A new empirical atmospheric density model is developed using the CIRA72 (Jacchia 71) model as the basis for the diffusion equations. New solar indices based on orbit based sensor data are used for the solar irradiances in the extreme and far ultraviolet wavelengths. New exospheric temperature and semiannual density equations are employed to represent the major thermospheric density variations. Temperature correction equations are also developed for diurnal and latitudinal effects, and finally density correction factors are used for model corrections required at high altitude (1500-4000 km). The new model, Jacchia-Bowman 2006, is validated through comparisons of accurate daily density drag data previously computed for numerous satellites. For 400 km altitude the standard deviation of 16% for the standard Jacchia model is reduced to 10% for the new JB2006 model for periods of low geomagnetic storm activity.
I. Introduction

Density model errors on the order of 15%-20% one standard deviation have been recognized for all empirical models developed since the mid 1960s. These large density standard deviations correspond to maximum density errors of approximately 40-60% as observed in satellite drag data. There are two main reasons for these consistently large values. One is the result of not modeling the semiannual density variation as a function of solar activity, and the other results from not modeling the full thermospheric heating from solar ultraviolet radiation. Geomagnetic storms provide episodic, and overall smaller, contributions to the standard deviation. All previous empirical atmospheric models have used the $F_{10}$ and 81-day centered average $F_{10}$ proxies as representative of the solar ultraviolet (UV) heating. However, the unmodeled errors derived from satellite drag data, as displayed in Figure 1 for 1999, all show very large density errors with approximately 27-day periods, representing one solar rotation cycle. These errors are the result of not fully modeling the ultraviolet radiation effects on the thermosphere, which have a one solar rotation periodicity. The purpose of this paper is to describe a new atmospheric model that incorporates new solar indices and a new semiannual density model plus other corrections to the Jacchia model.

![dRho for Satellite 00011 - 560 km Perigee Ht](image)

Figure 1. Density errors, dRho, from Jacchia 70 during 1999 from analysis of the ballistic coefficient (B) values obtained from the orbit fits of the spherical satellite 00011 with a perigee height of 560 km.

The basis of the new Jacchia-Bowman JB2006 model is the CIRA72 model atmosphere. The CIRA72 model integrates the diffusion equations using the Jacchia 71 temperature formulation to compute density values for an input geographical location and solar conditions. The CIRA72 model was first converted to a CIRA "70" model by replacing the CIRA72 equations with equations from the Jacchia 70 model. This was done because the model corrections, for altitudes below 1000 km, obtained for temperature and density are based on the Jacchia 70 model, not the Jacchia 71 (CIRA72) model. New semiannual density equations were developed to replace the Jacchia formulation. New global nighttime minimum exospheric temperature equations, using new solar indices, replaced Jacchia's $T_c$ equation. In addition several other equations to correct errors in the diurnal (local solar time) modeling were also incorporated. Finally, new density factors were incorporated to correct model errors at altitudes from 1000 to 5000 km. All of these new equations and model corrections are discussed in the sections that follow.
II. Data Reduction

The density data used to develop the new model equations is very accurate daily values\textsuperscript{12} obtained from drag analysis of numerous satellites with perigee altitudes of 175 km to 1100 km. Daily temperature corrections to the US Air Force High Accuracy Satellite Drag Model’s (HASDM)\textsuperscript{13} modified Jacchia 1970 atmospheric model were obtained on the satellites throughout the period 1978 through 2004. Approximately 120,000 daily temperature values were computed using a special energy dissipation rate (EDR) method\textsuperscript{12}, where radar and optical observations are fit with special orbit perturbations. For each satellite tracked from 1978 through 2004 approximately 100,000 radar and optical observations were available for the special perturbation orbit fitting. 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\textsuperscript{14} were then used with the observed daily temperature corrections to obtain daily density values. The daily density computation was validated\textsuperscript{12} by comparing historical daily density values computed for the last 30 years for over 30 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.

III. Global Nighttime Minimum Exospheric Temperature

The ultraviolet solar radiation that heats the earth's thermosphere consists of two components, one related to active regions on the solar disk, and the other to the disk itself\textsuperscript{4}. The active regions produce density variations of one solar rotation period (27 days), while the disk itself produces density variations of approximately 11 years. The 10.7-cm solar flux, $F_{10}$, has been used to represent the 27-day EUV effect. However, new solar indices have been recently\textsuperscript{10} used to compute better density variation correlations with ultraviolet radiation covering the entire UV band, not just the EUV wavelengths. In determining a new $T_c$ temperature equation with the new solar indices the density values were converted into daily $T_c$ temperature values using the Jacchia 70 empirical atmospheric density model\textsuperscript{3}. To obtain accurate $T_c$ values the large semiannual density variations had to be correctly modeled. A major density variation, aside from the 11-year and 27-day solar heating effect, is the semiannual change. This can be as large as 250\% from a July minimum to an October maximum during solar maximum years, and as small as 60\% from July to October during solar minimum years (at 600 km)$^2$. The semiannual variation was computed on a yearly basis from the previously derived density data\textsuperscript{2}. Jacchia’s 70 model equation was then replaced using these observed semiannual yearly variations. A smaller correction to Jacchia’s model was also made for the observed errors in the latitude and local solar time density variations. From these different model corrections an accurate $T_c$ value, due almost entirely to solar heating, was obtained.

