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The Semiannual Thermospheric Density Variation At Altitudes of 160-300 km

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The goal of this study is to characterize the semiannual thermospheric density variation at low altitudes, covering the height range of 160 to 300 km. Historical radar observational data have been processed with special orbit perturbations on 36 highly eccentric satellites with very low perigee heights. Approximately 70,000 very accurate average daily perigee density values, covering the period from 1993 through 2003, have been obtained for all satellites using orbit energy dissipation rates. As with previous analyses by this author, the semiannual variation has been found to be variable from year to year. The magnitude of the maximum yearly difference, from the July minimum to the October maximum, is used to characterize the yearly semiannual variability. A high correlation has been found between this maximum difference and solar EUV values. This correlation is a function of altitude, with the correlation reversing sign as the altitude decreases from 300 km to 160 km.

Introduction

The semiannual density variation was first discovered in 1961[1]. Paetzold and Zschorner observed a global density variation from analysis of satellite drag data, which showed a 6-month periodicity maximum occurring in April and October, and minimum occurring in January and July. Many authors, such as King-Hele[2], Cook[3], and Jacchia[4], analyzed the semiannual effect from satellite drag during the 1960s and early 1970s. They found that the semiannual variation was a worldwide effect with the times of the yearly maximum and minimum occurring mostly independent of height. However, the semiannual period was found to be only approximate, as the times of occurrence of the minimums and maximums seemed to vary from year to year. Generally the October maximum exceeded that in April and the July minimum was deeper than that in January. None of the results showed any correlation of the semiannual variations with solar activity. Jacchia[4] first modeled the effect as a temperature variation. However, he soon discovered difficulties with the temperature model, and eventually modeled the semiannual variation as a density variation[5,6]. He also found that the amplitude of the semiannual density variation was strongly height-dependent and variable from year to year. However, because of the limited amount of data he had available he again found no correlation of the variation with solar activity. More recent studies[7] of the semiannual variation from 200-1100 km by this author have shown a high correlation of the yearly amplitude with the average yearly solar flux values.

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The purpose of this current study is to extend the previous study down to the lower altitudes where satellites regularly decay, and to characterize the semiannual density variations at low altitudes over the latest solar cycle.

True B Analysis

Previous analyses of the semiannual variation has been limited to heights above 200 km. The main reason for this is the rapid decay of a satellite with a perigee height below 200 km. To obtain a measure of the semiannual variation throughout a year the satellite needs to remain at these low altitudes for the entire year. In addition, a true ballistic coefficient[8] must be computed to obtain accurate density values. To compute a true B requires knowledge of either the physical parameters (frontal area, mass, drag coefficient) or computation of a long time (at least several years) average of the daily orbit fitted B values. Since no spheres have remained in orbit at these low altitudes over multiple years, it was necessary to determine the semiannual variations from other types of satellites. This means that computing a true B from orbit fits is the only accurate true B method available. Only highly eccentric orbits with very low perigee heights provides enough time at the low altitudes to cover many years of data. A large group of rocket bodies was found to be ideal for the analysis. This group consists of PAM-D rocket bodies used to launch the GPS Navstar satellites into highly eccentric transfer orbits prior to the GPS circularization at 20,000 km. Almost 40 launches of this type have occurred since 1989. The transfer orbits have initial perigees of 170 to 200 km with apogees of 20,000 km. The orbits have moderately low inclinations of 35 to 39 degrees, which means that lunar-solar gravitational effects will not change the perigee heights significantly as with higher inclination orbits. The PAM-Ds are solid fuel rocket bodies that remain in the transfer orbit. Unlike liquid fueled rockets the PAM-Ds should expend all of their fuel once ignition starts[9]. Therefore, all the PAM-Ds that launch GPS satellites should be identical in size, shape, and empty on-orbit mass, except for a possible small remaining amount of unburned fuel residual. The PAM-Ds are nearly spherical in shape with a nozzle attached to the chamber. When the GPS is released from the rocket body the PAM-D is kicked away with a tumble period of 20 to 30 seconds[9]. This has been verified through this author's optical tracking of different PAM-D rocket bodies. The rapid tumble period should have the effect of minimizing the effect of the nozzle on producing frontal area variations throughout each perigee passage. All of this means that the A/M ratio should be constant and identical for any PAM-D at the same perigee height. Only a different perigee height will change the B value due to a change in the drag coefficient. If the above assumptions are correct then all these advantages lead to the conclusion that once a true B is obtained on one PAM-D then, after a correction for the drag coefficient due to altitude differences, this true B can be used for any other GPS PAM-D. To validate these assumptions 13 PAM-Ds, that have been in orbit for at least several years, were used in an analysis of true B values. Table 1 list these satellites along with their orbital parameters and computed true B values. Different time spans were used to compute the true B values. Also, these 13 PAM-Ds all have perigee heights within the height range of 180 to 205 km, which means that all the drag coefficients should be nearly the same. The standard deviation of the true B values about the average is less than 2%, which validates all the above assumptions about the standardized empty mass value and the expected constant frontal area.

