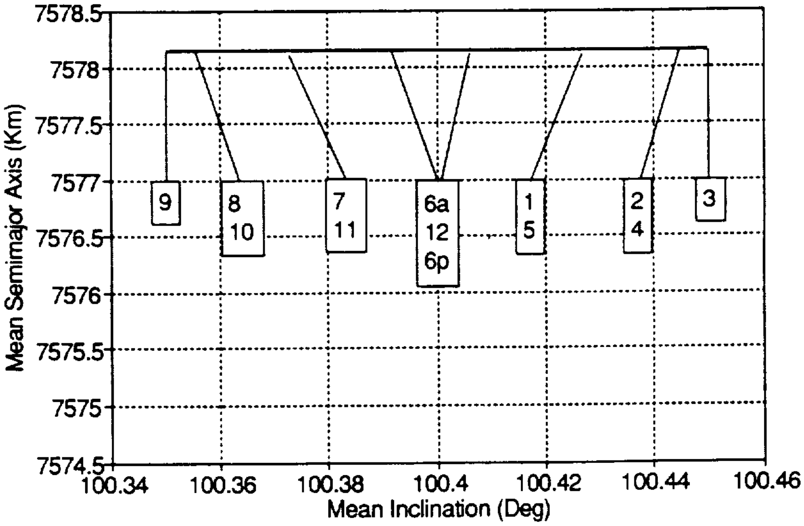


Figure 8d. **Effect of Initial MLT on Altitude Decay and Inclination Drift: Mean Altitude = 1200 km, Mean Inclination = 100.4 deg**

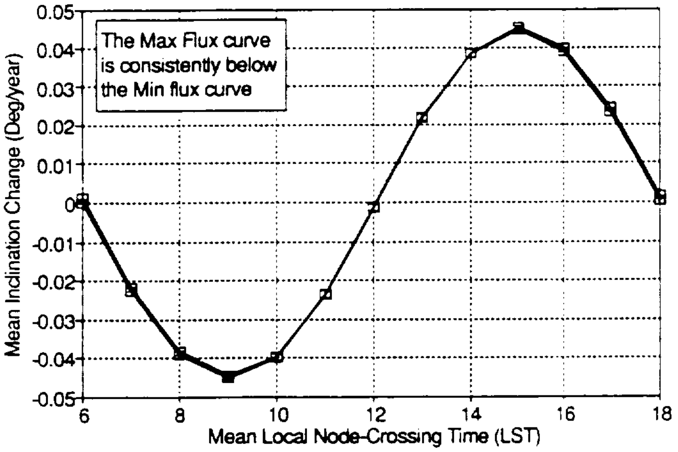


Figure 9a. **Effect of Solar Maximum v. Solar Minimum Flux Predictions and MLT on Inclination Drift**

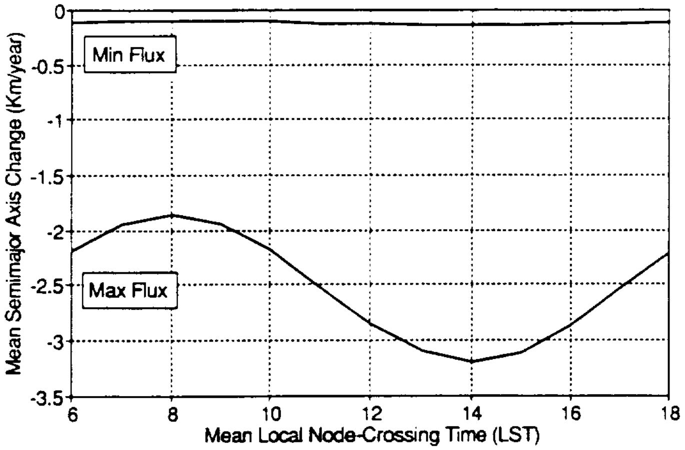


Figure 9b. **Effect of Solar Maximum v. Solar Minimum Flux Predictions and MLT on Altitude Decay Rate**

