

# **NASA Marshall Engineering Thermosphere Model—Version 2.0**

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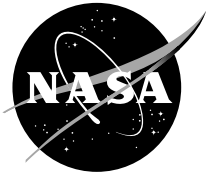
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## LIST OF ACRONYMS AND SYMBOLS

Ar	argon
CH	coronal hole
CME	coronal mass ejection
CPU	central processing unit
EUV	extreme ultraviolet
GRAM-99	Global Reference Atmosphere Model—1999 Version
He	helium
ISES	International Space Environment Service
J64	Jacchia 1964
J70	Jacchia 1970
J71	Jacchia 1971
JD	Julian date
MET	Marshall Engineering Thermosphere
MET-V2.0	Marshall Engineering Thermosphere Model-Version 2.0
MKS	meter-kilogram-second
MSFC	Marshall Space Flight Center
N <sub>2</sub>	nitrogen oxide
O	oxygen
[O]	atomic oxygen
O <sub>2</sub>	oxide
[O <sub>2</sub> ]	molecular oxygen density
SAO	Smithsonian Astrophysical Observatory
UT	universal time
UTC	coordinated universal time
UV	ultraviolet

## NOMENCLATURE

$A_p$	planetary geomagnetic index (24-hr average)
$\bar{A}_p$	average (13-mo smoothed) planetary geomagnetic index
$a$	coefficient
$a_p$	planetary geomagnetic index (3-hr value)
$b$	coefficient
$CN$	coefficient
$c$	coefficient
$c_n$	coefficient
$c_p$	constant pressure
$c_v$	constant volume
$d$	number of days
$E$	difference between the apparent solar time and the mean solar time (equation of time)
$F_{10.7}$	solar flux
$\bar{F}_{10.7}$	average over six solar rotations
$g$	acceleration due to gravity
$g$	mean anomaly
$g_o$	gravitational acceleration at sea level
$G_x$	gradient
$H$	solar hour angle
$i$	individual species (index)
$K$	logarithmic representation of geomagnetic measurements
$K_p$	planetary geomagnetic index
$k$	coefficient
$L$	mean longitude
$M$	constant
$\bar{M}$	molecular mass
$m$	parameter
$N$	number density
$N_A$	Avogadro's number



## NOMENCLATURE (Continued)

$n$	number of Julian days
$p$	constant
$q_o$	volume fraction of a species in the atmosphere
$R$	quantity; universal gas constant
$R_E$	effective radius assuming a spherical Earth
$T$	local temperature
$t$	UT in minutes
$T_\infty$	exospheric temperature
$Y$	length of a tropical year
$z$	altitude
$z_b$	base fairing height
$\alpha$	thermal diffusion factor; solar right ascension
$\beta$	constant
$\gamma$	constant
$\Delta$	incremental change
$\delta_s$	solar declination
$\varepsilon$	obliquity of the ecliptic
$\Lambda$	longitude of the point for which the calculation is being performed
$\lambda_s$	solar ecliptic longitude
$\rho$	total mass density

## TECHNICAL MEMORANDUM

### NASA MARSHALL ENGINEERING THERMOSPHERE MODEL–VERSION 2.0

#### 1. BACKGROUND

The region of the Earth's atmosphere between about 90- and 500-km altitude is known as the thermosphere. The region above  $\approx 500$  km is known as the exosphere. The temperature in the lower thermosphere increases rapidly with increasing altitude from a minimum near 90 km but eventually becomes altitude independent at upper thermospheric altitudes. This asymptotic temperature, known as the exospheric temperature, does not vary with height at any given time due to the extremely short thermal conduction time. However, the exospheric temperature does vary with time because of solar activity and other factors discussed below.

The neutral thermosphere is important for two reasons: (1) Even at its low density, it produces significant torques and drag on orbiting spacecraft and orbital debris, and (2) the density/height profile of the atmosphere above 100-km altitude modulates the flux of trapped radiation encountered at orbital altitudes. The state of the neutral thermosphere is most conveniently described in terms of a mean, with spatial and temporal variations about that mean.

The NASA Marshall Engineering Thermosphere (MET) model of the Earth's atmosphere at spacecraft orbital altitudes has evolved, based on work conducted at Marshall Space Flight Center (MSFC), over a long period of time. The model is based on the extensive work of Luigi Jacchia and his colleagues at the Smithsonian Astrophysical Observatory (SAO) during the 1960's and 1970's and was developed primarily for application to satellite orbital lifetime prediction, mission analysis relative to future reboost requirements, etc. This Technical Memorandum describes the second version of the MET model, attributes of the atmosphere at orbital altitudes, and the methods used to model those attributes.

Short-period atmospheric waves are localized in both time and space in a way that has thus far been unpredictable. Consequently, these waves are not explicitly included in NASA Marshall Engineering Thermosphere Model–Version 2.0 (MET–V 2.0). Thermospheric winds are also not included. At low latitudes (less than  $28.5^\circ$ ), wind speeds range from 100 to 200 m/s. At high latitudes (greater than about  $65^\circ$ ), speeds can be 1,500 m/s or more. Rapid (minutes) changes in wind direction (to  $180^\circ$ ), probably driven by gravity waves, have been observed by a satellite.

## **2. DEVELOPMENT**

### **2.1 Jacchia 1964 Model**

Reference 1 contains a description of the Jacchia 1964 (J64) model. It provides tables of atmospheric density and composition computed for a wide range of exospheric temperatures, starting from a fixed set of boundary conditions at 120 km. The diffusion equation is integrated following empirical temperature profiles of exponential form capable of reproducing the densities derived from atmospheric drag effects on satellites. Formulae are given that relate the exospheric temperature to solar and geomagnetic activity and allow for the diurnal and semiannual variations. The response of the density at the 200-km level to different types of heating is briefly discussed.

In the mid-1960's, personnel of the Aerospace Environment Division at MSFC were responsible for providing orbital altitude density inputs for satellite orbital decay prediction. They began studies to determine which atmospheric model, when combined with the appropriate orbit propagation program, would most accurately predict the observed decay histories of 39 satellites. Since the observed satellite decay histories were already available, a number of available models of the thermosphere were selected for testing in appropriate orbital lifetime computer programs. Because the satellites had decayed prior to the start of the study, actual values of proxy input parameters (described in sec. 3) required by the models were used. These proxy parameters were representative of actual solar conditions that occurred during the decay periods of the satellites. The J64 model, described in reference 1, had the best performance statistically of the models studied and, therefore, was selected for use by MSFC.

### **2.2 Jacchia 1970 Model**

The Jacchia 1970 (J70) model, described in reference 2, is patterned after the 1964 model. The main differences consist in the lower height (90 km instead of 120 km) of the constant boundary surface and a higher ratio of atomic oxygen to molecular oxygen density ( $[O]:[O_2] \approx 1.5$  at 120 km instead of 1.0). Mixing is assumed to prevail to a height of 105 km; diffusion occurs above this height. All the recognized variations that could be connected with solar, geomagnetic, temporal, and geographic parameters are represented by empirical equations.

Due to the great similarity between the 1964 and 1970 models, and confirmation from observed data of the existence of the major differences, the decision was made by MSFC personnel to use the newer model. One key difference from the J64 model, in which the temperature-induced density bulge remained on the equator all year, was that the J70 model bulge followed the latitudinal excursions of the Sun.

## 2.3 Jacchia 1971 Model

In 1971, SAO published the Jacchia 1971 (J71) model.<sup>3</sup> Although an effort was made in the earlier models to increase the ratio of [O] to [O<sub>2</sub>], new observational evidence showed that the increase had not been large enough. This model was an attempt to meet as closely as possible the composition and density data derived for a height of 150 km by Von Zahn<sup>4</sup> on the basis of all the available mass spectrometer and extreme ultraviolet (EUV) absorption data. Mixing is assumed to prevail to a height of 100 km; diffusion occurs above this height. All the recognized variations that can be connected with solar, geomagnetic, temporal, and geographic parameters are represented by empirical equations. Some of the previous Jacchia model equations have been revised, not only in their numerical coefficients but also in their form, as a result of new analyses. The J71 model was not considered to be as representative of the atmospheric density as the J70 model relative to use in satellite orbital lifetime prediction programs. However, it contained some aspects that proved useful in improving MSFC's thermospheric modeling capability.