The solar UV absorption in the thermosphere was analyzed to determine what new solar indices were required for the new temperature equation development. Figure 2 is a plot of the altitude at which the maximum absorption rate of solar UV radiation occurs as a function of wavelength\textsuperscript{10}. The solar index $F_{10}$ is really a proxy index because it is measured at a 10.7-cm wavelength (off the scale below), which is not a direct measure of any ultraviolet radiation. Direct ultraviolet heating indices were recently developed that represent the extreme (EUV), far (FUV), and mid (MUV) solar UV radiation. Figure 2 below suggests that, besides an EUV index, an FUV index needs to be considered to capture most of the potential UV heating of the thermosphere.

Based on the previous solar indices analysis\textsuperscript{11} the daily indices selected for this model development include $F_{10}$, $S_{\text{EUV}}$, and $Mg_{10}$. 

American Institute of Aeronautics and Astronautics
**Altitude of Maximum Rate of Absorption of Solar UV Radiation**

![Altitude of Maximum Rate of Absorption of Solar UV Radiation](image)

Figure 2. The altitude of the maximum rate of absorption of solar ultraviolet radiation as a function of solar spectrum wavelength. EUV - extreme ultraviolet, FUV - far ultraviolet, and MUV - mid ultraviolet region. The relevant atomic/molecular species for absorption are also listed.

**F<sub>10</sub>:** The 10.7-cm solar radio flux, F<sub>10</sub>, is produced daily by the Canadian National Research Council’s Herzberg Institute of Astrophysics at its ground-based Dominion Radio Astrophysical Observatory located in Penticton, British Columbia. The physical units of F<sub>10</sub> are W m<sup>-2</sup> Hz<sup>-1</sup> and more conveniently expressed in solar flux units (1 sfu = 1×10<sup>-22</sup> W m<sup>-2</sup> Hz<sup>-1</sup>). For example, a 10.7-cm radio emission of 150×10<sup>-22</sup> W m<sup>-2</sup> Hz<sup>-1</sup> is simply referred to as F<sub>10</sub> = 150 sfu. A running 81-day centered smoothed set of values using the moving boxcar method was created, and these data are referred to as F<sub>10</sub>. Linear regression with daily F<sub>10</sub> has been used to scale and report all other solar indices in units of sfu.

**S<sub>EUV</sub>:** The NASA/ESA Solar and Heliospheric Observatory (SOHO) research satellite operates in a halo orbit at the Lagrange Point 1 (L1) on the Earth-Sun line, approximately 1.5 million km from the Earth. One of the instruments on SOHO is the Solar Extreme-ultraviolet Monitor (SEM) that has been measuring the 26–34 nm solar EUV emission since launch in December 1995. This integrated 26–34 nm emission has been normalized and converted to sfu through linear regression with F<sub>10</sub>, producing the new index S<sub>EUV</sub>. The broadband (wavelength integrated) SEM 26–34 nm irradiances are EUV line emissions dominated by the chromospheric He II line at 30.4 nm with contributions from other chromospheric and coronal lines. This energy principally comes from solar active regions.

**Mg<sub>10</sub>:** The NOAA series of operational satellites, e.g., NOAA 16 and NOAA 17, host the Solar Backscatter Ultraviolet (SBUV) spectrometer that has the objective of monitoring ozone in the Earth’s lower atmosphere. In its discrete operating mode, a diffuser screen is placed in front of the instrument’s aperture in order to scatter solar MUV radiation near 280 nm into the instrument. This solar spectral region contains both photospheric continuum and chromospheric line emissions. The chromospheric Mg II h and k lines at 279.56 and 280.27 nm, respectively, and the weakly varying photospheric wings (or continuum longward and shortward of the core line emission), are operationally observed by the instrument. The Mg II core-to-wing ratio (cwr) is calculated between the variable lines and nearly non-varying wings. The result is a measure of chromospheric and some photospheric solar active region activity independent of instrument sensitivity change through time, and is referred to as the Mg II cwr, which is provided daily by NOAA Space Environment Center (SEC). The Mg II cwr have been used in a linear regression with F<sub>10</sub> to derive the Mg<sub>10</sub> index in sfu units.
A. Tc Temperature Equation

The solution of the best Tc equation was obtained using numerous satellites for the years from 1996 through 2004 when all new solar indices were available. The resulting equation is:

\[ Tc = 379.0 + 3.353 F_{10} + 0.358 \Delta F_{10} + 2.094 \Delta S_{EUV} + 0.343 \Delta Mg_{10} \]  

(1)

The \( F_{10} \) represents the 81-day centered average value of the \( F_{10} \) index. The delta values (\( \Delta F_{10}, \Delta S_{EUV}, \Delta Mg_{10} \)) represent the difference of the daily and 81-day centered average value of each index. The 81-day (3 solar rotation period) centered value was determined to be the best long term average to use. Table 1 below shows the results of using a 2, 3, and 4 solar rotation period for the centered indices.

To avoid increases in Tc due to geomagnetic storms all daily data with the geomagnetic index \( a_p > 25 \) were rejected. This meant that if a solar index required a lag time of 5 days, each of the 5 days prior to the current time had to have \( a_p < 25 \) for the current daily density data to be used.

It was determined that a lag time of 1 day was the best to use for the \( F_{10} \) and \( S_{EUV} \) indices. However, for using the \( Mg_{10} \) index the analysis initially centered on using an index \( E_{SRC} \) representing the FUV solar radiation from the Schumann-Runge continuum shown in Figure 2. From the analysis it was determined that the \( Mg_{10} \) index could be used as an excellent proxy for the real FUV \( E_{SRC} \) index. The best time lag determined for both \( E_{SRC} \) and \( Mg_{10} \) corresponded to a 5-day lag, which was used in determining the new Tc equation above.

B. 11-Year Cycle Temperature Fits

Table 1 lists the results of using 2, 3, and 4 solar rotation centered periods for the long-term averages of \( F_{10}, S_{EUV}, \) and \( Mg_{10} \) indices. Use of the 3-solar rotation period produces the best RMS average.