NORAD	PAM-D	Launch		Decay		Y Range	Q Range	True B	True B
	Navstar						km		%Error
21932	25	APR	92	AUG	98	93-96	200-180	0.02264	1.7
22016	26	JUL	92	NOV	99	94-98	195-190	0.02236	0.4
22233	28	NOV	92	MAR	101	94-99	205-180	0.02287	2.7
22277	29	DEC	92			94-00	210-215	0.02237	0.5
22448	30	FEB	93	SEP	102	94-01	205-190	0.02191	-1.6
22659	32	MAY	93	JAN	101	94-99	200-185	0.02236	0.4
22781	34	AUG	93			94-03	205-220	0.02272	2.1
22879	35	OCT	93	JAN	104	94-03	180-210	0.02241	0.7
23029	36	MAR	94	MAR	101	95-00	190-180	0.02149	-3.5
23835	37	MAR	96	SEP	101	97-00	200-180	0.02236	0.4
23955	38	JUL	96			97-03	190-200	0.02227	0.0
25935	46	OCT	99			00-03	205-200	0.02145	-3.7
26362	47	MAY	100			01-03	195-200	0.02221	-0.2
							Ave	0.02226	
							Std	0.00042	1.9 %

Table 1. List of satellites used for the PAM-D true B analysis. Listed are the range of years (Y Range) and perigee heights (Q Range) used to compute the true B values. The percentage error in each satellite's true B from the average true B is listed in the last column along with the average true B's standard deviation.

The last step in the true B analysis was to determine a drag coefficient correction as a function of altitude. It is known[13] that the drag coefficient decreases with altitude, and this must be account for when determining accurate density values using fitted and true B values. First, an average yearly correction for density variations must be computed. The 13 PAM-Ds listed above were used to obtain this average correction for each year from 1993 through 2003 when they were at altitudes ranging from 180 to 200 km. As the perigee height of each PAM-D gradually changed due to drag and lunar-solar gravitational perturbations this provided an opportunity to examine the B values at lower altitudes. Figure 1 shows the plots of the change in B, after the average yearly correction was applied, as a function of solar conditions and altitude. The delta B value of zero corresponds to the 180-200 km height range that was used to compute the true B values. Below 180 km the delta B values decrease by approximately 7%, which represents the decrease in the drag coefficient as the altitude decreases to 150 km. There does not appear to be any delta B change as a function of solar conditions. This is the result of the application of the average yearly correction at 190 km that was computed above. This correction had the effect of removing any average yearly bias produced by increasing solar flux values from 1993 through solar maximum. The resulting curve in Figure 1 can now be used to correct the average true B value for any PAM-D rocket body depending upon the average yearly perigee height.