## 2.4 MSFC/J70 Orbital Atmosphere Model

An unpublished study by environmental personnel at MSFC showed that the J70 model could be improved by incorporating the J71 model formulations of seasonal/latitudinal variations in the lower thermosphere density below 170 km and seasonal/latitudinal variations in helium (He) above 500 km, while retaining the orbital decay prediction accuracy of the J64 model.

Reference 5 contains a description of the MSFC/J70 Orbital Atmospheric Density model, a modified version of the J70 model. The algorithms describing the MSFC/J70 model are provided as well as a listing of the computer program. The estimated future 13-mo smoothed values of solar flux ( $\bar{F}_{10.7}$ ) and geomagnetic index ( $\bar{A}_p$ ), which are required as inputs for the MSFC/J70 model when computing future estimates of orbital altitude density conditions, are also discussed.

## 2.5 NASA Marshall Engineering Thermosphere Model–1988 Version

The modifications made and used in the MSFC/J70 Orbital Atmosphere Density model spuriously introduced step function increases in density requiring minor fairing modifications for their elimination. In the late 1980's, this fairing routine was added, minor programming errors were corrected, and the complete program was made more understandable and user friendly. In addition, the calculation of atmospheric thermodynamic properties was included, and the entire program was updated from FORTRAN IV to FORTRAN 77. These modifications and additions produced the first version to be known as the MET model used at MSFC.

Reference 6 contains a description of the MET model–1988 Version, which is a modified version of the MSFC/J70 Orbital Atmospheric Density model. The modifications to the MSFC/J70 model required for the MET model are described, graphical and numerical examples of the models are included, as is a listing of the MET model computer program. Major differences between the numerical output from the MET model and the MSFC/J70 model are discussed.

In the course of using this model and plotting the results, it was discovered that density discontinuities were occasionally present over certain geographic locations. These were traced to an occasional problem with the integration routine used in the model. It was replaced with a more accurate numerical integration algorithm to solve the problem. Reference 7 contains a detailed description of the replacement integration scheme for the integration of the barometric and diffusion equations in the MET model. This integration scheme is based upon Gaussian quadrature. Extensive numerical testing reveals it to be numerically faster, more accurate, and more reliable than the MSFC/J70 model integration scheme (a modified form of Simpson's rule), which was previously used in the MET model. Numerous graphical examples are provided, along with a listing of the modified form of the MET model in which subroutine INTEGRATE (using Simpson's rule) is replaced by subroutine GAUSS (which uses Gaussian quadrature).

## **2.6 NASA Marshall Engineering Thermosphere Model–1999 Version**

While reviewing the 1988 version of MET, it was determined that the model would not correctly adapt to the change of the approaching new millennium. While performing this update, it was decided to also update the calculation of the solar position to use the more recent standard epoch, J2000.0, which corresponds to January 1.5, 2000, or Julian date (JD) 2451545.0. This is the standard epoch now recommended for use in dynamical astronomy.

An improvement to the model was also achieved in calculating the solar coordinates. A low precision ephemeris for the Sun can be calculated using relatively simple equations.<sup>8</sup> This simpler scheme for computing the solar position requires fewer arithmetic calculations, yet it maintains more than adequate accuracy. The apparent coordinates of the Sun are obtained to a precision of  $0^{\circ}.01$ ; i.e., better than an arc minute, and the equation of time to a precision of 0.1 min between 1950 and 2050.

The other significant modification to the 1988 version of the MET model is in the fairing subroutine, which controls the transition from the lower altitude density profile to that of the upper altitude region where seasonal/latitudinal variation of He is significant. The previous version of this subroutine made the transition in a series of small steps. The new scheme introduced in MET–V 2.0 provides a smooth functional form for the transition. The developmental MET–1999 Version was incorporated into the MSFC Global Reference Atmosphere Model–1999 Version (GRAM–99).<sup>9</sup>

### 3. DESCRIPTION

The MET-V 2.0 is a semiempirical model using the static diffusion method with coefficients obtained from satellite drag analyses. It is based on the 1988 version<sup>6,7</sup> of MET and work done on the 1999 version, developed from the Jacchia series of models. Most of the following description also applies to the 1988 and 1999 versions of the MET model. With the proper input parameters, specified below, an approximate exospheric temperature can be calculated. With exospheric temperature specified, the temperature can be calculated for any altitude between 90 and 2,500 km from an empirically determined temperature profile. In the original development phase of the Jacchia model, the prime objective was to model the total neutral mass density of the thermosphere by adjusting temperature profiles until agreement between modeled and measured total densities (derived from satellite drag observations) was achieved. Agreement between modeled temperatures and those derived from later satellite drag and in situ measurements was not always achieved. Thomson-scatter radar temperature measurements generally show that the diurnal temperature maximum lags the density maximum by a couple of hours, whereas in the MET-V 2.0 model, the temperature and the density maxima and minimal are in phase.

Studies of the accuracy with which thermospheric models estimate the neutral density have shown that an apparent “barrier” exists at the 15-percent level, and models have not thus far been able to achieve better performance. A recent study of this type by Marcos et al.<sup>9</sup> has shown that, historically, this level of accuracy was first achieved by the J70 and J71 models. Figure 1 illustrates this point. The MET-V 2.0 model was not explicitly included in this study. However, since MET-V 2.0 incorporates the best aspects of Jacchia’s 1970 and 1971 models, it clearly performs at the current 15-percent accuracy state-of-the-art in thermospheric neutral density calculation, while being easier to use than other approaches. It was also derived explicitly for use in operational satellite/spacecraft drag applications, unlike most thermospheric density models. The MET-V 2.0 model reflects the J70/J71 models’ accuracy results.

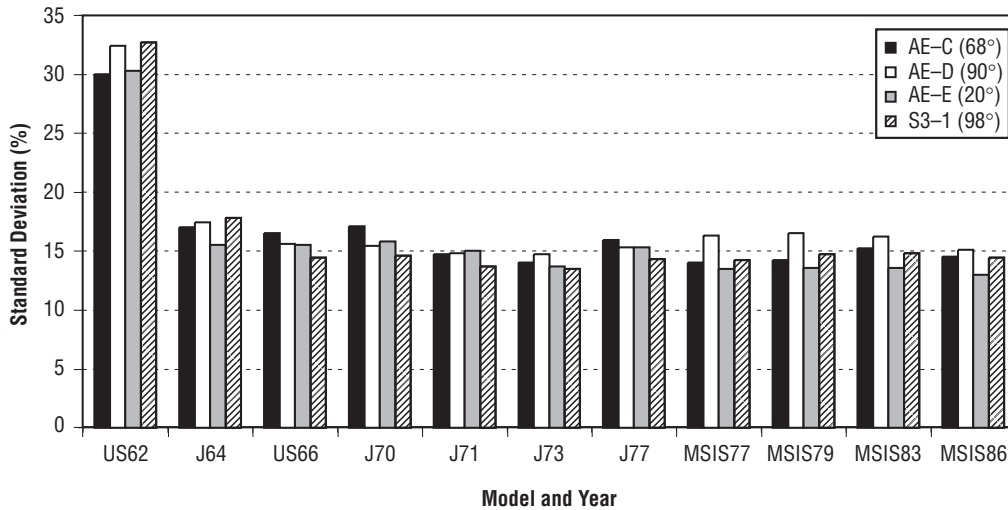


Figure 1. Statistical evaluation of thermospheric neutral density models.