Table 1 also lists the results of using 81-day centered values of either \( F_{10}, S_{EUV}, \) or \( Mg_{10} \) for the representation of the long-term 11-year solar cycle variation. The customary index in use for all previous models has been \( F_{10} \). In the analysis the 81-day centered \( S_{EUV}, \) and then the \( Mg_{10}, \) values were used to replace the \( F_{10} \) value to represent the long-term effects. Using the \( F_{10} \) value is significantly better than using either of the other long-term indices.

<table>
<thead>
<tr>
<th>Run</th>
<th>RMS (dTc deg)</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20.2</td>
<td>54-day centered</td>
</tr>
<tr>
<td>2</td>
<td><strong>19.7</strong></td>
<td>81-day centered</td>
</tr>
<tr>
<td>3</td>
<td>21.5</td>
<td>108-day centered</td>
</tr>
<tr>
<td>4</td>
<td><strong>19.7</strong></td>
<td>( F_{10} )</td>
</tr>
<tr>
<td>5</td>
<td>30.6</td>
<td>( S_{EUV} )</td>
</tr>
<tr>
<td>6</td>
<td>41.6</td>
<td>( Mg_{10} )</td>
</tr>
</tbody>
</table>

Table 1. The RMS values are listed for the Tc fits based on using 54-day, 81-day, and 108-day centered average values for \( F_{10}, S_{EUV}, \) and \( Mg_{10} \). Also listed are the RMS results using \( F_{10}, S_{EUV}, \) or \( Mg_{10} \) 81-day centered averages to represent the 11-year solar variability.

C. Density Comparisons

The testing of the new Tc equation was done by placing the new equation (1) into the Jacchia 70 atmospheric model, along with the real observed yearly semiannual variations. This was then used to compute new ballistic coefficient (DB) variations for the spherical satellite 12388 at a 400 km perigee
altitude. Any unmodeled density variations are aliased into the B solution during the orbit determination process. Figure 3 shows the results of the recomputed DB variations for 2000. The figure shows a marked improvement in reducing the DB variations with respect to the 27-day solar rotation period.

![Figure 3. The delta ballistic coefficient (DB) variations are listed for satellite 12388 for a time period during 2000. The Jacchia data is based on orbit corrections using the original Jacchia 70 model with the observed 2000 semiannual applied. The JB2006 data uses the new complete Tc equation (1) with the observed 2000 semiannual variation applied. The indices F_{10}, S_{EUV}, and a_p are also plotted.](image)

**IV. Semiannual Density Variation**

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.

For the new JB2006 model the semiannual variations were computed\(^2\) first by differencing the real daily density values with density values obtained from the Jacchia model without applying Jacchia’s semiannual equations. For a perfect model the resulting differences would only contain the observed semiannual variation. Figure 4 shows examples of the individual density differences obtained from the data. Also shown are Jacchia’s semiannual density variation, and a Fourier series fitted to smoothed density difference values. This Fourier function is discussed in detail below. As can be observed in the figure, there is a very large unmodeled 27-day variation in the difference values. Therefore, it was decided to smooth the values with a 28-day moving filter. The resulting values would then produce a smoother fit with the Fourier series.

It is interesting to note how the semiannual variation changes with height and time. Figure 4 shows the variation during a year near solar maximum (2002). The semiannual amplitude is measured from the yearly minimum, normally occurring in July, to the yearly maximum, normally in October. During solar maximum, the semiannual variation can be as small as 30% at 220 km, and as large as 250% near 800 km. During solar minimum, the maximum variation near 800 km is only 60%. Thus, there is a major difference in amplitudes of the yearly variation from solar minimum to solar maximum, unlike Jacchia’s model, which maintains constant amplitude from year to year.
A. Semiannual Density Variation Function

Jacchia’s model represented the semiannual density variation in the form:

$$\Delta_{SA} \log_{10} \rho = F(z) \cdot G(t)$$  \hspace{1cm} (2)

F(z) represents the variation amplitude (i.e. the difference in $\log_{10}$ density between the principal minimum in July and the principle maximum in October) as a function of altitude. G(t) represents the average density variation as a function of time in which the amplitude has been normalized to 1.

It was previously determined that a Fourier series could accurately represent Jacchia’s G(t) equation structure and simplify the solution of the coefficients. It was determined that a 9 coefficient series, including frequencies up to 4 cycles per year, was sufficient to capture all the variability in G(t) that had been previously observed.

It was also determined that a simplified quadratic polynomial equation in z could sufficiently capture Jacchia’s F(z) equation and not lose any fidelity in the observed F(z) values.

The resulting equations used for modeling the observed yearly variations were:

$$F(z) = B_1 + B_2 z + B_3 z^2 \hspace{1cm} (z \text{ in km})$$  \hspace{1cm} (3)

$$G(t) = C_1 + C_2 \sin(\omega) + C_3 \cos(\omega) + C_4 \sin(2\omega) + C_5 \cos(2\omega) + C_6 \sin(3\omega) + C_7 \cos(3\omega) + C_8 \sin(4\omega) + C_9 \cos(4\omega)$$  \hspace{1cm} (4)

where $$\omega = 2\pi \theta \quad \theta = (t - 1.0)/365 \quad t = \text{day of year}$$
B. Semiannual F(z) Height Function

The amplitude, F(z), of the semiannual variation was determined on a year-by-year and satellite-by-satellite basis. The smoothed density difference data was fit each year for each satellite using the 9 term Fourier series (Equation (4)). The F(z) value was then computed from each fit as the difference between the minimum and maximum values for the year.

\[ F(z) = B_1 + B_2 F_{10} + B_3 F_{10} z + B_4 F_{10}^2 z^2 + B_5 F_{10} z^4 + B_6 F_{10}^2 z^4 \]  

(5)

where \( z = \text{height (km) / 1000} \), and \( F_{10} \) is the 81-day centered average of \( F_{10} \) centered at the July minimum time. Table 2 shows the Equation (5) B global coefficients for F(z) used in the JB2006 model.