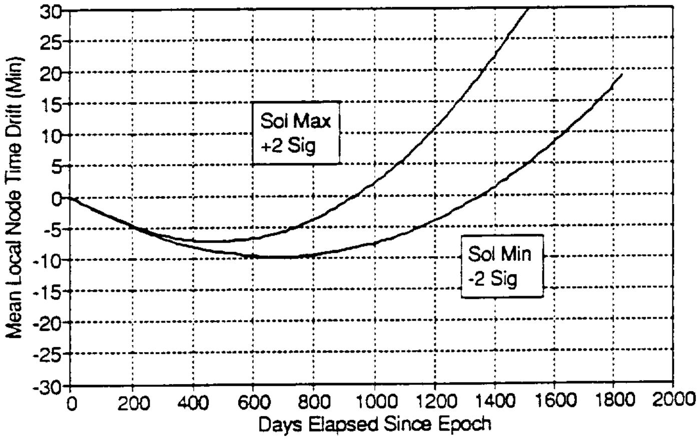


Figure 10. **5-Year MLT Drift in the NOAA O,P,Q P.M. Orbit Solar Maximum v. Solar Minimum Flux Predictions**

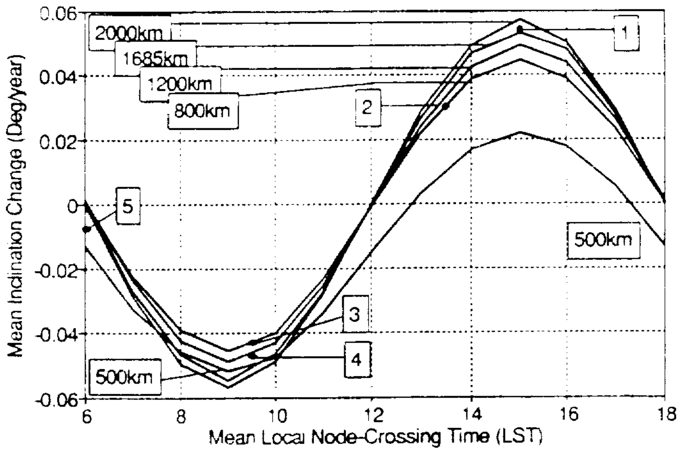


Figure 11a. **Effect of Initial MLT on Inclination Drift at Varying Altitudes**

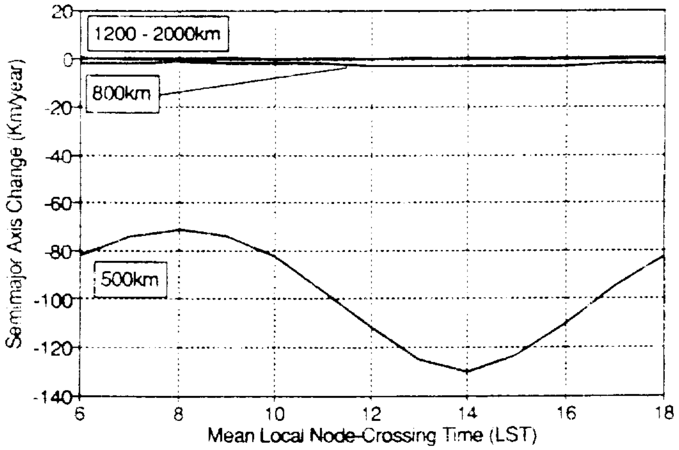


Figure 11b. **Effect of Initial MLT on Altitude Decay Rate at Varying Altitudes**

