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Neutral Orbital Altitude Density Effects on the International Space Station

O. E. Smith,* S. I. Adelfang,* and R. E. Smith†
Computer Sciences Corporation, Huntsville, Alabama 35824-6405

One of the design requirements of the International Space Station (ISS) is that, each year, accelerations of 1 μg cannot be exceeded at the ISS internal payload location for six periods of not less than 30 consecutive days. Although there are other causes, this study deals only with the accelerations caused by atmospheric drag. The critical ambient neutral density, computed using the Marshall engineering thermosphere model, required to produce accelerations of 1 μg on the ISS, is estimated using an atmospheric-drag acceleration equation. Results show that the design requirements may be difficult to meet during periods of extremely high solar activity; the planned reboost and altitude strategies for the ISS may have to be revised to allow for the uncertainty in the prediction of neutral atmospheric density within the 100-day period established for orbital decay before reboost.

Nomenclature

$F_{10.7}$ = daily value of 10.7-cm solar radio noise flux, 10^{-22} W(m^2/Hz)$^{-1}$ bandwidth or 10^4 Jansky
$\bar{F}_{10.7}$ = average value of $F_{10.7}$
i = inclination, 51.6 deg
r_o = Earth's equatorial radius, 6.37814×10^6 m
V_c = satellite circular velocity, m/s
Z = altitude above the Earth, m
μ = Earth's gravitational parameter, 3.986012×10^{14} m^3/s^2
ρ = neutral density, kg/m^3
ρ_Z = density at altitude Z
ω = Earth's rotation rate, 7.2921×10^{-5} rad/s

Introduction

BOTH the microgravity experiment acceleration requirements and the altitude and reboost strategies of the International Space Station (ISS) are dependent on the combination of the ballistic coefficient of the ISS and the neutral orbital-altitude mass density. Predicting the orbital-altitude neutral mass density for the time period of the assembly and operation of the ISS with any accuracy is extremely difficult because the exact relationship between the solar inputs that affect the atmosphere and the magnitude of the change they cause are poorly known. To make matters worse, predictions of the proxy solar inputs used in the Marshall engineering thermosphere (MET) model are even more difficult.

This study estimates what might occur by simulating ISS operations during selected periods in the historical database of required inputs to the neutral-atmosphere model used in the ISS development program. Results are compared to the ISS design requirements and planned reboost and altitude strategies. The database of inputs required for the MET model of the neutral thermosphere extends from 1947 through 1994.

Background

NASA has specified that the MET model of the neutral atmosphere is to be used in the design, development, and testing phases of the ISS.[1] The MET model is a computer code[2,3] based on the Jacchia 70 (Ref. 4) and the Jacchia 71 (Ref. 5) (for seasonal variation) thermosphere models. The Jacchia 70 atmospheric model[4] documentation states that the density output of the model was referenced to the 81-day mean values of the 10.7-cm solar radio noise flux $\bar{F}_{10.7}$. Discussions and studies conducted in the middle to late 1970s and a recent study[6] established that use of the 81-day running mean prior to the time of application produced predicted lifetimes for Earth-orbiting satellites that were in better agreement with the actual lifetimes than the 162-day average 10.7-cm values required for implementation of the original version of the MET model.[2] Although the decay histories of satellites can be acceptably duplicated after the fact by using the MET model with the actual parameters designated in the original documentation, decay histories of satellites at future times depend entirely on the accuracy of 1) the ballistic coefficient and 2) the proxy solar parameters required as inputs to the model. Results of studies that were conducted to determine what $F_{10.7}$ values could be predicted for use in the prediction of decay rates at future times showed that values of the 10.7-cm solar radio noise flux and the 3-h average geomagnetic index averaged over less than 13 months could not be predicted with sufficient accuracy for the application.

Discussion

The neutral-atmosphere parameter that affects the microgravity acceleration design requirement and the altitude strategy plan of the ISS is the ambient mass density. This analysis of these two portions of the ISS program uses the 1947–1994 historical database of the parameters that are required inputs to the MET model. It is, in essence, a look at the ISS as if it were in orbit at selected time periods between 1947 and 1994, primarily periods with high levels of solar activity.

Calculation of ambient mass density with the MET model is based on determination of the temperature structure above 90-km altitude, which is determined by construction of a temperature profile that begins at 90 km with a fixed boundary condition (defined in the next paragraph) and ends at about 350 km, where the temperature is defined as the exospheric temperature. The exospheric temperature is the key variable for determination of the variability of ambient orbital density. The exospheric temperature is highly dependent on the euv output of the sun and the solar storms that inject energetic particles into the Earth's atmosphere. Because neither of these parameters is measurable at the Earth's surface, proxy parameters that are available are used as inputs to the model. The 10.7-cm solar radio noise flux, both the average and daily values, is a proxy for the euv; the 3-h average geomagnetic index a_p is a proxy for the joule heating of the atmosphere that results from the deposition of the energetic particles.