<table>
<thead>
<tr>
<th>B Coef</th>
<th>Term</th>
<th>Value</th>
</tr>
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<tr>
<td>2</td>
<td>F</td>
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</tr>
<tr>
<td>3</td>
<td>F x Z</td>
<td>1.26190E-02</td>
</tr>
<tr>
<td>4</td>
<td>F x Z^2</td>
<td>-1.00664E-02</td>
</tr>
<tr>
<td>5</td>
<td>F^2 x Z</td>
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</tr>
<tr>
<td>6</td>
<td>F^2 x Z^2</td>
<td>2.60759E-05</td>
</tr>
</tbody>
</table>

Table 2. Equation (5) coefficients for global F(z) function. \( F = F_{10} \) and \( Z = z \) height function.
Figure 6 shows the observed yearly $F(z)$ values at 500 km and the fitted $F(z)$ global values at 500 km plotted as a function of year. Also shown are the average $F_{10}$ values. The strong correlation of the yearly $F(z)$ values with $F_{10}$ is readily apparent. Also apparent are the occasional large deviations in the observed values from the global model values. These deviations are mostly the result of large variations in the 27-day $F_{10}$ flux occurring during the July semiannual minimum time.

![Semiannual Variation at 500 km](image)

Figure 6. The observed $F(z)$ value at 500 km height for each year plotted by year. Also shown are the computed global $F(z)$ values. The $F_{10}$ average, F10B, is displayed, along with Jacchia’s constant 500 km amplitude value.

C. Semiannual $G(t)$ Yearly Periodic Function

The $G(t)$ yearly 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 7 shows the results obtained for the year 1990 for the majority of the satellites. Note the tight consistency of the curves for all heights, covering over 800 km in altitude. A yearly $G(t)$ function was then fit using the data for all the satellites for each year. Figure 7 also shows the yearly $G(t)$ equation values, with a standard deviation of 0.11 in $\log_{10}n$. A small sigma was obtained for every year’s fit, especially during solar maximum years. Figure 8 shows the yearly $G(t)$ fits for 1999 through 2001. It is readily apparent that the series changes dramatically from year to year. During solar maximum the July minimum date can vary by as much as 80 days. The variability is especially large for defining the time of the July minimum during solar maximum, while the solar minimum July minimum times are much more consistency from year to year.
Figure 7. The individual satellite G(t) fits are plotted for 1990. The Jacchia model and yearly fit equation are also shown. The standard deviation, ‘Sig\text{Year}’, for the year G(t) equation values are displayed.

Figure 8. The individual satellite fits for 3 different years are shown. The year G(t) equation values are highlighted. Each set of curves for 1999 and 2001 has been offset by +1.00 and –1.00 respectively in G(t) for clarity.

**D. Semiannual G(t) Global Function**

A global G(t) function was obtained using all satellite data for all years. Since the yearly G(t) functions demonstrated a dependence on solar activity it was decided to expand the series as a function of the average $F_{10}$. The following equation was finally adopted for the global G(t) function:
The standard deviation, ‘Sig’, of the global fit is displayed.

Table 3 below lists the least squares fitted values for the $C_i$ coefficients in equation (6) that are used in the JB2006 model.

<table>
<thead>
<tr>
<th>C Coef</th>
<th>Term</th>
<th>Value</th>
<th>C Coef</th>
<th>Term</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$1$</td>
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<td>13</td>
<td>$F \times \sin 2\omega$</td>
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<tr>
<td>2</td>
<td>$\sin \omega$</td>
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<td>14</td>
<td>$F \times \cos 2\omega$</td>
<td>$-0.142888D-02$</td>
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<td>3</td>
<td>$\cos \omega$</td>
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<td>$\sin 2\omega$</td>
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<td>$F \times \cos 3\omega$</td>
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<td>5</td>
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<td>6</td>
<td>$\sin 3\omega$</td>
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<td>18</td>
<td>$F \times \cos 4\omega$</td>
<td>$0.491286D-03$</td>
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<tr>
<td>7</td>
<td>$\cos 3\omega$</td>
<td>$-0.380037D-01$</td>
<td>19</td>
<td>$F^{10}$</td>
<td>$-0.391484D-04$</td>
</tr>
<tr>
<td>8</td>
<td>$\sin 4\omega$</td>
<td>$-0.150991D-01$</td>
<td>20</td>
<td>$F^{10} \times \sin \omega$</td>
<td>$-0.126854D-04$</td>
</tr>
<tr>
<td>9</td>
<td>$\cos 4\omega$</td>
<td>$-0.541280D-01$</td>
<td>21</td>
<td>$F^{10} \times \cos \omega$</td>
<td>$0.134078D-04$</td>
</tr>
<tr>
<td>10</td>
<td>$F$</td>
<td>$0.119554D-01$</td>
<td>22</td>
<td>$F^{10} \times \sin 2\omega$</td>
<td>$-0.614176D-05$</td>
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<td>12</td>
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<td>$-0.369016D-02$</td>
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</table>

Table 3. C coefficient values for equation (6), where $F = \overline{F_\nu}$.