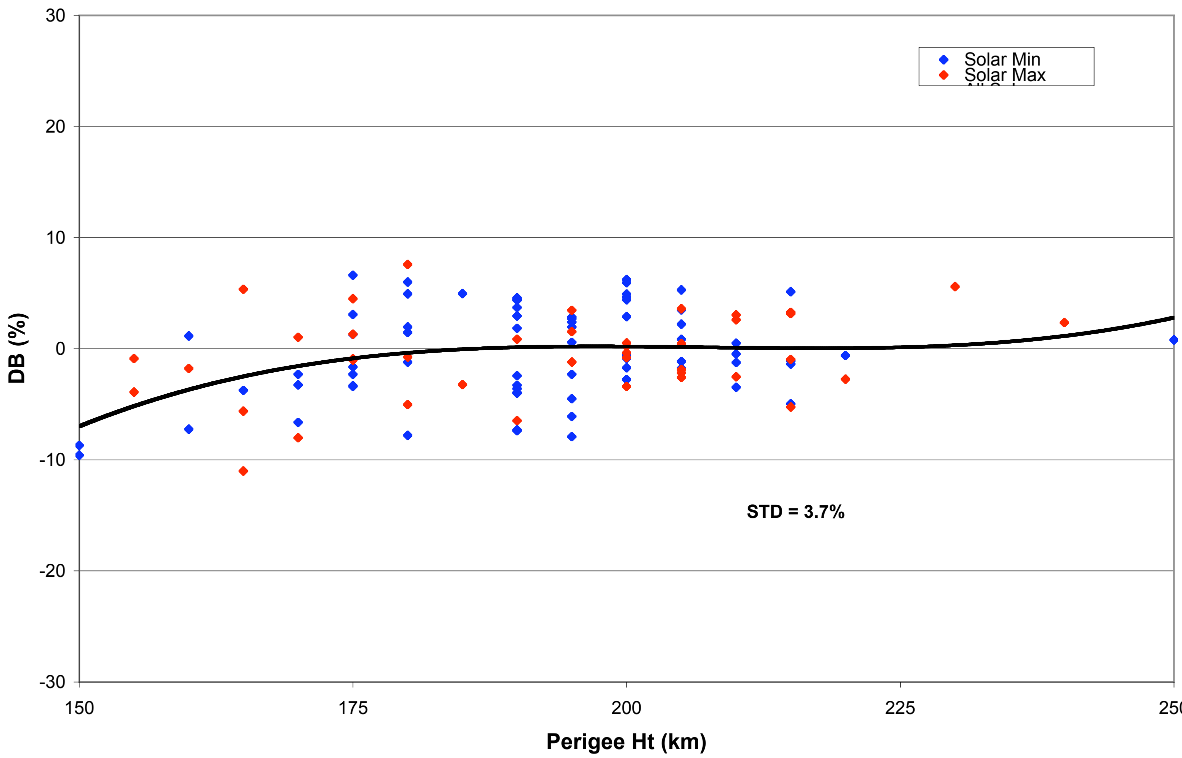

Figure 1. Delta B (average yearly values) for PAM-D rocket bodies are plotted as a function of perigee altitude. Values for solar maximum and solar minimum years are separated by color.

Density Computations

Daily temperature corrections to the US Air Force High Accuracy Satellite Drag Model's (HASDM)[10,11] modified Jacchia 1970[6] atmospheric model were obtained on 36 highly eccentric low perigee height satellites throughout the period 1993 through 2003. Twenty-four PAM-D rocket bodies, 5 SL-12 rocket bodies, and 7 other satellites were used. Approximately 70,000 daily temperature values were obtained using a special energy dissipation rate (EDR) method[12], where radar and optical observations are fit with special orbit perturbations. A differential orbit correction program was used to fit the observations to obtain the standard 6 Keplerian elements plus the ballistic coefficient. "True" ballistic coefficients, computed from yearly averaging and corrected for drag coefficient variability described above, were then used with the observed daily temperature corrections to obtain daily density values. The daily density computation was previously validated[3] by comparing historical daily density values computed for a 30 year period for over 30 higher altitude satellites. The accuracy of the density values was determined from comparisons of geographically overlapping perigee location data, with over 8500 pairs of density values used in the comparisons. The density errors were found to be less than 4% overall, with errors on the order of 2% for values covering the latest solar maximum.

Semiannual Density Variation Function

Initially Jacchia[4] represented the semiannual density variations as a temperature variation. However, many difficulties arose from this that could not be explained in temperature space, so, to remove these difficulties, Jacchia eventually had to assume that the semiannual variation was not cause by temperature, but by direct density variations. From Jacchia's analysis of 12 years of satellite drag data[5,6] he obtained the following equations. Jacchia represented the semiannual density variation, Δ_{SA}, as a delta log density function in the form:

$$\Delta_{SA} \log_{10} \rho = F(z)\, G(t) \tag{1}$$

G(t) represents the average density variation as a function of time in which the amplitude (i.e. the difference in $\log_{10}$ density between the principal minimum in July and the principle maximum in October) is normalized to 1, and F(z) is the relation between the amplitude and the height z. Jacchia's 1977[14] Model F(z) function is:

$$F(z) = \left[0.04\left(\frac{z}{100}\right)^2 + 0.05\right] e^{\left(-0.25\left(\frac{z}{100}\right)\right)}, \quad (\text{ z in km }) \tag{2}$$