The MET model is used to compute total mass density from 250- to 500-km altitude using the available 47-year (1947–1994) daily values for the 10.7-cm solar flux and the 3-h (8 per day) average values of the geomagnetic index a_p. These mass densities then are used 1) to compute microgravity levels as a function of altitude for comparison with the specified design requirements and 2) in orbital decay analyses for comparison with the altitude strategy plan.

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*Senior Scientist, Applied Technology, PrISMS, P.O. Box 240005. Member AIAA.
†Senior Scientist, Applied Technology, PrISMS, P.O. Box 240005.

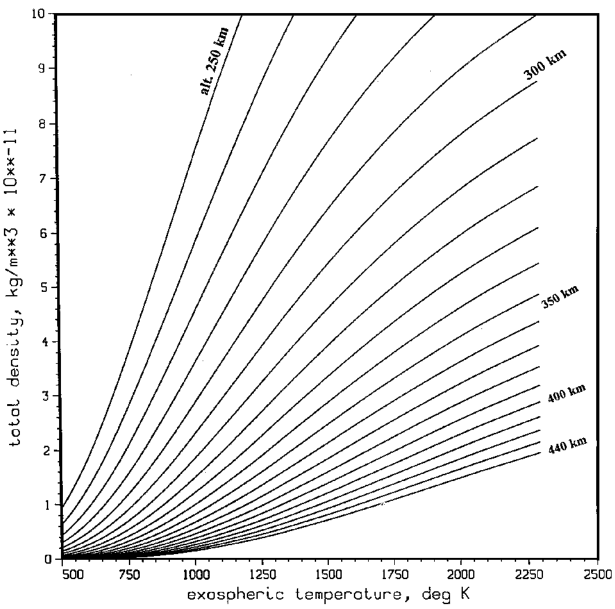


Fig. 1 Density–altitude vs exospheric temperature from Table A1.

Once the variations in the exospheric temperature over the globe are computed, the only other parameter needed to describe the thermosphere density is the fixed boundary condition at 90-km altitude, which is a density value of 3.46×10^{-6} kg/m^3, an ambient temperature of 183 K, and a mean molecular mass $\bar{M}_{90}$ of 28.878 g/mole.

The Appendix (Table A1) gives mass density vs altitude [250 (δ10) 500 km] and exospheric temperature [600 (δ200) 2200 K]. This convenient reference table for density was computed using the MET model for the assigned values of T_E. Table A1 covers the planned operating altitude range for the ISS. The values for density match those from the Jacchia 70 model[4] for $T_E > 700$ K; at 600 K the differences in density are less than 1% at 500-km altitude. This density difference is attributed to the difference in the numerical integration techniques used to evaluate the diffusion equation. The density from Table A1 is illustrated in Fig. 1.

Density variations in the MET model are based on the following.

1) The 10.7-cm solar radio noise flux, which was measured at Ottawa, Ontario, Canada, from 1947 to June 1991 and since June 1991 has been measured at Penticton, British Columbia, Canada.

2) The planetary geomagnetic index. This index is made available through the International Union of Geophysics and Geodesy, Göttingen, Germany.

3) The rotation of the Earth (diurnal variation).

4) The Earth's rotation about the sun (semiannual variation).

5) Seasonal–latitudinal variations below 170-km altitude. This variation is established by a set of empirical equations that correct the mass density between 90- and 170-km altitude. This variation does not affect density above 170 km.

6) Seasonal–latitudinal variations in helium for altitudes greater than 500 km.

The required input parameters for this application of the MET model are as follows.

1) Date (month, day, year).

2) Greenwich Mean Time (GMT) from midnight, 0000 GMT, in hours and minutes.

3) Latitude, degrees.

4) Longitude, degrees.

5) Altitude, kilometers.

6) Daily value for the 10.7-cm solar flux, $F_{10.7}$, for the day prior to the date of interest.

7) The 81-day average 10.7-cm solar flux, $\bar{F}_{10.7}$, 81 days prior to the date of interest.

8) The 3-h planetary geomagnetic index a_p, 6.7 h prior to the time of interest.

The key equations (1–14) of the MET model that relate to the solar flux and the planetary geomagnetic index are presented next.

The nighttime minimum global exospheric temperature T_C, when the geomagnetic index a_p is zero, is

$$T_C = 383 + 3.32\bar{F}_{10.7} + 1.8(F_{10.7} - \bar{F}_{10.7}) \tag{1}$$

In Eq. (1), the empirical coefficients ensure correct units.