The essence of the MET-V 2.0 model is the calculation of atmospheric density in two major regions: the lower thermosphere (altitude  $90 \text{ km} \leq z \leq 105 \text{ km}$ ) and the upper thermosphere ( $z > 105 \text{ km}$ ). Between the base of the thermosphere (assumed here to be at 90 km) and 105 km, turbulent mixing is assumed to predominate, and diffusion dominates at higher altitudes. The density for all points on the globe at 90-km altitude is assumed constant and mixing of atmospheric constituents prevails to 105 km. Between these two altitudes, the mean molecular mass varies as a result of dissociation of  $[\text{O}_2]$  to  $[\text{O}]$ . An empirical process is employed in the determination of the mean molecular mass distribution between 90 and 105 km, such that the ratio of  $[\text{O}]$  to  $[\text{O}_2]$  is 1.5 at 120 km. This makes it agree more closely with observations as reviewed by Von Zahn.<sup>4</sup> The input parameters required by the program are altitude, latitude, longitude, date (month, day, and year), time (hour and minute), 3 hourly geomagnetic index (linear or logarithmic), and the daily 10.7-cm solar radio flux and its average over six solar rotations referenced to the midpoint. These parameters and their application will be discussed further in section 4. They are essentially the same as provided by the 1988 version of the MET model, but with changes made to the computer program to improve the representativeness of the model's output products and efficiency of the computation.

### 3.1 Density Distribution

#### 3.1.1 Barometric and Diffusion Equations

Density between 90 and 105 km is calculated by integration of the barometric equation. In the lower thermosphere, the atmospheric density is computed by integrating the barometric equation:

$$\rho(z) = \rho_{90} \left( \frac{\bar{M}(z)}{\bar{M}_{90}} \right) \left( \frac{T_{90}}{T(z)} \right) \exp \left( - \int_{z_0}^z \frac{\bar{M}(z') g(z')}{RT(z')} dz' \right), \quad (1)$$

where  $\bar{M}$  is the mean molecular mass,  $g$  is the acceleration due to gravity,  $T$  is the local temperature (all of which are functions of altitude  $z$ ), and  $R$  is the universal gas constant  $8.31432 \text{ J K}^{-1} \text{ mole}^{-1}$ . The lower boundary ( $z_{90} = 90 \text{ km}$ ) is assumed to have the following conditions:

$$\rho_{90} = 3.46 \times 10^{-9} \text{ g cm}^{-3}$$

$$T_{90} = 183 \text{ K}$$

$$\bar{M}_{90} = 28.878 \text{ g mole}^{-1}.$$

For altitudes above 105 km, the diffusion equation for each of the individual species ( $\text{O}_2$ ,  $\text{O}$ ,  $\text{N}_2$ ,  $\text{He}$ , and  $\text{Ar}$ ) is integrated upward from the 105-km level. The number density for an individual species in the altitude range  $90 \leq z \leq 105$  is calculated using a partition function based upon the sea level composition, and this calculation establishes the values for  $N_{105}$  used below. For  $\text{N}_2$ ,  $\text{Ar}$ , and  $\text{He}$ , the number density is given by

$$n(i) = q_o(i) \frac{\rho(z) N_A}{28.96}, \quad (2)$$

where  $i$  denotes the species ( $N_2$ , Ar, or He),  $q_o(i)$  is the appropriate volume fraction for species  $i$ , and  $N_A$  is Avogadro's number. The values of  $q_o(i)$  used in MET-V 2.0 are 0.78110 for  $N_2$ , 0.20955 for  $O_2$ ,  $1.289 \times 10^{-5}$  for He, and 0.009343 for Ar. For O and  $O_2$ , the equations used are

$$n = \frac{2\rho(z)N_A}{\bar{M}(z)} \left( 1 - \frac{\bar{M}(z)}{28.96} \right) \quad (3)$$

and

$$n = \frac{\rho(z)N_A}{\bar{M}(z)} \left\{ \frac{\bar{M}(z)}{28.96} [1 + q_o(O_2)] - 1 \right\}, \quad (4)$$

respectively.

In the upper thermosphere ( $z > 105$  km), the density computation is accomplished by integrating the diffusion equation:

$$N(z) = N_{105} \left( \frac{T_{105}}{T(z)} \right)^{1+\alpha} \exp \left( - \int_{105}^z \frac{M(z)g(z)}{RT(z)} dz' \right), \quad (5)$$

where  $N$  is the number density of the species for which the calculation is being done,  $\alpha$  is the thermal diffusion factor (zero for all species except He, for which a value of  $-0.380$  is used), and the lower boundary is at 105 km. It should be noted that, in this case, the molecular mass  $M$  is a constant, since the concern is for only one species at a time. In both cases, MET-V 2.0 computes the integral using Gaussian quadrature.

The number density of H is assumed to be negligible below 500 km and in diffusive equilibrium above this altitude. Thus, the lower boundary is taken to be at 500 km for this constituent, and its number density at this lower boundary is given empirically by

$$\log_{10} N_{500} = 73.13 - 39.40 \log_{10} T_{\infty} + 5.5 (\log_{10} T_{\infty})^2, \quad (6)$$

where  $T_{\infty}$  is the exospheric temperature given by equation (25). The integration of the diffusion equation then proceeds upward from 500-km altitude.

### 3.1.2 Composition

In the lower thermosphere ( $90 \text{ km} \leq z \leq 105 \text{ km}$ ), the mean molecular mass is computed empirically using the equation



$$\overline{M}(z) = \sum_{n=0}^6 c_n (z-100)^n , \quad (7)$$

where the coefficients,  $c_n$ , are used to fit the profile in this region. The result of equation (7) is then used in the barometric equation, equation (1), to calculate the total mass density,  $\rho$ . The values of  $c_n$  used in the MET-V 2.0 model are, following Jacchia,<sup>2</sup> 28.15204,  $-0.085586$ ,  $1.284 \times 10^{-4}$ ,  $-1.0056 \times 10^{-5}$ ,  $-1.021 \times 10^{-5}$ ,  $1.0544 \times 10^{-6}$ , and  $9.9826 \times 10^{-8}$ , respectively.

In the upper thermosphere ( $z > 105$  km), the number densities for the individual species are determined by integrating the diffusion equation; i.e., from equation (5), with the values at the lower boundary (105 km) given by equations (2)–(4). The total mass density is then given by

$$\rho(z) = \sum_{i=1}^6 \frac{M_i(z)N_i(z)}{N_A} , \quad (8)$$

and the mean molecular weight is

$$\overline{M}(z) = \frac{\rho(z)N_A}{\sum_{i=1}^6 N_i(z)} , \quad (9)$$

where  $i$  denotes the individual species ( $N_2$ ,  $O_2$ ,  $O$ ,  $Ar$ ,  $He$ , or  $H$ ).