From this author's previous analyses the amplitude, F(z), of the semiannual variation, determined on a year-by-year basis, is shown in Figure 2. The previous analysis showed that the F(z) amplitude function reached much higher maximum values during solar maximum (2002) conditions than during solar minimum (1993), as demonstrated in Figure 2. The maximum amplitudes occurred at altitudes near 750 km.

However, the curves plotted in Figure 2 suggest that at very low altitudes the semiannual amplitude during solar maximum may fall below the amplitude during solar minimum. The current analysis was undertaken to help answer this question.

For computing G(t) in this study, as in the author's previous study[7], a Fourier series of 9 coefficients, including frequencies up to 4 cycles per year, was used to capture the variability in G(t) that had been previously observed.

$$\begin{aligned} G(t) = {} & C_1 + C_2 \sin(\omega) + C_3 \cos(\omega) + C_4 \sin(2\omega) + C_5 \cos(2\omega) \\ & + C_6 \sin(3\omega) + C_7 \cos(3\omega) + C_8 \sin(4\omega) + C_9 \cos(4\omega) \end{aligned} \tag{3}$$

where $\omega = 2\pi\theta$ $\quad \theta = (t - 1.0)/365$ $\quad$ t = year day

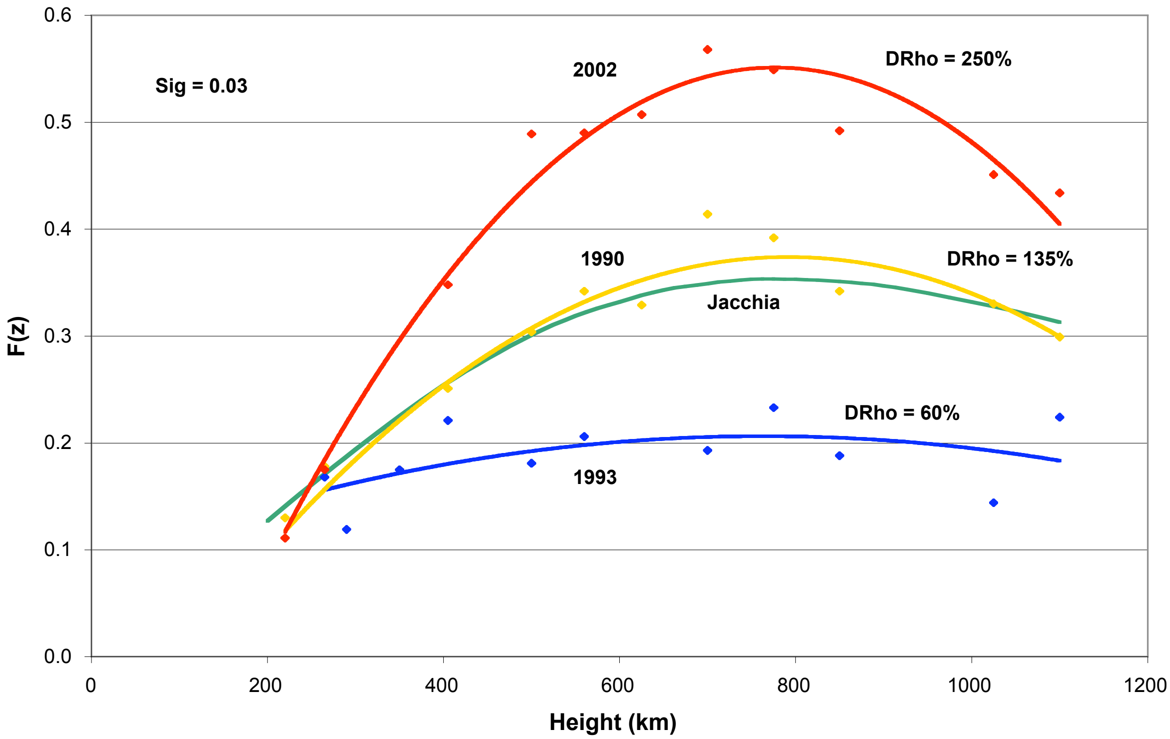

Figure 2. The amplitude function F(z) for three different years (1990, 1993, 2002), with semiannual amplitudes plotted for each satellite for each year. The standard deviation, 'sig', of the fits is shown. The constant F(z) function from Jacchia is also plotted.