The daytime maximum exospheric temperature T_D is

$$T_D = RT_C \tag{2}$$

where R, a function of the 400-day average solar flux, varies from 0.27 to 0.40 and has an average value of 0.31 (Ref. 4).

The variation in the exospheric temperature due to the 3-h geomagnetic index a_p is

$$\Delta T_g = 1.0\, a_p + 100\,[1 - \exp(-0.08\, a_p)] \tag{3}$$

The a_p index has only discrete values between zero and 400, whereas ΔT_g ranges from 0 to 500 K. The variable ΔT_g is the single most important contributor to exospheric temperature change within a day. Three hours is the highest time resolution obtainable from the MET model because of the 3-h intervals for a_p.

The semiannual contribution to the exospheric-temperature (K) variation is

$$\Delta T_s = 2.41 + \bar{F}_{10.7}\, g(t) \tag{4}$$

where

$$g(t) = [0.349 + 0.206 \sin(360°\tau + 226.5°)][\sin(720°\tau + 247.6°)]$$

and

$$\tau = \frac{d}{y} + 0.1145\left(\left\{\frac{1 + \sin[360°(d/y) + 342.3°]}{2}\right\}^{2.16} - \frac{1}{2}\right)$$

where d is days since Jan. 1 and y is the length of the tropical year, 365.2422 days. Figure 2 presents the evaluations for $g(t)$.

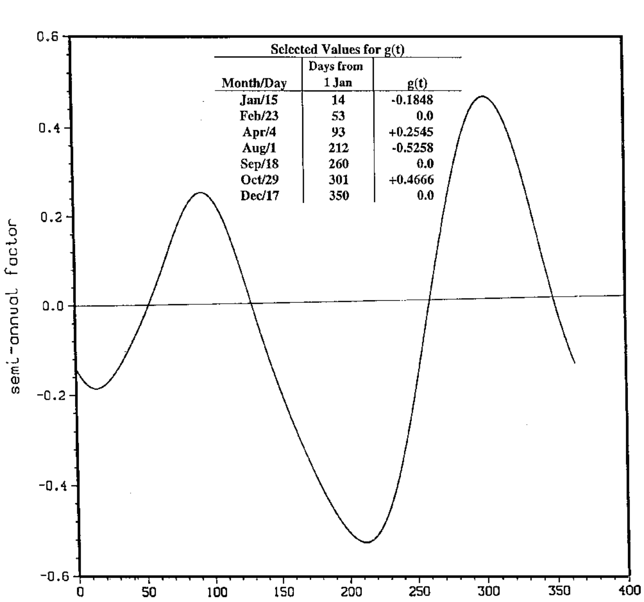
The global maximum exospheric temperature is

$$T_{\max} = (1.0 + R)T_C + \Delta T_g + \Delta T_s \tag{5}$$

This value occurs at the latitude of the subsolar point with a time lag of approximately 2 h or at 1400 hours local sun time. At any altitude in the thermosphere, the largest density occurs at the location of $T_{\max}$.

The minimum exospheric temperature is

$$T_{\min} = T_C + \Delta T_g + \Delta T_s \tag{6}$$



Selected Values for g(t)

Month/Day	Days from 1 Jan	g(t)
Jan/15	14	-0.1848
Feb/23	53	0.0
Apr/4	93	+0.2545
Aug/1	212	-0.5258
Sep/18	260	0.0
Oct/29	301	+0.4666
Dec/17	350	0.0

Fig. 2 Term $g(t)$ for semiannual variation in exospheric temperature.

The global averages for density and exospheric temperature in simplified satellite orbital decay models are estimated from

$$\bar{\rho}_G = \tfrac{1}{2}[\rho(T_{\max}) + \rho(T_{\min})] \tag{7a}$$

$$T_{\mathrm{av}} = (1 + R/2)T_C + \Delta T_s + \Delta T_g \tag{7b}$$

For applications requiring determination of the density along a satellite trajectory in orbit, the exospheric temperature as a function of latitude, longitude, and time is required. This local exospheric temperature is

$$T_L = T_C(1 + R\sin^m\theta)\left[1 + R\left(\frac{\cos^m\eta - \sin^m\theta}{1 - R\sin^m\theta}\right)\cos^n\frac{\tau}{2}\right] \tag{8}$$

where $\tau = H + \beta + p\sin(H + \gamma)$, $(-\pi < \tau < \pi)$; H is the hour angle of the sun, $m = 2.5$, $n = 3.0$, $\beta = -37$ deg, $p = +6$ deg, $\gamma = +43$ deg, and $\eta = \frac{1}{2}|\mathrm{LAT} - \mathrm{DL}|$, $\theta = \frac{1}{2}|\mathrm{LAT} + \mathrm{DL}|$, where LAT is the latitude of the satellite and DL is the sun declination angle.