Figure 9. The $G(t)$ curves for different solar activity as computed from the $G(t)$ global equation are shown. The standard deviation, ‘Sig’, of the global fit is displayed.
Figure 9 is a plot of the global G(t) equation (6) as fitted with all the satellite data. Jacchia’s equation for G(t) is also shown. It is interesting to note that the solar minimum and solar maximum plots are significantly different except near the October maximum, which appears to have only a slight phase shift among the different curves. The April maximum variation is much larger in amplitude, though not in phase. Jacchia’s function overestimates the October maximum for all solar activity, and only correctly estimates the April maximum during average solar activity. The curves once again demonstrate the need for solar activity to be included in the semiannual G(t) function.

The resulting new semiannual equation for $A_{sa} \log_{10} \rho$ used in the JB2006 model is obtained using F(z) and G(t) from equations (5) and (6) in the standard semiannual equation (2).

V. Diurnal Density Correction

Daily temperature corrections$^{12}$, dTc, to the Jacchia 1970 atmospheric model were obtained on 79 calibration satellites for the period 1994 through 2003, and 35 calibration satellites for the solar maximum period 1989 through 1990. All the “calibration” satellites have moderate to high eccentricity orbits, with perigee heights ranging from 150 to 500 km. This means that the daily dTc correction value obtained for a satellite represents the temperature correction needed for a specific local solar time, latitude, and height corresponding to the perigee location.

Corrections to the diurnal (local solar time) and latitude equations were then obtained in the following manner. The dTc values on all the calibration satellites were least squares fit daily as a function of height. These daily fits represented the global dTc correction on a day-by-day basis. The daily fit values of dTc were then removed from the original dTc temperature corrections obtained for each satellite. The resulting $\Delta$Tc corrections could then be attributed to model errors in local solar time and latitude. The original approach to correcting the observed model errors was to obtain, using the new $\Delta$Tc values, new coefficients to Jacchia’s original diurnal equations. However, this proved unfruitful because of the complexity of the errors, so a polynomial approach was adopted. Since the observed errors showed variations as a function of local solar time, latitude, height, and $F_{10}$, the objective was to obtain polynomial fits with the least number of trigonometry functions to facilitate computer computation time. These daily $\Delta$Tc values were all lumped together, and equations were least squares fit as a function of local solar time, latitude, height, and solar flux. Figure 10 shows the $\Delta$Tc values at 200-300 km altitude along with the fitted equation as a function of local solar time. The $\Delta$Tc values are for solar minimum conditions. Figure 11 shows the $\Delta$Tc values with the fitted equation for solar maximum conditions at an altitude of 400-500 km. Finally, Figure 12 shows the fitted equations in $\Delta$Tx for a range of altitudes below 200 km for moderate solar conditions. The correction in Tx, the inflection point temperature, was used for heights below 200 km because it better represented density variations than Tc for these very low altitudes. As can be seen in the figures the $\Delta$Tc correction equations vary significantly with respect to local solar time, height, and solar flux. The resulting $\Delta$Tc equations are divided into heights above 250 km (equation (7)) and between 200 km and 250 km (equation (8)). Below 200 km a $\Delta$Tx correction (equation (9)) was obtained. The intermediate altitude equation (8) was obtained from spline fitting equation (7) with the boundary conditions in $\Delta$Tc obtained from equation (9), where the boundary value and slope of equation (8) agrees with the values of equation (7) and the $\Delta$Tc values computed from equation (9) at the respective boundary altitudes. Table 4 lists all the coefficients values for these three equations.

Finally, either the $\Delta$Tc or the $\Delta$Tx values computed from equations (7), (8), or (9) are added to the Tc or Tx values in the JB2006 model to obtain the Tc and Tx values used for the density computations.
Figure 10. $\Delta T_c$ values for solar minimum conditions as a function of local solar time.

Figure 11. $\Delta T_c$ values for solar maximum conditions as a function of local solar time.

Figure 12. $\Delta T_x$ values for solar moderate conditions as a function of local solar time and altitude.
\[ F = (F_{10} - 100)/100 \]
\[ \dot{e} = (\text{local solar time}(hr))/24 \]
\[ \dot{\phi} = \cos(\text{latitude}) \]
\[ z = \text{height (km)} \]

For 700 km \( \geq z \geq 250 \) km:
\[ H = z/100 \]

\[ \Delta Tc = B_1 + F \left( B_2 + B_3 \dot{e} + B_4 \dot{e}^2 + B_5 \dot{e}^3 + B_6 \dot{e}^4 + B_7 \dot{e}^5 \right) \]
\[ + \dot{\phi} \left( B_8 \dot{e} + B_9 \dot{e}^2 + B_{10} \dot{e}^3 + B_{11} \dot{e}^4 + B_{12} \dot{e}^5 \right) \]
\[ + \dot{\phi} \dot{H} \left( B_{13} + B_{14} \dot{e} + B_{15} \dot{e}^2 + B_{16} \dot{e}^3 + B_{17} \dot{e}^4 + B_{18} \dot{e}^5 \right) + B_{19} \dot{\phi} \] (7)

For 250 km \( \geq z \geq 200 \) km:
\[ H = (z - 200)/50 \]

\[ \Delta Tc = H C_1 + H F \left( C_2 + C_3 \dot{e} + C_4 \dot{e}^2 + C_5 \dot{e}^3 + C_6 \dot{e}^4 + C_7 \dot{e}^5 \right) \]
\[ + \dot{\phi} \dot{H} \left( C_8 \dot{e} + C_9 \dot{e}^2 + C_{10} \dot{e}^3 + C_{11} \dot{e}^4 + C_{12} \dot{e}^5 + C_{13} + C_{14} F + C_{15} \dot{e} + C_{16} \dot{e}^2 \right) \]
\[ + C_{17} + \dot{\phi} \left( C_{18} \dot{e} + C_{19} \dot{e}^2 + C_{20} \dot{e}^3 + C_{21} \dot{e}^4 + C_{22} \dot{e} + C_{23} \dot{e}^2 \right) \] (8)