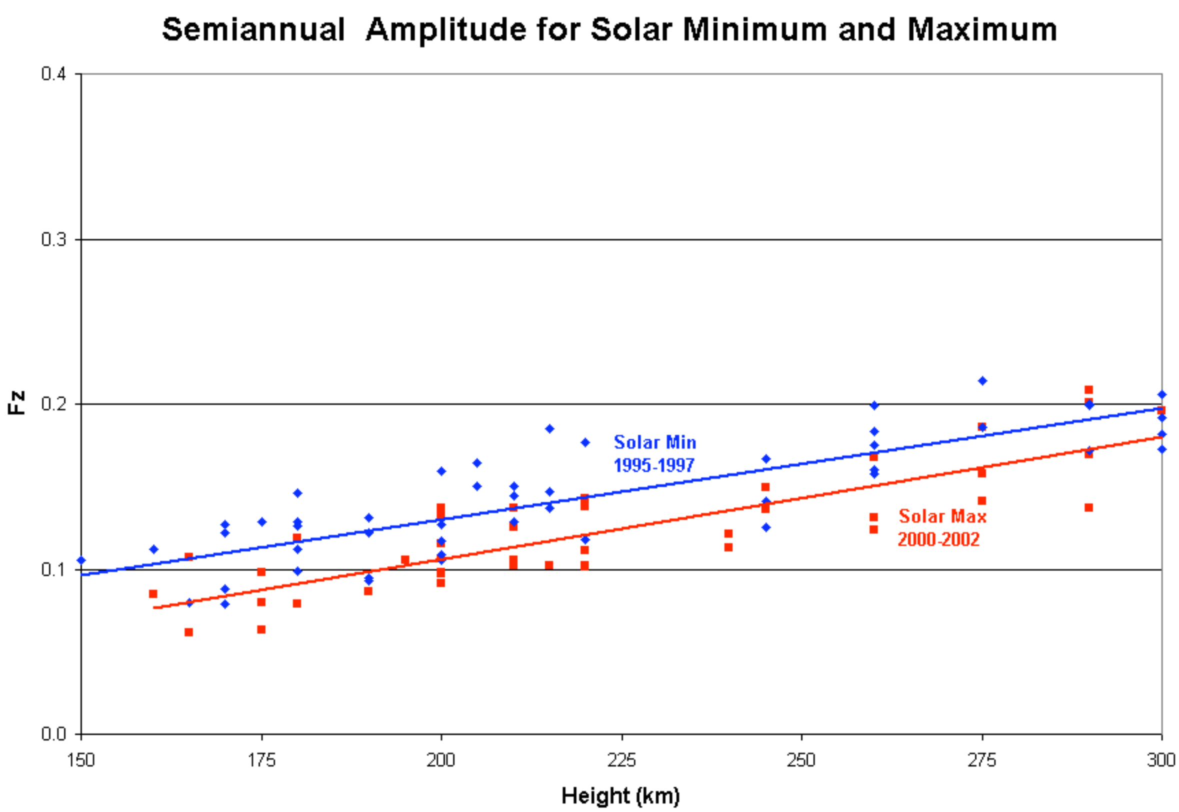

Figure 3. The semiannual amplitude function F(z) is plotted for solar minimum (1995-1997) and solar maximum (2000-2002) years as a function of height.