### 3.1.3 Gravity Field

The altitude coordinate system used in the MET-V 2.0 model is referenced to the “surface” of the geoid. However, the gravitational field is computed by assuming a spherical planet with an effective radius,  $R_E = 6356.766$  km, where the gravitational acceleration at sea level is assumed to be  $g_o = 9.80665$  m s<sup>2</sup>. These two values are self-consistent and correspond to values of  $g_o$  and  $R_E$  at a latitude of  $45^\circ 32' 40''$  with centrifugal acceleration included. Thus, the gravitational acceleration as a function of altitude is given, for purposes of the model, by the equation

$$g(z) = \frac{g_o}{\left(1 + \frac{z}{R_E}\right)^2} . \quad (10)$$

### 3.1.4 Temperature Profile

The temperature varies both temporally and spatially, but its basic profile is defined by a boundary value  $T_{90} = 183$  K and an inflection point at  $z_x = 125$  km. The temperature at the inflection point is defined empirically by

$$T_x = a + bT_\infty + c \exp(\bar{k}T_\infty) , \quad (11)$$

where the coefficients  $a$ ,  $b$ ,  $c$ , and  $\bar{k}$  are 444.3807, 0.02385, 392.8292, and 0.0021357, respectively<sup>2</sup> and  $T_\infty$  is the exospheric temperature from equation (25). For the low altitude portion of the profile; i.e., for  $90 < z < 125$ , the temperature is defined by a fourth degree polynomial:

$$T(z) = T_x + \sum_{n=1}^4 c_n (z - z_x)^n , \quad (12)$$

where the coefficients  $c_n$  are determined by requirements placed on the derivatives of the profile. Since the lower boundary of the MET-V 2.0 model is taken to be, essentially, the mesopause, the temperature there must be  $T(90) = T_{90} = 183$  K, and the gradient there (being a minimum) must be  $G_o = 0$ . At the inflection point, the second derivative must be zero, and the gradient  $G_x$  must satisfy the condition

$$\frac{4}{3} < \frac{z_x - 90}{T_x - T_{90}} G_x < 2 \quad (13)$$

in order to have no inflections in the region  $90 < z < z_x$ . A value of 1.90 for  $G_x$  was found by experimentation to be best<sup>2</sup>, so MET-V 2.0 uses

$$c_1 = 1.9 \frac{T_x - T_{90}}{z_x - 90} = 1.9 \frac{T_x - T_{90}}{35} \quad (14)$$

$$c_2 \equiv 0 \quad (15)$$

$$c_3 = -1.7 \frac{T_x - T_{90}}{(z_x - 90)^3} = -1.7 \frac{T_x - T_{90}}{35^3} \quad (16)$$

$$c_4 = -0.8 \frac{T_x - T_{90}}{(z_x - 90)^4} = -0.8 \frac{T_x - T_{90}}{35^4} . \quad (17)$$

For  $z > z_x$ ; i.e.,  $z > 125$  km, the temperature profile is calculated using the empirical relation

$$T(z) = T_x + A \tan^{-1} \left\{ \frac{G_x}{A} (z - z_x) \left[ 1 + B (z - z_x)^n \right] \right\} , \quad (18)$$

where  $A = \frac{2}{\pi} (T_\infty - T_x)$ ,  $B = 4.5 \times 10^{-6}$  for  $z$  in km, and  $n = 2.5$ .

## 3.2 Variations

### 3.2.1 Solar Activity

Solar electromagnetic radiation at ultraviolet (UV) and EUV wavelengths changes substantially with the level of solar activity. Thus, thermospheric density is strongly dependent on the level of solar activity. An average 11-yr solar cycle variation exists; similarly, a “typically” 27-day variation in density exists, which is related to the average 27-day solar rotation period. Variations, however, tend to be slightly longer than 27 days early in the solar cycle when active regions occur more frequently at higher solar latitudes and slightly shorter than 27 days later in the solar cycle when the active regions occur more frequently closer to the Sun’s equator. Coronal holes and active longitudes also affect this average 27-day variation. Changes in the thermospheric density related to changes in level of solar (and geomagnetic) activity; e.g., flares, eruptions, coronal mass ejections (CMEs), and coronal holes (CHs), can begin almost instantaneously (minutes to hours), although more often a lag of a day or more occurs.

Various surrogate indices are used to quantify levels of solar activity; one is the 10.7-cm solar radio flux, designated  $F_{10.7}$ . Although EUV radiation heats the atmosphere, this radiation cannot be measured from the ground. The  $F_{10.7}$  can be measured from the ground and correlates well with the EUV radiation. Figure 2 shows the variability of the  $F_{10.7}$  index during a period of low solar activity.

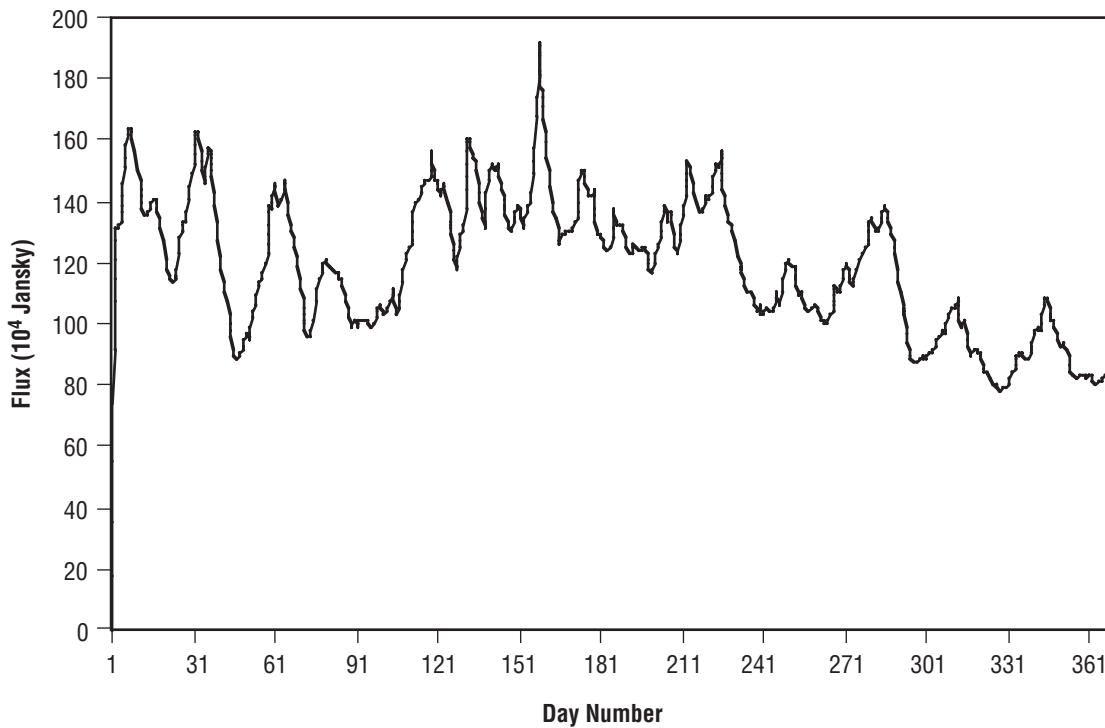


Figure 2. Variation in daily  $F_{10.7}$  flux in 1983.

The exospheric temperature is computed in the MET-V 2.0 model from a base state temperature parameterized using the 10.7-cm solar radio flux. Then several variations due to diurnal variations, geomagnetic activity, and semiannual variations are added to the base state to form an empirical estimate

of the exospheric temperature. The base state equation is for the global minimum of the exospheric temperature distribution (which occurs at night) when the planetary geomagnetic index  $a_p$  (or  $K_p$ ) is zero (see sec. 3 for an explanation of these indices):

$$T_c = 383 + 3.32 \bar{F}_{10.7} + 1.8(F_{10.7} - \bar{F}_{10.7}) , \quad (19)$$

where  $F_{10.7}$  is the 10.7-cm (2,800 MHz) solar radio flux in units of  $10^4$  Jansky (a Jansky is defined as  $10^{-26} \text{ W m}^{-2} \text{ Hz}^{-1}$  bandwidth). The bar over  $F_{10.7}$  indicates an average over three solar rotations prior to the day for which we are doing calculations and three solar rotations afterward; i.e., six solar rotations, for a total of 162 days as used by Jacchia in the model development. (See appendix.)

### 3.2.2 Diurnal

Rotation of the Earth induces a diurnal (24-hr period) variation (diurnal tide) in thermospheric temperature and density. Due to a lag in response of the thermosphere to the EUV heat source, density maximizes around 2 p.m. local solar time for orbital altitudes at a latitude approximately equal to the subsolar point. The lag decreases with decreasing altitude. Similarly, minimum density occurs between 3 and 4 a.m. local solar time at about the negative of the subsolar latitude; i.e., in the diametrically opposite hemisphere. In the lowest regions of the thermosphere (120 km and below), where characteristic thermal conduction time is on the order of a day or more, the diurnal variation is not a predominant effect.