The local exospheric temperature T_E is then

$$T_E = T_L + \Delta T_g + \Delta T_s \tag{9}$$

There are sets of empirical equations that define the temperature vs altitude T_Z between the temperature at 90 km (183 K) and T_E (at about 350 km) that are functions of altitude and the exospheric temperature only. The hydrostatic equation is integrated numerically using these functions, T_Z, and the boundary conditions at 90-km altitude to obtain the neutral mass density up to 105-km altitude. For altitudes above 105 km, the diffusion equation is used to compute number densities of the atmospheric constituents and total mass density. For altitudes above 500 km, a correction is made to the density for the seasonal variation in helium.

The value for T_E [Eq. (9)] lies between $T_{\min}$ [Eq. (6)] and $T_{\max}$ [Eq. (5)], i.e.,

$$T_{\min} \le T_E \le T_{\max} \tag{10}$$

The orbit of a low-Earth-orbiting satellite will retrograde approximately 4 deg per day; considering this, there is a good chance that any satellite with an inclination ≥ 23.45 deg will pass through $T_{\min}$ and $T_{\max}$ at least one time in 30 days.

Analysis

Figure 3 presents the daily values for the 10.7-cm solar flux for a period covering the latter part of solar cycle 18, all of cycles 19, 20, and 21, and most of cycle 22. The 3-h planetary geomagnetic index a_p for this period of record is shown in Fig. 4. The daily and 81-day prior average (in this case) solar flux and a_p are used to compute the daytime daily maximum global exospheric temperature shown in Fig. 5 (top curve); the differences between the daily global maximum [Eq. (5)] and daily global minimum [Eq. (6)] exospheric temperature also are shown in Fig. 5 (bottom curve).

The largest daily maximum exospheric temperature, 2152.2 K, and the largest thermospheric density, as computed by the MET model, occurred during solar cycle 19 on Sept. 23, 1957, at 0600 GMT. The density values vs altitude can be read from Table A1 for $T_E = 2150$ K. For example, at 450, 400, and 300 km, the density values are 0.15699×10^{-10}, 0.26025×10^{-10}, and 0.83120×10^{-10}, respectively. Table A1 can be used to obtain the density for any arbitrarily assigned or known value of the exospheric temperature.

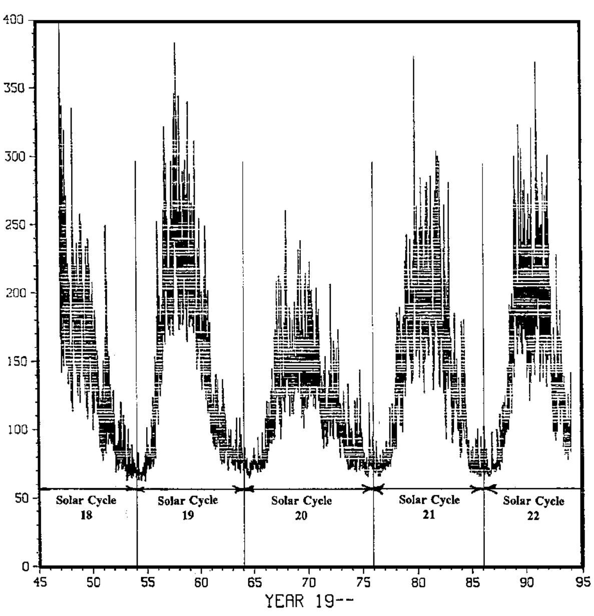


Fig. 3 Daily values for 10.7-cm solar flux for period of study.

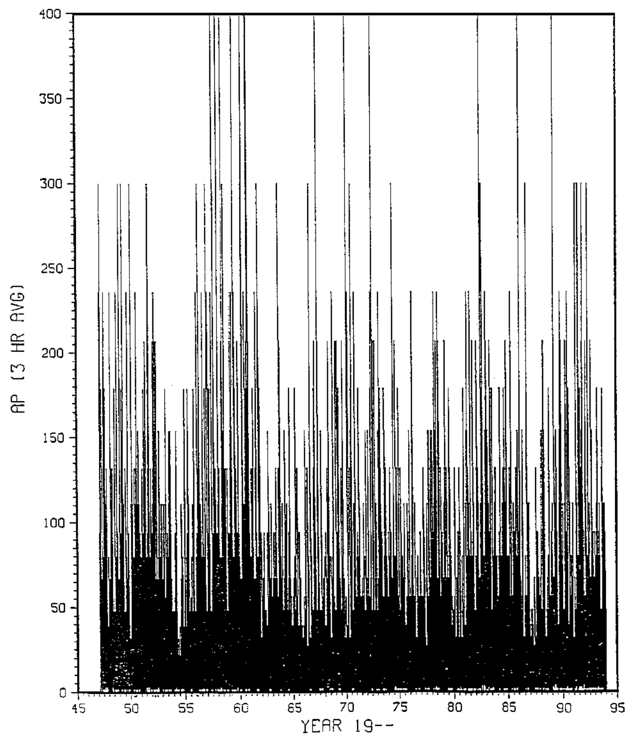


Fig. 4 Planetary geomagnetic index (3-h a_p).