In the current analysis the semiannual F(z) function was computed for each of the 36 satellites when a year's worth of density data was available. Figure 3 shows the results of three years of solar minimum data (1995-1997) and three years of solar maximum data (2000-2002) as a function of perigee height. Linear fits were then computed and plotted for the two time periods. From Figure 3 during solar maximum the semiannual variation has a smaller amplitude than the solar minimum variation, which is contrary to the higher altitude results shown in Figure 2. However, this difference is mostly due to the compression of the atmosphere during solar minimum, where lower densities occur when comparing the same altitude at solar minimum with solar maximum densities. Therefore, to compare the true semiannual variation over different solar conditions, the solar minimum heights were adjusted upward to a height where the density was the same as the solar maximum density for the uncorrected height. As an example the density during solar minimum at 300 km corresponds to the density at approximately 370 km during solar maximum. Therefore, the solar minimum height is adjusted upward to 370 km to equally compare values throughout all solar conditions. The solar minimum adjusted data points and linear fit are plotted in Figure 4 along with the original solar maximum data. Above 250 km the semiannual variation amplitude definitely increases with increasing solar activity, as is shown in Figure 2 at higher altitudes (up to 700-800 km). However, below 225 km the reverse appears to occur, with the amplitude larger during solar minimum than during solar maximum times. The reason for this phenomenon is unclear at this time, and continued theoretical research into the cause of the semiannual variation will eventually shed some light on these low altitude results.

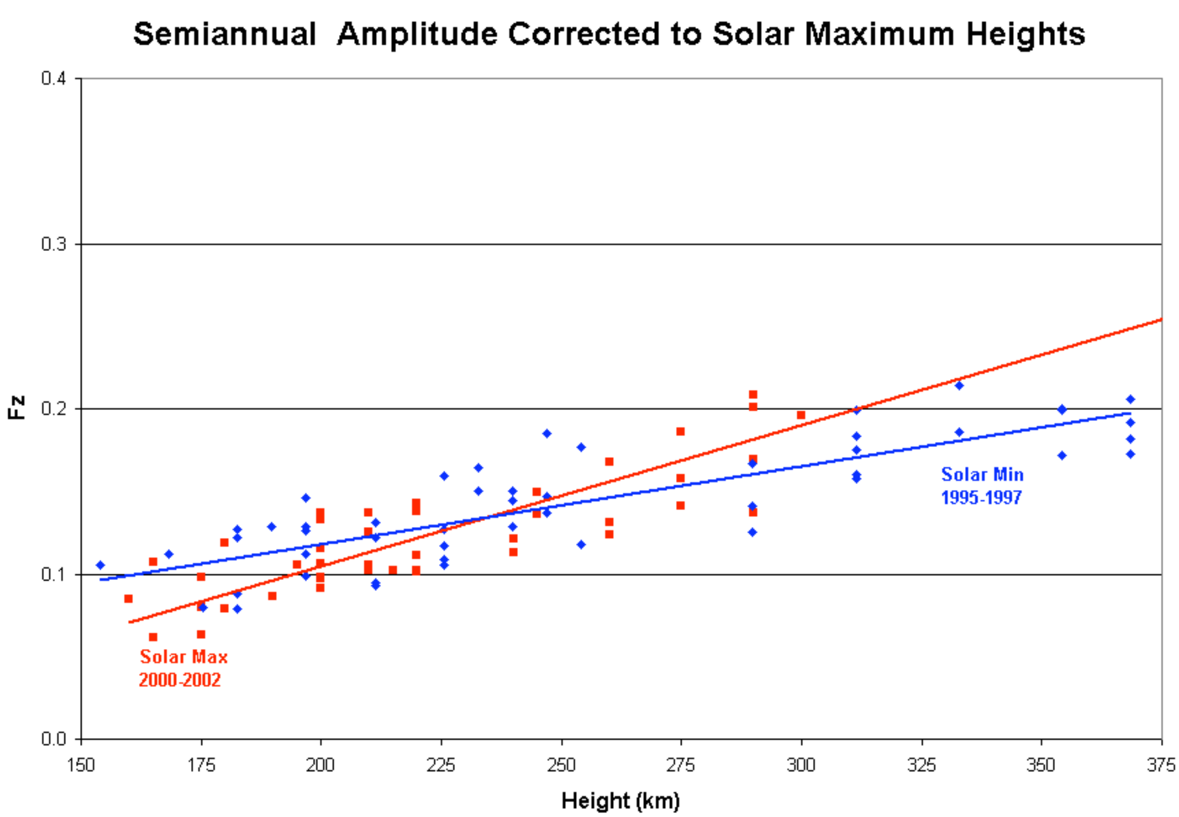

Figure 4. The semiannual amplitude function F(z) is plotted for solar minimum (1995-1997) and solar maximum (2000-2002) years as a function of height. The solar minimum heights were corrected to correspond to solar maximum heights of equal average density.