For 200 km \( \geq z > 140 \) km:
\[ H = z/100 \]

\[ \Delta Tc = D_1 + \left( D_2 \dot{e} + D_3 \dot{e}^2 + D_4 \dot{e}^3 + D_5 \dot{e}^4 \right) \]
\[ + H \left( D_6 + D_7 \dot{e} + D_8 \dot{e}^2 + D_9 \dot{e}^3 \right) + F \left( D_{10} + D_{11} \dot{e} + D_{12} \dot{e}^2 \right) \] (9)

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<th>C Value</th>
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Table 4. Coefficient values for equations (7), (8), and (9).
VI. High Altitude Density Correction

All atmospheric models developed to date have only been able to incorporate small amounts of neutral density values above 1000 km due to lack of data at these higher altitudes. The models developed by Jacchia\textsuperscript{3,5} only used a few satellites to correlate long-term density variations with the 11-year variation of the $F_{10}$ index, and those satellites were all below 800 km altitude. Later work by Hedin\textsuperscript{6,8} in developing the MSIS models still used only density data below 1000 km. Only a handful of density analyses have been done for satellites in the 1500 km to 4000 km height range. A number of papers were published in the 1970s based on analyses of the orbital decay of the Pageos 1 and Dash-2 balloons. Prior\textsuperscript{17} found hydrogen concentrations about 3 times that of the U.S. Standard 1966 Atmosphere Supplement\textsuperscript{13} for both Pageos and Dash-2 during 1967 when they were at approximately 3500-km altitude. Rousseau\textsuperscript{19} analyzed Dash-2 data in the height range of 1500 to 3000 km and found that the Jacchia 70 model underestimated the density values by about a factor of 3. Slowey\textsuperscript{20} reduced Dash-2 data for selected time spans between 1964 and 1971, and found the Jacchia 70 model again underestimated the density by about a factor of 3. From the previously analyses it appeared that the Jacchia 70 model underestimated the densities at 1500 km to 3500 km by up to a factor of 3, which prompted a more complete analysis of this underestimated high altitude variation.

The above-mentioned analyses for the height range of 1500 km to 4000 km covered only a short time span relative to the solar 11-year sunspot cycle, and thus no correlation was obtained between density variations and the $F_{10}$ solar index. The current JB2006 model uses a recent analysis\textsuperscript{21} of over 30 years of density data, in the height range of 1500 km to 4000 km obtained from 25 satellite orbits, to formulate density variations with respect to altitude and the $F_{10}$ index.

A. High Altitude Density Analysis

The analysis method was described previously\textsuperscript{22} from the long-term orbit perturbation analysis of West Ford needles’ orbits. A semi-analytical integrator was developed using the perturbations in the semi-major axis from atmospheric drag, solar radiation pressure, and earth albedo. The drag equations consisted of orbit-averaged perturbation equations derived by King-Hele\textsuperscript{23}. The solar radiation pressure equations were orbit-averaged equations in the semi-major axis developed by Koskela\textsuperscript{24}. The earth albedo model consisted of orbit-averaged equations developed by Anselmo\textsuperscript{25}, where albedo perturbations on the semi-major axis accounted for the albedo differences of the northern and southern hemispheres.

The atmospheric drag equations required modification for the variation of the drag coefficient. For a circular satellite below 600 km height, the $C_D$ value remains almost constant at 2.2 throughout the 11-year solar cycle. However, $C_D$ is a function of the mass and velocity of the atmospheric constituents, which means that it will increase with altitude as the abundance of the lighter elements increases with altitude. As the height increases, the lighter atomic and molecular species become predominant, depending upon the level of solar activity present. At 3500 km the $C_D$ value can be higher than 4.0, where atomic hydrogen is the dominant species during solar minimum. Figure 13 shows the log densities of the different high altitude species as a function of solar activity. During high solar activity atomic oxygen is dominant at altitudes from 500 km up to 1200 km, while during solar minimum conditions it loses dominance just above 500 km. During solar minimum the lightest element hydrogen becomes dominant above 800 km, while during solar maximum it does not start showing an effective presence until altitudes over 4000 km have been reached. Therefore, the $C_D$ value changes greatly depending upon altitude and solar conditions.

For analyzing the data a non-linear least squares program was developed to fit the NORAD mean semi-major axis ($a$) values. For each satellite included in the analysis the semi-major axis was integrated over a data span between 20 and 35 years, depending upon data availability. The perturbations from the orbit-averaged equations were integrated over the span with a 2-day step size. The semi-major axis was used as the element of interest, since there are no long periodic or secular perturbations in $a$ from any gravitational effects for these orbits of interest. NORAD mean elements were available every 3 to 10 days for the satellites for up to 35-year time spans. During the integration the other predicted orbital elements were constrained to the values of the real mean elements obtained from the NORAD element sets. This method avoids non-linear variations in $a$, and allows good convergence in the solution coefficients. The long-term
solution parameters included density correction factors for hydrogen and helium, a direct solar radiation pressure coefficient, the initial semi-major axis value, and several long-term albedo coefficients. The drag coefficient $C_D$ was modeled to account for the dominance of different atomic and molecular species. Each fit consisted of using 500 to 1000 sets of orbit elements. The density factors obtained for hydrogen and helium represent 20 to 35-year averages of density variations at altitudes above 1500 km. The density factors are multiplication factors of the CIRA72 species densities before all the species densities are combined into the model density value used in the drag equations. The CIRA72 model atmosphere was selected for the analysis because it integrates the diffusion equations to any altitude as opposed to using predefined lookup tables that stop at 2500-km altitude. The previous paper lists the fit results for 20 West Ford needles clusters.