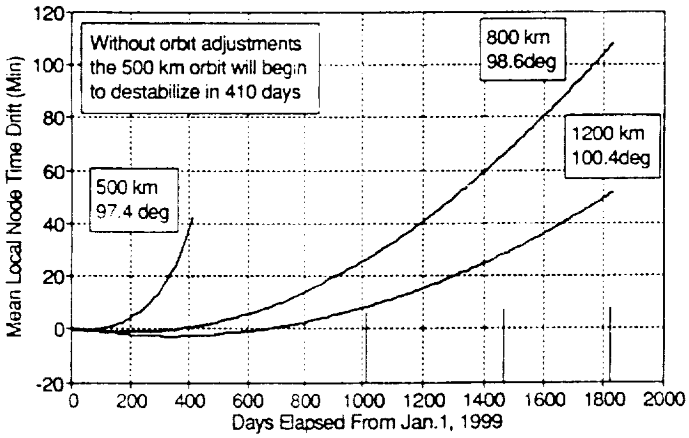


Figure 11c. **Effect of Initial Altitude and Inclination on MLT Drift Rates for 1430 LST Sun-Synchronous Orbits**

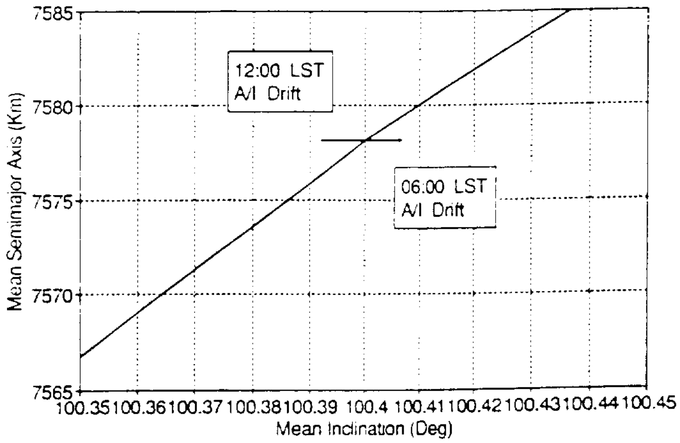


Figure 12a. **A/I Drift From the Sun Line at Specified MLTs: 1200-km Sun-Synchronous Orbit at 06:00 and 12:00 LST**

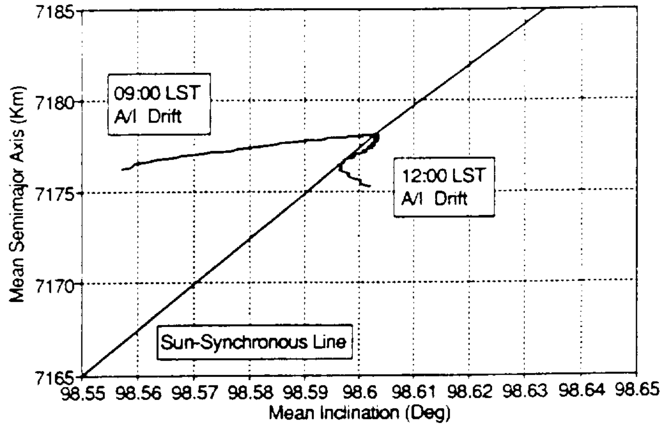


Figure 12b. **A/I Drift From the Sun Line at Specified MLTs: 800-km Sun-Synchronous Orbit at 09:00 and 12:00 LST**

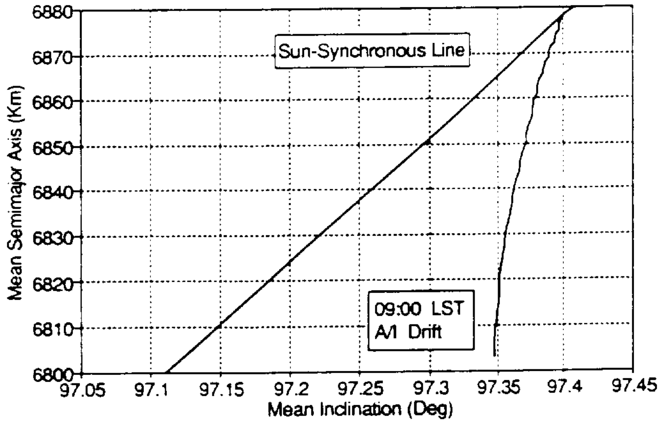


Figure 12c. **A/I Drift From the Sun Line at Specified MLTs: 500-km Sun-Synchronous Orbit at 09:00 LST**