Harmonics of the diurnal tide are also induced in the Earth's atmosphere. A semidiurnal tide (period of 12 hr) and a terdiurnal tide (period of 8 hr) are important in the lower thermosphere (below  $\approx 160$  km for the semidiurnal tide and much lower for the terdiurnal tide). Because of large damping effects of molecular viscosity, these diurnal harmonic tides are not important at orbital altitudes.

The diurnal variation is included in MET-V 2.0 under the assumption that the daytime maximum  $T_M$  and nighttime minimum temperatures occur at latitudes which are diametrically opposed to one another on the geoid; i.e., they occur at latitudes  $\phi$  equal to  $\pm \delta_s$ , respectively, where  $\delta_s$  is the solar declination. This is accomplished by writing the exospheric temperature as

$$T_l = T_c \left( 1 + R \sin^m \theta \right) \left[ 1 + R \cos^n \frac{\tau_d}{2} \left( \frac{\cos^m \eta - \sin^m \theta}{1 + R \sin^m \theta} \right) \right] , \quad (20)$$

where the fitting parameters are  $R = 0.31$ ,  $m = 2.5$ , and  $n = 3$  and the arguments of the trigonometric functions are  $\eta = |\phi + \delta_s|/2$ ,  $\theta = |\phi - \delta_s|/2$ ,  $\tau_d = H + \beta + p \sin(H + \gamma)$ .

The diurnal variation is contained in the expression for  $\tau_d$  in which  $H$  is the solar hour angle measured from upper culmination (the computation of which will be discussed in section 3.4) and the constants  $\beta$ ,  $p$ , and  $\gamma$  are determined from observations to be  $-0.6457718$ ,  $0.1047198$ , and  $0.7504916$ , respectively; i.e.,  $-37^\circ$ ,  $6^\circ$ , and  $43^\circ$ , respectively. The quantity  $R$  is really  $T_M/T_c - 1$  and is known to be correlated with solar activity and with geomagnetic activity.<sup>3</sup> Reference 2 provided equations for

computing  $R$  from annual running means of  $K_p$  or from averaged  $F_{10.7}$ . It was concluded from later analyses that the available data were insufficient to establish the rules of the variation, so using a constant, average value of  $R$  was the best approach.<sup>3</sup> MET-V 2.0 uses the average value from the J70 model,<sup>2</sup> as reflected in the 1988 version of MET.

### 3.2.3 Geomagnetic Activity

Interaction of solar wind with the Earth's magnetosphere (referred to as geomagnetic activity) leads to a high-latitude heat and momentum source for the thermospheric gases. Some of this heat and momentum is convected to low latitudes. Geomagnetic activity varies, usually having one peak in activity just prior to and another just after the peak activity of the solar cycle as defined by the 10.7-cm solar radio flux. Also, larger solar cycle peaks are associated with more intense geomagnetic activity. A seasonal variation of geomagnetic activity occurs with maxima in March ( $\pm 1$  mo) and September ( $\pm 1$  mo) each year. This variation is possibly related to the tilt of the Sun's rotational axis toward the Earth.

There are two geomagnetic indices that may be used in the MET-V 2.0 model. A logarithmic representation of the maximum range over which the magnetic field components vary is designated  $K$ . Values of  $K$  may range from zero to 9, and cover a 3-hr interval. The  $K$  values from 12 standard stations at latitudes from  $48^\circ$  to  $63^\circ$  and fairly evenly distributed in longitude are averaged to obtain the planetary index,  $K_p$ , used in MET-V 2.0. The other index, which may be used in MET-V 2.0, is  $a_p$ , which is a linear index derived from  $K_p$  and ranges from zero to 400. Sometimes a 24-hr average of the 3 hourly  $a_p$  values is quoted, in which case the convention is to designate it  $A_p$ . Although high-latitude ionospheric current fluctuations drive the magnetic field fluctuations observed at these stations, the magnetic field fluctuations do not drive the thermosphere. Thus, good correlations are not always found between observed density changes and the  $a_p$  index. Figure 3 shows a year of  $a_p$  data during a period of low solar activity.

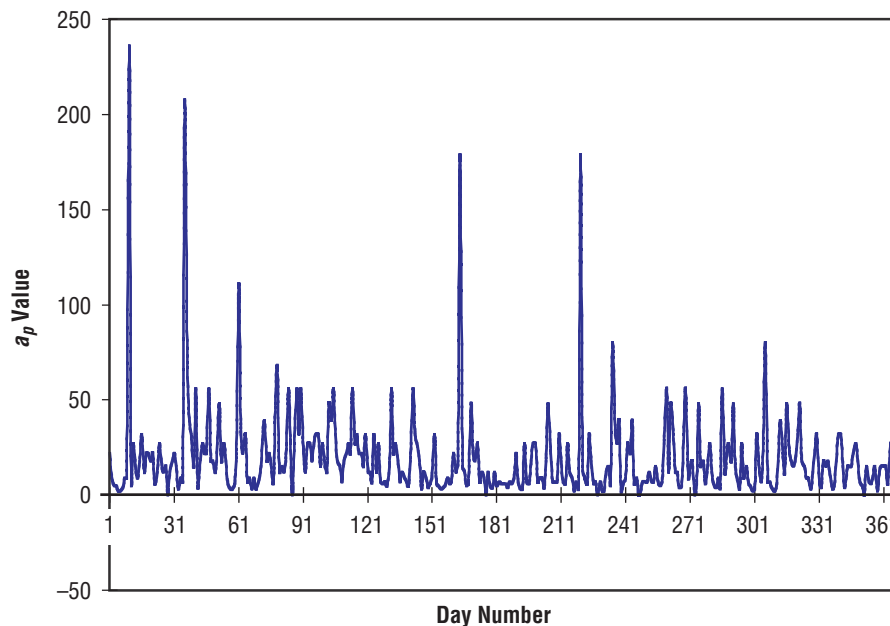


Figure 3. Variation in 3 hourly geomagnetic index,  $a_p$ , in 1983.

When the logarithmic  $K_p$  index is used, MET-V 2.0 computes the adjustment to the exospheric temperature using

$$\Delta T_g = 28 K_p + 0.03 \exp(K_p) , \quad (21)$$

but if the linear  $a_p$  index is used, the equation

$$\Delta T_g = a_p + 100[1 - \exp(-0.08 a_p)] \quad (22)$$

is used. There is a time lag between changes in the geomagnetic indices and temperature variations which averages  $\approx 6.7$  hr; so, whichever index is used, its value should be from a time  $\approx 6.7$  hr prior to the time for which the exospheric temperature is to be computed.

### 3.2.4 Semiannual

This variation in thermospheric density is still poorly understood, but it is believed to be a conduction mode of oscillation driven by a semiannual variation in Joule heating in the high-latitude thermosphere (as a consequence of a semiannual variation in geomagnetic activity). The variation is latitudinally independent and is modified by compositional effects. The amplitude of the variation is height dependent and variable from year to year with a primary minimum in July, primary maximum in October, secondary minimum in January, followed by a secondary maximum in April. Magnitude and altitude dependence of the semiannual oscillation vary considerably from one solar cycle to another. This variation is important at orbital altitudes.

The MET-V 2.0 formulation of the semiannual variation is accomplished through the exospheric temperature. The variation is roughly proportional to the 10.7-cm solar radio flux and may be computed as

$$\Delta T_s = 2.41 + \bar{F}_{10.7} \left[ 0.349 + 0.206 \sin(2\pi\tau_s + 226^\circ.5) \right] \sin(4\pi\tau_s + 247^\circ.6) , \quad (23)$$

where

$$\tau_s = \frac{d}{Y} + 0.1145 \left\{ \left[ \frac{1 + \sin\left(\frac{2\pi d}{Y} + 342^\circ.3\right)}{2} \right]^{2.16} - \frac{1}{2} \right\} , \quad (24)$$

with  $d$  being the number of days since January 1 and  $Y$  the length of a tropical year; i.e., 365.2422 days. Note that  $d$  is not the day number of the year.