The long-term (20 to 35-year) best-fit solution for each satellite contains the solar radiation pressure and albedo coefficients for the satellite. The previous analysis demonstrated that the satellite area-to-mass (A/M) ratio could be determined within 15% accuracy using each satellite solution’s long-term solar radiation pressure coefficient. Once the A/M ratio was determined, short-term density factors could be obtained by holding the long-term solar radiation pressure and albedo coefficients constant, and fitting only the initial $a$ and one density factor for each short interval selected. The resulting density factor represents a 1 to 2-year average compared with the CIRA72 density values. Fits of less than 1 year showed too much variability in the drag coefficients, which is typical of least squares orbit determinations when coefficient observability is a problem. Thus, the short term fit spans were limited to 1 to 2-year intervals based on drag coefficient observability.

Density factors were obtained for 25 satellites spanning a period of over 30 years. Eighteen West Ford needles clusters were used in the height range of 1450 km to 3600 km. All the needles clusters had large A/M ratios greater than 0.75 m$^2$/kg. Five pieces of Delta 1 rocket body debris were used for density variations in the height range of 1600 to 1750 km. The A/M ratios of these pieces were all greater than 0.10 m$^2$/kg, which was sufficient to determine density variations at these lower altitudes. Finally, two balloon satellites, Pageos-1 and Dash-2, were included in the analysis.

Following determination of the 1 to 2-year average density factors for each satellite, the data was plotted with respect to time and the 81-day average $F_{in}$ solar index. Figure 14 shows an example of the data obtained for the needle cluster 02530 over the 30-year period of analysis for this satellite. The factors can be separated into periods when hydrogen was dominant ($\tilde{n}_{H_2}/\tilde{n}_H < 0.3$), when helium was dominant.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{species-abundances.png}
\caption{Species abundances as a function of altitude and solar conditions. The three regions above are separately scaled in log densities for clarity.}
\end{figure}
(\(\bar{n}_{\text{He}}/\bar{n}_{\text{H}} > 3\)), and when an approximately even mixture of hydrogen and helium occurred. The CIRA72 model was used to determine the concentration of each species. Satellite 02530 remained in the height range of 3000 km to 3600 km during the entire 30-year span. Figure 14 shows that hydrogen was dominant during periods of low solar activity (\(\bar{F}_{\text{10}} < 90\)), while helium was dominant during periods of high solar activity (\(\bar{F}_{\text{10}} > 150\)).

Approximately 500 density factors were obtained from data from all 25 satellites covering more than 30 years of time. The density factors were then fit as a function of height and \(\bar{F}_{\text{10}}\).

Figure 14. Density factors obtained for satellite 02530 from 1970 through 2000 as a function of \(\bar{F}_{\text{10}}\), with the dominant species shown for the different solar conditions.

Figure 15. Density factors for the CIRA72 (Jacchia 71) model plotted as a function of altitude and \(\bar{F}_{\text{10}}\) for altitudes from 1000 km to 3500 km.
B. High Altitude Density Equations

The new JB2006 equation plots are shown in Figure 15 as a function of height and $F_{10}$ values. The least-squares model obtained from fitting the factor data for $z > 1500$ km is

$$F_n = C_1 + C_2 F_{10} + C_3 z + C_4 z F_{10}$$

where $z =$ height (km), $F_{10} =$ 81-day $F$ average (10)

![Table 5. Coefficient values for equation (10), where $F = F_{10}$.](image)

Between 1000 km (factor = 1.0) and 1500 km the factor equation was obtained as a spline fit (factor value and slope equal at boundary values of 1000 km and 1500 km).

For $1500 \text{ km} > z > 1000 \text{ km}$ the spline fit equation is

$$F_{1500} = \text{density factor at 1500 km}$$

$$\frac{\partial F_{1500}}{\partial z} = 500 (C_3 + C_4 F_{10})$$

$$F_p (H) = 1 + \left(F_{100} - 500 \frac{\partial F_{1500}}{\partial z} - 3 \right) H^2 + \left(500 \frac{\partial F_{1500}}{\partial z} - 2 F_{1500} + 2 \right) H^3$$

(11)

$F_p$ is the density factor applied to the JB2006 high altitude density computations.

The plots in Figure 15 agree very well with other author's previous results mentioned earlier, with the Jacchia models underestimating the densities in the 1500-3500 km altitude range by up to a factor of 3.5, depending upon solar conditions.

VII. Model Density Errors

The new equations (1,5,6,7,8,9,10, and 11) described above were incorporated into the JB2006 model, and differential orbit corrections were obtained on different satellites using this new model. Figure 16 shows a plot of delta ballistic coefficient values (corrections to the true value) for one of the satellites during 2001. The JB2006 curve uses the full JB2006 model, the Jacchia 70 curve uses the unmodified Jacchia 70 model, and the intermediate curve uses the JB2006 model but with the original Jacchia semiannual equations in place of the new semiannual equations. The delta B values can be attributed strictly to density variations since this satellite is a sphere at a constant perigee height of 400 km. The standard deviation for the Jacchia model has decreased from approximately 16% to just under 10% using the complete new JB2006 model. Other orbit corrections showed that the new diurnal corrections accounted for approximately 0.5% reduction in the standard deviation. Therefore, the remaining (almost half) of the decrease in the standard deviation can be attributed to using the new $T_c$ equation with the new solar indices.
Finally, Figure 17 shows the standard deviations for the Jacchia 70 model and the new JB2006 model as a function of altitude. The density standard deviations were computed from a comparison of historical density values with model density values over the eight-year period of 1997 through 2004. Only low to moderate solar activity ($a_p < 35$) was considered in the evaluations. The resulting decrease, from 16% to 10%, in the standard deviation at 400 km altitude agrees very well with the results from direct orbit fits using the different models. More detailed comparisons using several different neutral density models were undertaken to globally quantify the improved results obtainable when using the new JB2006 model.