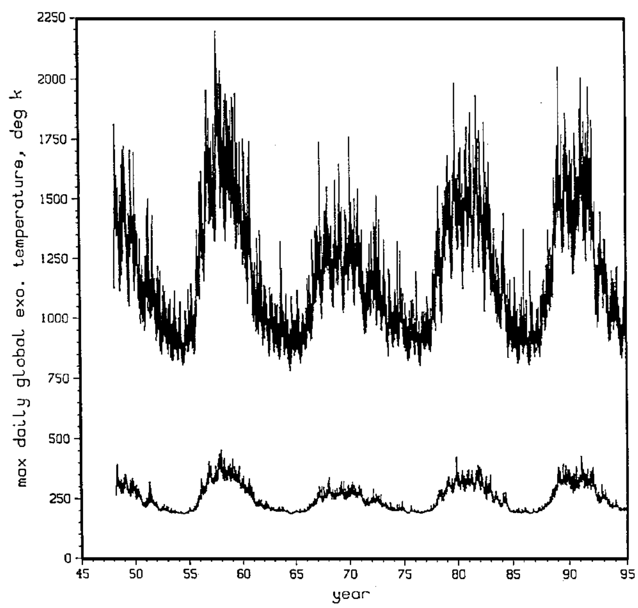


Fig. 5 Daily maximum global exospheric temperature (top curve) and differences in daily maximum and daily minimum global exospheric temperature (bottom curve).

The ISS microgravity experiment requirement from the system specification document for the ISS[1] is as follows:

> The Space Station shall provide the following microgravity acceleration performance for at least 50 percent of the internal payload locations for 180 days per year in continuous time intervals of at least 30 days. At the centers of the internal payloads, a quasi-steady (<0.01 Hz) acceleration: (a) magnitude less than or equal to one micro-g and (b) component perpendicular to the orbital average acceleration vector less than or equal to 0.2 micro-g.

There are also vibration acceleration limits for the frequency range $0.01 \leq f \leq 300$ Hz.

The variability of atmospheric density during one microgravity experiment (30 days' duration) and the ISS response during this period are important factors that contribute to the residual acceleration.

Atmospheric-Drag Acceleration

The atmospheric-drag acceleration D (m/s^2) is given by

$$D = \tfrac{1}{2} C_D (A/m) V_{\mathrm{rel}}^2 \rho \tag{11}$$

where $C_D = 2.2$, $A = 2673$ m^2, and $m = 420{,}000$ kg for the ISS. These estimates yield

$$C_D(A/m) = 0.014\,(\mathrm{m^2/kg})$$

where ρ is atmospheric density and V_{rel} is the relative velocity between the ISS and the atmosphere. For a spherical Earth and a circular orbit, V_{rel} is a function of the circular velocity V_C at altitude Z, inclination (51.6 deg for the ISS), and latitude. At 0° latitude and an inclination of 51.6 deg, V_{rel} at $Z = 300$ km is 7422 m/s, and at $Z = 400$ km, V_{rel} is 7359 m/s. For illustration purposes, V_{rel} is taken as 7400 m/s. From these parameters and assumptions, the atmospheric-drag acceleration D [Eq. (11)] can be approximated by

$$D = 383{,}320/\rho \tag{12}$$

To convert Eq. (12) to microgravity (μg), divide by $g_0 \times 10^{-6}$, where $g_0 = 9.80665$ m/s^2:

$$\mu g = 39{,}089 \times 10^6\,\rho \tag{13}$$

For example, when $\rho = 2.5583 \times 10^{-11}$, Eq. (13) gives 1 μg. Hence, when $\rho \geq 2.5583 \times 10^{-11}$, the atmospheric-drag acceleration equals or exceeds 1 μg. Figure 6 shows $\rho = 2.5583 \times 10^{-11} \pm 20\%$, which is a reasonable uncertainty for the MET model, as a function of exospheric temperature and altitude. The values in Fig. 6 are important in planning altitude strategies for the microgravity experiments. The curves in Fig. 6 represent the exospheric temperature to be used to estimate the altitude above which 1 μg will not be exceeded if the MET model density 1) has no uncertainty (curve A), 2) is underestimated by 20% (curve B), or 3) is overestimated by 20% (curve C). To protect the ISS for the worst case, which is when MET underestimates the density, curve B is applicable. For no uncertainty in the density (curve A), 1-μg acceleration would not have been exceeded at altitudes greater than 397 km because T_E is not greater than 2152.2 K (Fig. 5) for the entire period of record (1947–1994). To protect for the worst-case uncertainty, the altitude would have to be at least 422 km to ensure that 1 μg is not exceeded for the entire period of record (curve B). Similarly, if protection is required for solar activity levels associated with $T_E \leq 1700$ K, which excludes very high solar activity, the minimum altitude is 363 km for no uncertainty (curve A) and 380 km for the worst case (curve B).

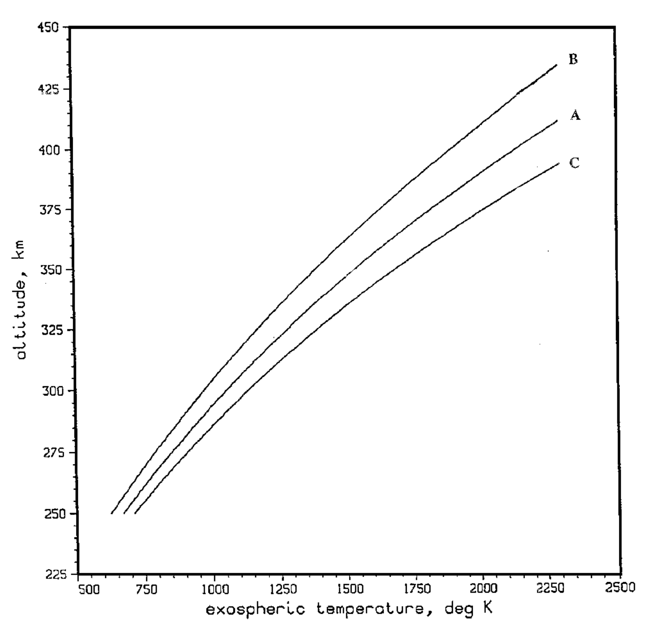


Fig. 6 Altitude vs exospheric temperature: A, $\rho^* = 2.5583 \times 10^{-11}$ kg/m^3 = 1 μg; B, 0.80 ρ^*; and C, 1.20 ρ^* for the ISS.

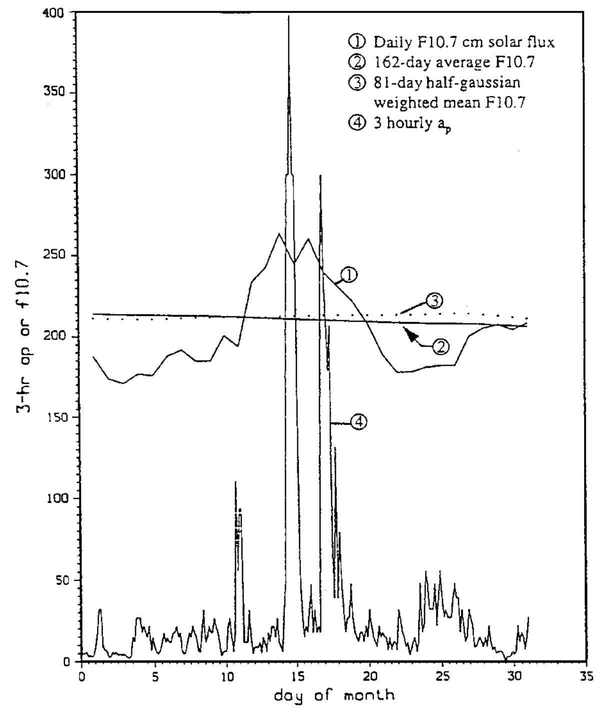


Fig. 7 Solar activity data for July 1959.

A comparison of the mass spectrometric measurements from the Atmospheric Explorer-E (AE-E) satellite with the density computed from the MET model using the 162-day centered-average 10.7-cm solar flux, the 81-day prior-average solar flux, and the $\frac{1}{2}$ Gaussian-weighted prior-average solar flux revealed that a better agreement exists between the MET model and the AE-E densities using the 81-day average flux or the 81-day Gaussian average flux than the 162-day average solar flux.[6] The Gaussian average flux, the daily flux, and a_p shown in Fig. 7 for July 1959 were used in the MET model for the analysis of the ISS in circular orbit at 300-km altitude (Fig. 8). As shown, the density exceeded the critical value for 1 μg for most of the orbits for the entire month of July 1959. This example is for high solar activity. For periods of low solar activity, 1 μg is not exceeded for 30 or more days. For this paper, $T_E > 1500$ K is considered high solar activity, $T_E < 1000$ K is low solar activity, and the values between 1000 and 1500 K are intermediate solar activity.