Having computed the various adjustments as described above, the exospheric temperature is given by

$$T_{\infty} = T_l + \Delta T_g + \Delta T_s , \quad (25)$$

which provides the appropriate value for use in equations (6) and (11) for computing the H number density at 500 km and the temperature at the inflection point of the temperature profile, respectively.

### 3.2.5 Seasonal/Latitudinal

The total mass density is modified further by the effects of seasonal/latitudinal density variation of the lower thermosphere below 170-km altitude and seasonal/latitudinal variations of He above 500 km. These two effects were incorporated into MET–V 2.0 using the equations developed by Jacchia for his 1971 thermospheric model.<sup>3</sup>

**3.2.5.1 Lower Thermosphere.** The barometric and diffusion differential equations were solved by assuming fixed boundary conditions at  $z = 90$  km. In reality, the values at that height vary as a function of both season and latitude. These seasonal/latitudinal variations are driven in the thermosphere by the dynamics of the lower atmosphere (mesosphere and below). Amplitude of the variation maximizes in the lower thermosphere between about 105 and 120 km and diminishes to zero around 200 km. Although the temperature oscillation amplitude is quite large, corresponding density oscillation amplitude is small. This variation is not important at orbital altitudes.

Computation of this variation in MET–V 2.0 follows the J71 model.<sup>3</sup> In the interest of simplicity, the boundary conditions are left fixed, and the density variations are computed using the empirical relation

$$\Delta \log_{10} \rho(z) = S(z) \frac{\phi}{|\phi|} P \sin^2 \phi , \quad (26)$$

where

$$S(z) = 0.014(z - 90) \exp[-0.0013(z - 90)^2] \quad (27)$$

and

$$P = \sin \left[ \frac{2\pi}{Y} (d + 100) \right] . \quad (28)$$

This equation is only applied below  $z = 170$  km, since the effect on density variation is negligible above this altitude.

**3.2.5.2 Helium.** Satellite mass spectrometers have measured a strong increase in He above the winter pole. Over a year, the He number density varies by a factor of 42 at 275 km, 12 at 400 km, and a factor of 3 or 4 above 500 km. Formation of the winter He bulge is primarily due to effects of global scale winds that blow from the summer to the winter hemisphere. Amplitude of the bulge decreases with increasing levels of solar activity due to increased effectiveness of exospheric transport above 500 km, carrying He back to the summer hemisphere. Also, a very weak dependence exists of He bulge amplitude on magnitude of the lower thermospheric eddy diffusivity.

As was just noted, the seasonal/latitudinal variation of He decreases with increasing altitude. However, He is a sufficiently small fraction of the total density at low altitudes that its seasonal/latitudinal variation is negligible below  $\approx 500$  km. Above 500 km, MET-V 2.0 uses the equation

$$\log_{10} n(\text{He}) = \log_{10} n(\text{He}) + 0.65 \left| \frac{\delta_s}{\varepsilon} \right| \left[ \sin^3 \left( \frac{\pi}{4} - \frac{\phi}{2} \frac{\delta_s}{|\delta_s|} \right) - \sin^3 \frac{\pi}{4} \right], \quad (29)$$

where  $\varepsilon$  is the obliquity of the ecliptic, following the J71 model.<sup>3</sup>

### 3.3 Fairing Between Lower and Upper Thermosphere

In order to produce a smoother, more continuous transition from the densities computed below 500 km to those computed above, a fairing algorithm is applied to the base 10 logarithm of the total density and He number density for altitudes between 440 and 500 km. The faired density is given by

$$\rho(z) = \rho_1(z)C(z) + \rho_2(z)[1 - C(z)], \quad (30)$$

where  $\rho_1$  is the density before adjusting for the seasonal/latitudinal variation of He and  $\rho_2$  is the density afterward, and the fairing coefficient is

$$C(z) = \cos^2 [3(z - z_b)/2], \quad (31)$$

where  $z_b$  is the base fairing height at which the fairing calculation begins, 440 km in this case. The fairing coefficients have been chosen such that a gradual transition occurs from the density variation below 440 km to the variation above 500 km.

### 3.4 Solar Position

It is evident from the preceding discussion that a key element in the computation of densities in the MET-V 2.0 model is the exospheric temperature, which in turn depends upon the solar hour angle and declination. The solar declination is given by

$$\delta_s = \sin^{-1}(\sin \varepsilon \sin \lambda_s), \quad (32)$$



where  $\varepsilon$  is the obliquity of the ecliptic; i.e., the angle between the plane defined by the Earth's equator and the ecliptic plane, and  $\lambda_s$  is the solar ecliptic longitude. Due to Earth's nutation, the obliquity of the ecliptic is not constant. (Nutation is the slight periodic wobbling motion of the Earth's rotation axis caused by the varying distances and relative directions of the Sun and Moon.) In MET-V 2.0, it is computed as

$$\varepsilon = 23^\circ.439 - 0^\circ.0000004n , \quad (33)$$

where  $n$  is the number of Julian days from J2000.0 for the Julian date (JD) corresponding to the date specified in the input

$$n = \text{JD} - 2451545.0 . \quad (34)$$

The Julian date is computed using the Fliegel and Van Flandern algorithm.<sup>10</sup>

The solar ecliptic longitude can be computed by

$$\lambda_s = L + 1^\circ.915 \sin g + 0^\circ.020 \sin 2g , \quad (35)$$

where  $L$  is the mean longitude corrected for aberrations and  $g$  is the mean anomaly; i.e., the mean angle from pericenter traveled from some arbitrary starting time assuming constant angular speed. These may be computed from

$$L = 280^\circ.460 + 0^\circ.9856474n \quad (36)$$

and

$$g = 357^\circ.528 + 0^\circ.9856003n , \quad (37)$$

respectively.

The solar hour angle is the angle between the local meridian and the right ascension of the Sun. It is given by

$$H = \frac{t}{4} - 180^\circ.0 + \Lambda + E , \quad (38)$$

where  $t$  is UT in minutes,  $\Lambda$  is the longitude of the point for which the calculation is being performed, and  $E$  is the difference between the apparent solar time and the mean solar time.  $E$  is known as the equation of time, and it may be computed to a good approximation by

$$E = L - \alpha , \quad (39)$$

where the solar right ascension  $\alpha$  is given by

$$\alpha = \tan^{-1}(\cos \varepsilon \tan \lambda_s) . \quad (40)$$

### 3.5 Thermodynamic Quantities

As an option, MET-V 2.0 computes some thermodynamic quantities, which were computed without option in the 1988 version of MET, but were not included in previous neutral thermosphere codes used by MSFC. The change to have these calculations be optional was incorporated to provide economy of CPU time for those applications; e.g., total density for satellite lifetime predictions, that do not use these thermodynamic quantities. These include the pressure, pressure scale height, specific heat at constant pressure, specific heat at constant volume, and the ratio of the specific heats. The equations used to calculate these quantities are presented in sections 3.5.1 through 3.5.3.

#### 3.5.1 Pressure

The pressure is calculated directly from the equation of state under the assumption that the atmosphere behaves essentially as an ideal gas. Since the number of moles of gas is given by the ratio of the mass of the gas to its molecular weight and the ratio of the mass of the gas to its volume is its density, the pressure at altitude  $z$  is given by

$$p(z) = \frac{\rho(z)}{\bar{M}(z)} RT(z) . \quad (41)$$

#### 3.5.2 Pressure Scale Height

The pressure scale height is, by definition, the inverse of the integrand in equation (1). It may be observed from equation (1) that this is just the change in height required to change the density of a gas of molecular mass  $\bar{M}$  by  $e^{-1}$  in an isothermal atmosphere. To compute this quantity in the MET-V 2.0 model, it was observed that solving equation (41) for  $RT$  and substituting the result into the definition of the scale height gives

$$H(z) = \frac{p(z)}{\rho(z)g(z)} , \quad (42)$$

where  $H(z)$  is the pressure scale height at altitude  $z$ .