Figure 5 shows the plots of the semiannual amplitude variation for years 1993 through 2003. The heights have been corrected for different solar conditions to match the densities during solar maximum. The curves confirm what Figure 4 showed, that above 250 km the variation increases with increasing solar active, and reverses the trend below 225 km.

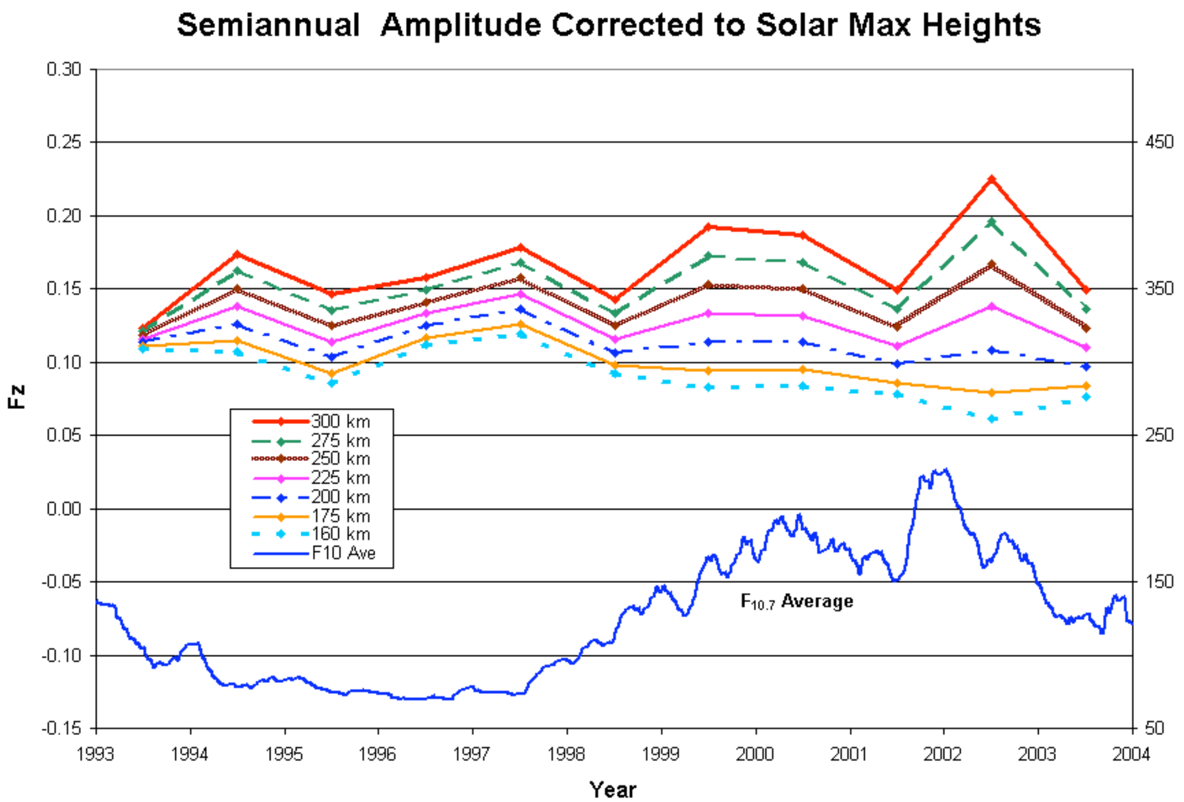

Figure 5. The semiannual amplitude function F(z) is plotted for a number of altitudes as a function of year. Also plotted is the average 90-day solar flux value, F10.7 Ave.