Variability of Density Within an Orbit

The variability of atmospheric density within an orbit is required for use in ISS engineering analyses of 1) the control-moment gyros' capability to control the torques produced by the difference between the center of pressure and the center of gravity and 2) the atmospheric-drag acceleration that may exceed 1 μg. Figure 9 for July 15–16, 1959, shows that the variation in density within an ISS orbit at 300-km altitude can exceed 2.6×10^{-11} kg/m^3 or 1 μg.

Table 1 Maximum 3-h change in thermosphere density for T_E = 1600 ± 200 K

T_E, K	ρ, kg/m^3	400-km $\Delta\rho$, kg/m^3	$\Delta\rho$ rel, %	ρ, kg/m^3	300-km $\Delta\rho$, kg/m^3	$\Delta\rho$ rel, %
1400	1.0136×10^{-11}	-0.4118×10^{-11}	−29	2.2861×10^{-11}	-2.5213×10^{-11}	−52
1600	1.4324×10^{-11}	0.0	0	4.8074×10^{-11}	0.0	0
1800	1.8642×10^{-11}	0.4318×10^{-11}	30	6.9264×10^{-11}	2.1191×10^{-11}	44

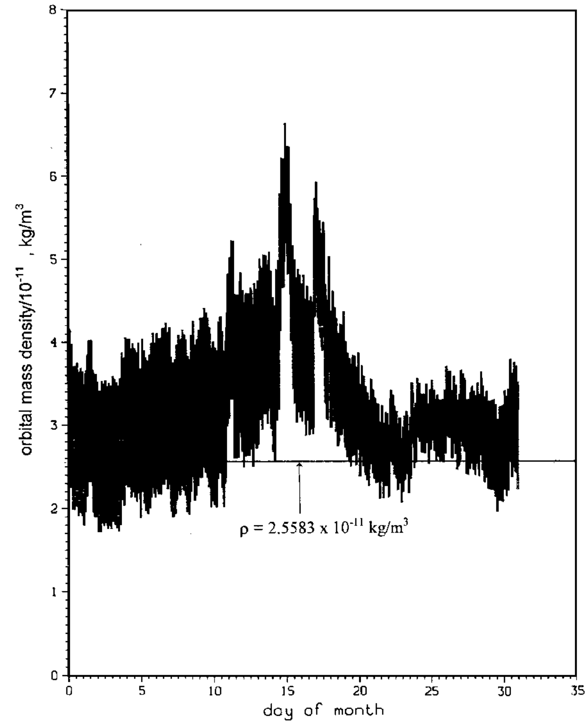


Fig. 8 MET model density using 81-day Gaussian mean 10.7-cm solar flux for ISS orbits at 300-km altitude for July 1959.

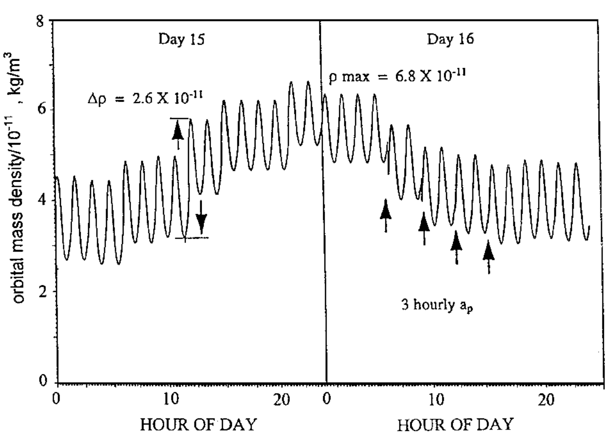


Fig. 9 MET model density using 81-day Gaussian mean 10.7-cm solar flux for ISS orbits at 300-km altitude for July 15–16, 1959.

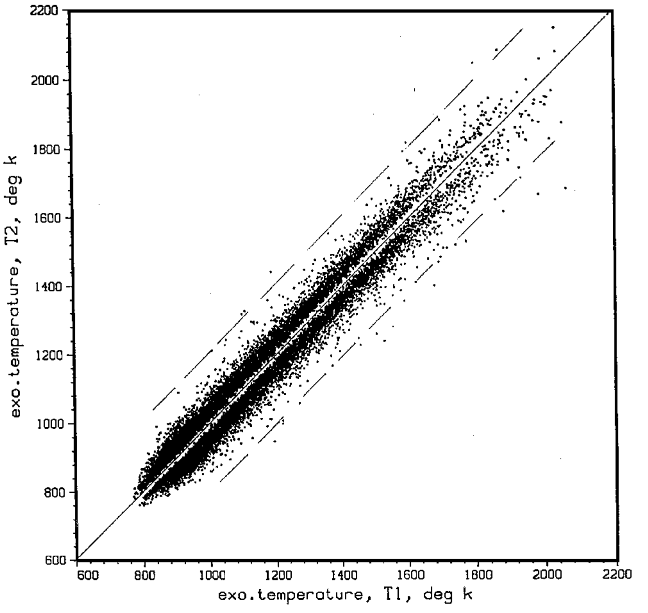


Fig. 10 Exospheric temperatures T_1, T_2 that produced the largest 3-h change in density for the period 1947–1994.