#### 3.5.3 Specific Heat Capacities

Under the assumption of an ideal gas, it can be shown by statistical mechanical methods that the molar specific heat at constant volume,  $c_v$  of a monatomic gas is  $3R/2$ , and for a diatomic gas it is  $5R/2$ . It can also be shown from the definitions of  $c_v$  and  $c_p$  (the molar specific heat at constant pressure) that, assuming an ideal gas,  $c_p$  is the sum of  $c_v$  and the universal gas constant  $R$ . Then, the ratio of the specific heats,  $\gamma \equiv c_p / c_v$ , is  $5/3$  for a monatomic gas and  $7/5$  for a diatomic gas. Therefore, the ratio of specific heats in the thermosphere is calculated in the MET-V 2.0 model using the weighted average

$$\gamma = \frac{1.67[n(\text{O}) + n(\text{Ar}) + n(\text{He}) + n(\text{H})] + 1.4[n(\text{O}_2) + n(\text{N}_2)]}{n(\text{O}) + n(\text{Ar}) + n(\text{He}) + n(\text{H}) + n(\text{O}_2) + n(\text{N}_2)} . \quad (43)$$

Using the equation of state and the fact that  $R = c_p - c_v$  in equation (43) yields<sup>6</sup>

$$c_v(z) = \frac{H(z)g(z)}{[\gamma(z) - 1]T(z)} . \quad (44)$$

Then, the specific heat at constant pressure is

$$c_p(z) = \gamma(z)c_v(z) . \quad (45)$$

## 4. PROGRAM USAGE

### 4.1 Input Parameters

The MET–V 2.0 model (code available from author) is designed to be very easy to use. Four basic types of input parameters are required by the model: time, location, solar activity, and geomagnetic activity. These may be provided to the model using the sample driver program provided, which reads an input data file, puts the data into the INDATA array, and calls the primary subroutine MET. The user is free to replace the driver program with his/her own, or to integrate MET–V 2.0 model into a larger program, to suit the needs of the project. Note that the INDATA array, and therefore all of its elements, is REAL\*4.

Table 1 presents a summary of the contents of the INDATA array. Note that the year is input as a four-digit number, while the month, day, hour, and minute are all required to be input as two-digit numbers. The first column contains the array element number; the second column identifies the corresponding parameter; the third column indicates the appropriate range of values, where applicable; and the fourth column identifies the proper units for that parameter, where applicable. Note that INDATA(9) controls whether INDATA(12) is interpreted as  $a_p$  or  $K_p$ , and INDATA(13) controls whether the additional thermodynamic quantities are calculated.

Table 1. INDATA array definition.

Element No.	Parameter	Range	Units
1	Altitude	90 to 2,500	Kilometers
2	Latitude	–90 to 90	Degrees
3	Longitude	–180 to 180	Degrees
4	Year	1950 to 2050	
5	Month	01 to 12	
6	Day	01 to 31	
7	Hour	00 to 23	
8	Minute	00 to 59	
9	Geomagnetic index type	1( $K_p$ ) or 2( $a_p$ )	
10	10.7-cm solar flux	0 to 400	$10^4$ Jansky
11	Average 10.7-cm solar flux	0 to 250	$10^4$ Jansky
12	Geomagnetic activity index	0 to 400 ( $a_p$ ) 0 to 9 ( $K_p$ )	
13	Thermodynamics flag	0 or 1	

There are three general categories of applications for the MET-V 2.0 model: (1) After-the-fact calculations of densities, (2) real-time (or near real-time) calculations of densities, and (3) future applications in which density estimates are required for sometime in the future. In each case, the time and location inputs are selected and entered according to the same rules. When entering the time, the year is entered in four-digit form, while the month, day, hour, and minute for which the calculation is to be done are each entered in two-digit form with the hour and minute being the coordinated universal time (UTC). For the position desired, enter the altitude in kilometers and geographic latitude and longitude in decimal degrees of the spacecraft location at the time of application. Note that the longitude is measured from the Greenwich meridian eastward. The selection of inputs for the solar and geomagnetic activity parameters depends upon which application category applies to the calculation as discussed in sections 4.1.1 through 4.1.3.

#### 4.1.1 After-the-Fact Calculations

This type of calculation is required for times more than 81 days in the past, such as the analysis of data from a space mission or testing model performance using observed orbital parameters for one or more spacecraft. In this case, solar activity is specified using the previous day's value of the 10.7-cm solar radio flux and the centered (about the day for which the calculation is to be done) average of the 10.7-cm solar radio flux over six solar rotations (162 days),  $\bar{F}_{10.7}$ . The geomagnetic index, either  $a_p$  or  $K_p$ , is the 3 hourly index value from 6 to 7 hr prior to the time of application.

#### 4.1.2 Real-Time Calculations

When the application requires that the density calculations be made for the current time, or less than 81 days in the past or future, averaging the observed 10.7-cm flux over six solar rotations as described above is clearly not possible. In this case, the previous day's value of the 10.7-cm solar radio flux is still used for the daily  $F_{10.7}$  value. However, for the average value, observed values are used where available, and the estimated future 13-mo smoothed value of the 10.7-cm solar radio flux is used as an estimate for the balance of the time period (for which observed daily  $F_{10.7}$  values are not available). These estimated future values of  $\bar{F}_{10.7}$  are published by the International Space Environment Service (ISES) and are available electronically via the internet (connect to <http://sec.noaa.gov/SolarCycle> and retrieve the "Table of Predicted Values With Expected Ranges"). The observed  $a_p$  or  $K_p$  from 6 to 7 hr prior to time of application is still appropriate for this application category except for the time period up to 81 days in the future, when the estimated future value of  $\bar{A}_p$  is used.

#### 4.1.3 Future Calculations

When the calculations of densities must be done for a date more than 81 days in the future; e.g., for estimating orbital lifetimes, the problem becomes more dependent upon estimates of future average values for the 10.7-cm solar radio flux,  $\bar{F}_{10.7}$ , and the average planetary geomagnetic index,  $\bar{A}_p$ . Now neither the daily nor the 162-day average 10.7-cm solar radio flux is known from observations, nor is the 3 hourly geomagnetic activity. In this case, the future estimate of the 13-mo smoothed value of  $\bar{F}_{10.7}$  from ISES, as described in section 4.1.2, is used as an estimate of both the previous day's value of the 10.7-cm solar radio flux input and of the 162-day average value. On average, a value of  $\approx 12$  may be used for the 13-mo smoothed estimate of the  $\bar{A}_p$  index for use as an estimate of the 3 hourly geomagnetic index input.

For future neutral density calculations, the accuracy of the calculation depends primarily upon two factors:

(1) The ability of the thermospheric model to represent the observed neutral density using the observed values of solar radio flux (proxy for solar EUV heating) and geomagnetic activity used in the development of the model.

(2) The accuracy with which future solar radio flux and geomagnetic activity can be estimated for use as inputs to the thermospheric model.

As noted in section 3, the MET–V2.0 model has an accuracy of  $\approx 15$  percent, which is the current state-of-the-art for thermospheric density model calculations. However, as noted by Vaughan et al.,<sup>12</sup> the major source of uncertainty for future thermospheric neutral density calculations is the estimation of future solar EUV heat input.