G(t) Periodic Function

The G(t) function, as previously discussed, consists of a Fourier series with 9 coefficients. The 28-day smoothed density difference data for each satellite was fitted with the Fourier series for each year. The density difference data is the accurate observed daily density values minus the Jacchia values without Jacchia's semiannual variation. The G(t) function was then obtained by normalizing to a value of 1 the difference between the minimum and maximum values for the year. The F(z) value for each satellite by year was used for the normalization. Figure 6 shows the results obtained for the year 2000 for the low altitude satellites. Note the tight consistency of the curves for all heights, covering altitudes from 180 km to 300 km. The yearly G(t) model function, obtained from the author's previous semiannual variation analysis[7] of satellites heights from 220 km to 1100 km, is included in Figure 6. The global model values for year 2000 obtained in the previous semiannual variation analysis[7] are also shown. It is interesting to note that the semiannual variation phase at the very low altitudes still compares extremely well with the previously derived yearly model phase obtained at altitudes up to 1100 km.

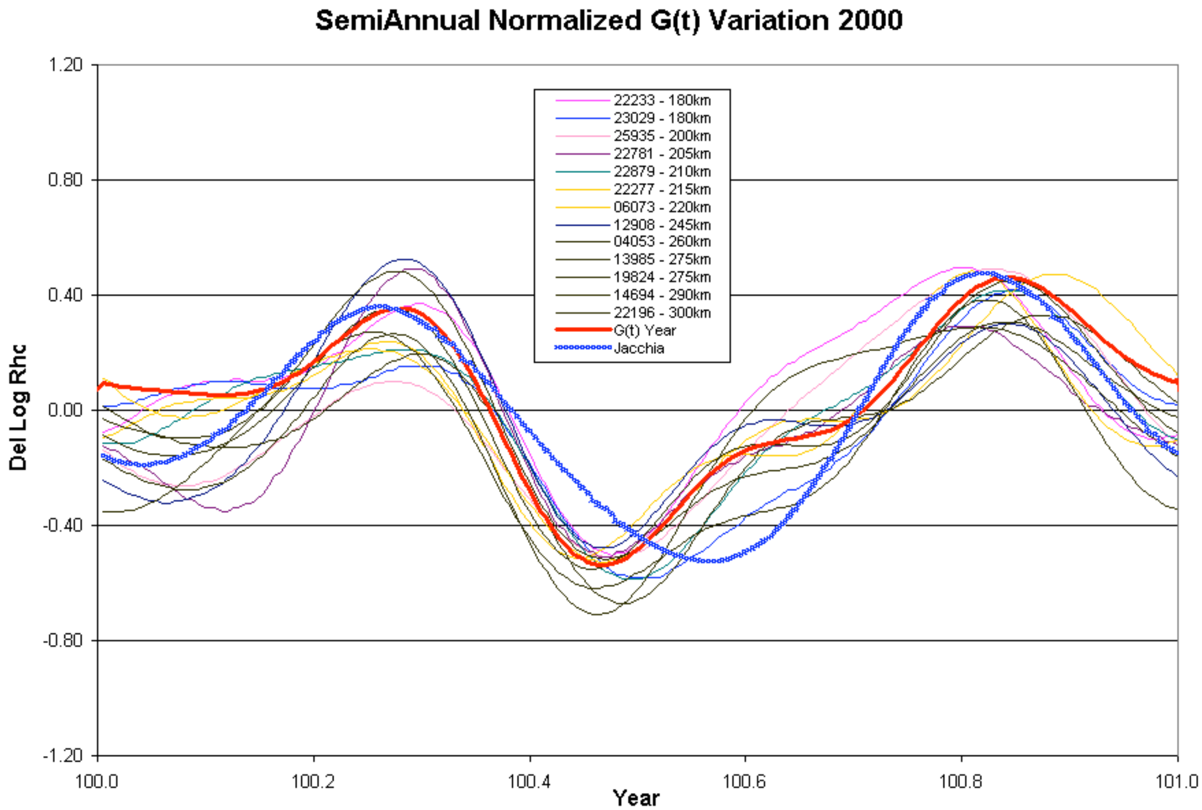

Figure 6. The low altitude individual satellite G(t) fits are plotted for year 2000. The Jacchia model and the yearly fit model are also shown.

Conclusions

The semiannual variation has been successfully obtained under differing solar conditions for altitudes from 160 to 300 km. It has been found that at low altitudes the amplitude still increases with increasing height, and above 250 km during solar maximum times it is larger than during solar minimum times. However, below 225 km the solar maximum amplitude appears to be lower than the amplitude found during solar minimum times. It has also been confirmed that the semiannual variation phase is independent of height, with the low altitude function agreeing extremely well with the high altitude values.

Acknowledgments

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