Figure 16. Ballistic coefficient variations for satellite 12388 during 2001 from orbit determinations using Jacchia 70 and JB2006 atmospheric density models.

Figure 17. Standard deviations of Jacchia 70 and JB2006 models as a function of altitude.
VIII. Jacchia Model Bias

In the past it has been customary to use a drag coefficient of 2.2 for low altitude satellites of compact shapes when calculating absolute atmospheric densities. To determine the validity of this assumption the drag coefficients of spheres were computed from observational drag data and also from theoretical models. A new density determination method was used to compute observed drag coefficients from the orbit decay of the ODERACS spheres, the Starshine spheres, several radar calibration Calspheres, and numerous Russian Taifun radar calibration spheres. The theoretical values were computed based on equations obtained from previous analyses of a few specialized satellites which provided information on energy accommodation and angular distributions of molecules reemitted from satellite surfaces. The mathematical models of physical drag coefficient were developed by Sentman and Schamberg. Although much of the early work was classified, the large drag coefficients calculated in Sentman’s 1961 papers were confirmed by the data and analyses eventually published by Bruce and by DeVries et al. In 1975, Imbro et al. demonstrated the utility of Schamberg’s model for investigating the effect of the angular distribution of reemitted molecules on the drag coefficient. In 1996 it was shown how the two models could be used together to calculate the effect of a completely diffuse distribution plus a quasi-specular fraction on the physical drag coefficients of a sphere and a cylinder. These two models were used in the study to calculate physical drag coefficients to compare with the observed drag coefficients obtained using the Jacchia 70 density model.

The observed drag coefficient differences from the theoretical values ( \( C_D - C_{DP} \) ) are shown in Figure 18 for different spheres. Part of the differences at 200 km may be caused by inaccuracies in the calculated physical drag coefficients. From previous analyses the physical drag coefficients of spheres with conventional surfaces have been firmly established with an uncertainty close to 3% at 200 km. The bias from Figure 18 is readily apparent. From the drag coefficient analyses the Jacchia model is therefore about 8% high at 200 km, and about 12-13% high at 500 km during sunspot maximum.

This bias in the Jacchia 70 model can also be examined by analyzing the data used by Jacchia in developing the model. Most of his density data was obtained from drag analysis of satellites during the 1965-1969 solar minimum time period. Three of the satellites he used extensively are listed in Table 6. The ballistic coefficient B that Jacchia used for each satellite is listed in the table, as well as the average (Ave) B obtained from fitting special perturbation B values over 15 to 30 years of daily values obtained from using the Jacchia 70 model atmosphere. If his atmospheric model represented his B values over the complete 11-year solar cycle then the average 15-30 year B values should agree with his B values used to compute the model. However, the average B values are all approximately 6% too low, which implies that his density model is approximately 6% too high, a result of using data covering only a partial 11-year solar cycle. In addition, he used a \( C_D \) value of 2.2 for satellite orbits under 400 km, which would produce an additional density error not observed by the average 15-30 year B values. Table 6 compares the correctly computed B values, obtained from using the theoretical partly quasi-specular \( C_D \) values, with the average 15-30 year B values obtained from the Jacchia 70 model. The \( C_D \) differences for these satellites are plotted in Figure 18. The differences are in excellent agreement with those obtained from the drag coefficient sphere data. The average B values are 8 to 13% low, depending upon height, from the computed theoretical values. This means that the Jacchia 70 model density values are too high by 8-13% for these heights in order to match the observed historical drag values.

Since the bias appears to be a function of altitude and solar conditions there was not enough data to obtain a global correction for the JB2006 model. Therefore, no bias correction has at present been applied to the new model. It should be noted that the mean value for Jacchia 70 is within +/-2% compared to both NRLMSIS, which incorporates satellite drag data, and MSIS90 which is based mainly on in situ mass spectrometer data. Future more complete analyses with more independent data should eventually allow the development of a global correction to empirical model absolute values.
Figure 18. C_D difference values are obtained from comparing the observed C_D values against the computed C_DP values of a variety of spheres. The difference values, in percent, are plotted as a function of height.

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Table 6. B values obtained from Jacchia, 15-30 year averages (Ave B), and theoretical computed values (Comp B). The D B % Comp column compares the computed with the long-term Ave B values.

IX. Conclusions

Significant improvements in empirical density modeling have been obtained using the new JB2006 model incorporating new solar indices and a new semiannual variation equation. Solar indices representing the EUV and FUV atmospheric heating have been used to develop a new temperature equation to replace the standard Jacchia Tc equation. A new semiannual equation as a function of solar activity has replaced the standard Jacchia formulization, and new diurnal temperature correction equations have been added to the new model. Finally, density correction factors have been utilized to correct for the large Jacchia underestimation of the density at altitudes of 1000 to 5000 km. The new model, Jacchia-Bowman 2006 (JB2006) provides standard deviations of approximately 10% at 400 km, a significant decrease from 16% previously obtained using the Jacchia 70 model.

Acknowledgments

We would like to acknowledge the support of the Air Force Space Battlelab under the Sapphire Dragon initiative to improve the 72-hour low earth orbit predictions.
References