## 4.2 Output Parameters

Upon completion of the calculation, the MET–V 2.0 model passes the results back to the calling routine through the OUTDATA and AUXDATA arrays, both of which are REAL\*4. These calculated results include the exospheric temperature, temperature at the input altitude ( $z$ ), number densities for each constituent, the mean molecular mass, total mass density and its logarithm, and when desired, gravitational acceleration at  $z$ , total pressure, pressure scale height, molar specific heat capacities at constant pressure and constant volume, and the ratio of the specific heat capacities. All of these parameters are expressed in MKS units. Table 2 details the output arrays. The first column identifies which element of which output array contains the data for the parameter in the second column. The notation used is AUX for the AUXDATA array (produced when thermodynamic quantities are computed) and OUT for the OUTDATA array. For example, AUX 2 indicates element 2 of the AUXDATA array, and OUT 5 indicates element 5 of the OUTDATA array. The third column gives the MKS units for the parameter identified in column 2. The total mass density, temperature, and individual species number densities all have the same phase variation in the MET–V 2.0 model.

Table 2. Summary of output parameters.

Location	Parameter	Units
OUT 1	Exospheric temperature	Kelvin (K)
OUT 2	Temperature	Kelvin (K)
OUT 3	N <sub>2</sub> number density	Molecules per cubic meter (m <sup>-3</sup> )
OUT 4	O <sub>2</sub> number density	Molecules per cubic meter (m <sup>-3</sup> )
OUT 5	O number density	Atoms per cubic meter (m <sup>-3</sup> )
OUT 6	Ar number density	Atoms per cubic meter (m <sup>-3</sup> )
OUT 7	He number density	Atoms per cubic meter (m <sup>-3</sup> )
OUT 8	H number density	Atoms per cubic meter (m <sup>-3</sup> )
OUT 9	Average molecular weight	Kilograms per kilo-mole (kg kmol <sup>-1</sup> )
OUT 10	Total mass density	Kilograms per cubic meter (kg m <sup>-3</sup> )
OUT 11	Log <sub>10</sub> mass density	
OUT 12	Total pressure	Pascal (Pa)
AUX 1	Local gravity acceleration	Meters per second squared (m s <sup>-2</sup> )
AUX 2	Ratio-specific heats	
AUX 3	Pressure scale height	Meters (m)
AUX 4	Specific heat constant $p$	m <sup>2</sup> s <sup>-2</sup> K <sup>-1</sup>
AUX 5	Specific heat constant $v$	m <sup>2</sup> s <sup>-2</sup> K <sup>-1</sup>

### 4.3 Sample Calculation

Suppose one wants MET–V 2.0 model results, including thermodynamic quantities, for a point at lat. 45° N., long. 120° W., and 350-km altitude on January 20, 1969, at 19:11 UTC. The 10.7-cm solar radio flux for the preceding day ( $136 \times 10^4$  Jansky) would first be found, then the average 10.7-cm solar radio flux be computed over six solar rotations (162 days,  $\pm 81$  days) centered on January 20, 1969 ( $155 \times 10^4$  Jansky). Then find the value of the geomagnetic index ( $a_p = 9$ ) at  $\approx 6.7$  hr earlier; i.e., at about 12:29 UTC on January 20, 1969. Using these values for a sample run with the driver program supplied with MET–V 2.0, the input data file (see table 1) reads as follows:

Altitude	=	350.00
Latitude	=	45.00
Longitude	=	-120.00
Year	=	1969.00
Month	=	1.00
Day	=	20.00
Hour	=	19.00
Minute	=	11.00
Geomagnetic Index Type	=	2.00
10.7-cm Solar Flux	=	136.00
Average 10.7-cm Solar Flux	=	155.00
Geomagnetic Activity Index	=	9.00
Thermodynamics Flag	=	1.00

Note that in the MET-V 2.0 model longitude is positive toward the east, so 120° west longitude is entered as -120. Performing this run will result in the creation of a file named OUTPUT.TXT containing the following output (all output in MKS units):

Exospheric temperature	= 1031.207 K
Temperature	= 1019.849 K
N2 number density	= 0.3289E+14 /m3
O2 number density	= 0.1660E+13 /m3
O number density	= 0.2811E+15 /m3
A number density	= 0.5398E+10 /m3
He number density	= 0.5449E+13 /m3
H number density	= 0.1000E+07 /m3
Average molecular wt.	= 17.110
Total mass density	= 0.9123E-11 kg/m3
Log10 mass density	= -11.040
Total pressure	= 0.4521E-05 Pa
Local grav. acceln.	= 8.80982 m.sec-2
Ratio specific heats	= 1.64095
Pressure scale-height	= 56254.6 m
Specific heat cons. p	= 1244.11 m2.sec-2.K-1
Specific heat cons. v	= 758.168 m2.sec-2.K-1



## 5. CONCLUDING REMARKS

Using current or past observations of solar radio flux and geomagnetic activity as inputs to the MET–V2.0 model will produce thermospheric density estimates with an accuracy of  $\approx 15$  percent. However, using future estimates of these input values from generally accepted statistical models (no physical solar model is currently available for use) will result in significantly (order of magnitude effects) reduced accuracy for the calculated thermospheric density values. These are key considerations to the prediction and statistical confidence of satellite orbital lifetimes, orbital insertion altitudes, reboost requirements, etc. for which the MET–V2.0 model (and its predecessors) was developed.

**APPENDIX—CORRESPONDENCE BY JACK W. SLOWEY, SMITHSONIAN  
ASTROPHYSICAL OBSERVATORY, MARCH 27, 1978**

SMITHSONIAN INSTITUTION  
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March 27, 1978

Dr. William W. Vaughan, Chief  
Atmospheric Sciences Division  
ES81, Building 4481  
George C. Marshall Space Flight Center  
Marshall Space Flight Center, Alabama 35812

Dear Bill:

It occurs to me that I promised to get back to you on the subject of smoothing to obtain the mean value of the solar flux. This hasn't quite reached the top of my list of "things to do today," but I'll have a go at it anyway.


Concerning the gaussian smoothing procedure given on page 20 of the 1977 Jacchia model, the "recommended" value of  $\tau$  should have been 70 days. This is the value we've used since we first began to use the method ourselves. Of course, I'm sure that we couldn't distinguish between this and the value of 71 days that is quoted. The association with "three solar rotations" may have been the result of poor arithmetic following this lesser corruption but, chicken or egg, it is not appropriate and should be deleted.

In the gaussian method, the scale factor  $\tau$  should not be confused with the larger interval over which the mean is to be taken. At an interval  $\tau$  from the time in question the weight of an included value of  $F$  would be  $1/e = .37$ , which is quite appreciable. You have to go to an interval of about  $3\tau$  before the weights really become insignificant. It is this limit,  $3\tau = 210$  days, that we apply to determine "final" values of  $\bar{F}$  with the gaussian method. It should be emphasized that the limit is applied both forward and backward in time: as in the older method,  $\bar{F}$  is assumed to be a centered mean of the values of  $F$ .

Concerning the older method, in which  $\bar{F}$  is taken as an unweighted running mean, the statement on the same page of the 1977 model that the model was based on means take-over s total of six solar rotations is correct. The unfortunate association of  $\bar{F}$  with the mean over three solar rotations that was made in both the 1970 and 1971 models is, again, not a correct reflection of our actual practice. I can't recall the exact chronology, but we may still have been getting  $\bar{F}$  from a hand-drawn curve through the monthly means when these models were published. In any event, when we did finally put the determination of  $\bar{F}$  on a more formal basis, we found that a total of six rotations were necessary to represent  $\bar{F}$  "correctly" as we saw it. We have used this value ( $\pm 3$  rotations) ever since. In particular, I have used this interval in connection with this kind of smoothing in all of the model computations I've made concerning Skylab.

Of course, I don't claim that anything we do with regard to the determination of  $\bar{F}$  is necessarily "best." It is all based on our own subjective feelings in the matter. I hope, however, that I have clarified what is consistent with our practice and "recommended" for use with the atmospheric models that result.

Sincerely yours,



Jack W. Slowey

JWS/pl

P.S. If I can possibly meet deadlines for New York meeting, I'll be happy to submit a paper.

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