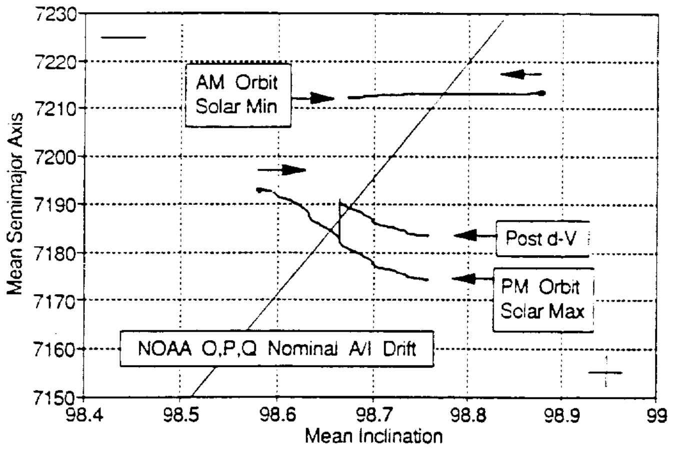


Figure 13a. Five-Year Altitude and Inclination Drift In NOAA O,P,Q Afternoon and Morning Biased Sun-Synchronous Orbits

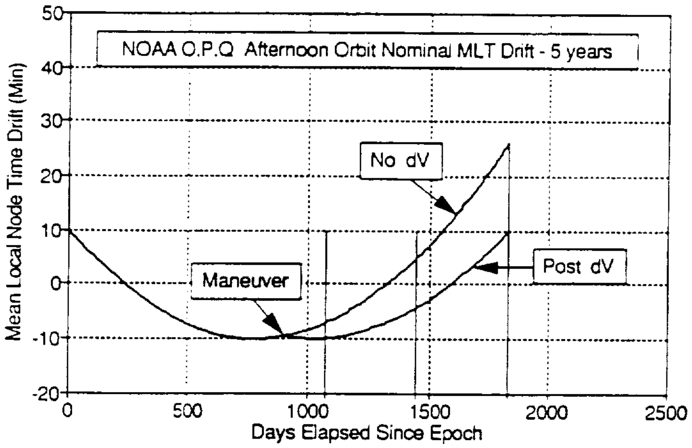


Figure 13b. Five-Year Mean Local Node Time Drift In the NOAA O,P,Q Afternoon Biased Sun-Synchronous Orbits

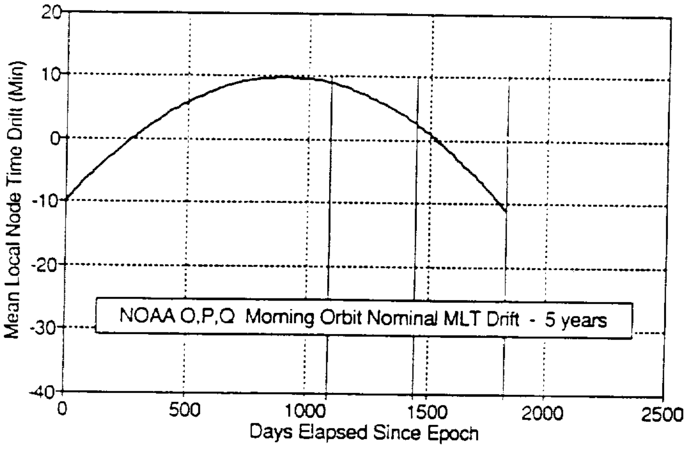


Figure 13c. Five-Year Mean Local Node Time Drift In the NOAA O,P,Q Morning Biased Sun-Synchronous Orbits