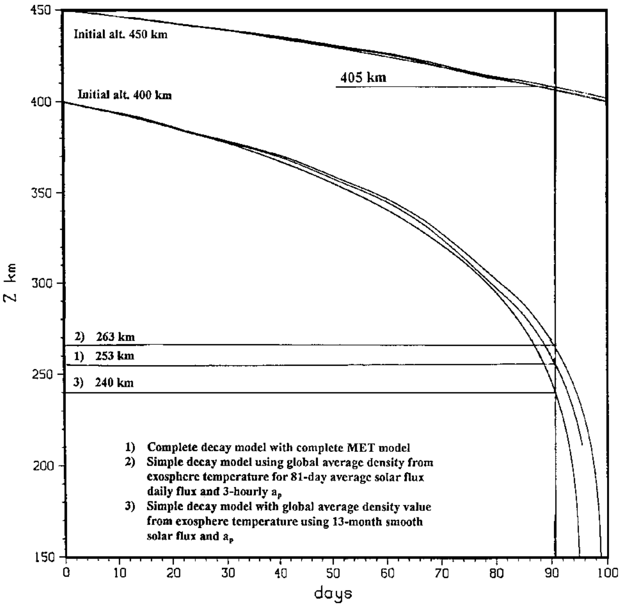


Fig. 11 ISS orbital decay from three models for altitudes of 400 and 450 km for beginning date Jan. 22, 1958, high-solar-activity case.

To obtain the upper limits on the range of density for this purpose, the largest 3-h change in the exospheric temperature from the MET model was computed. The exospheric temperatures associated with the largest daily 3-h changes (T_1, T_2) are shown in Fig. 10; the range of temperature for $T_E > 1000$ K is approximately ±200 K. Densities from Table A1 for $T_E = 1600$ K ± 200 K at 400 and 300 km are listed in Table 1.

ISS Orbital Decay

Three different models are used to compute the ISS orbital decay. They are model 1, a complete orbital decay model whereby the decay rate is calculated for each orbit by integrating the densities (computed using the MET model with the prior 81-day means, prior day value, and the value of a_p 6.7 h prior to the time of interest) at 90 evenly spaced points around the orbit; model 2, a simple orbital decay model (described later) using a single average global thermosphere density computed from Eq. (7) based on the same inputs to the MET model as model 1 and updated at 3-h intervals; model 3, same as model 2 but using the 13-month smoothed 10.7-cm solar flux and 13-month smoothed geomagnetic index a_p in the MET model with the daily flux set equal to the 13-month smoothed solar flux. The results for the complete orbital decay model for ISS initial altitudes of 450 and 400 km beginning Jan. 22, 1958, a high solar activity condition, are illustrated in Fig. 11.

A simple orbital decay model for a circular orbit can be expressed as

$$\frac{\mathrm{d}Z}{\mathrm{d}t} = C_D\left(\frac{A}{m}\right)(r_o + Z)\rho_Z V_C\left\{1 - \left[\frac{\omega(r_o + Z)\cos i}{V_c}\right]^2\right\} \tag{14}$$

where $r_o = 6{,}378{,}140$ m, Z is the altitude above the Earth, ρ_Z is the density at altitude Z (m), V_c is the satellite circular velocity (m/s), where

$$V_c = \left[\frac{\mu}{(r_o + Z)}\right]^{\frac{1}{2}}$$

$\mu = 3.986012 \times 10^{14}$ m^3/s^2, $\omega = 7.2921 \times 10^{-5}$ rad/s, and $i = 51.6$ deg. The other parameters are as defined in Eq. (11); $(\mathrm{d}z/\mathrm{d}t)$ is the orbital decay rate (m/s).

From model 1, ISS decayed from the initial altitude of 400 km to 253 km in 90 days. From model 2 [Eq. (14)], using the same solar inputs as in model 1, the ISS altitude decayed from 400 to 263 km in 90 days. From model 3, the ISS altitude decayed from 400 to 240 km in 90 days (lower curves, Fig. 11). For the ISS at an initial altitude of 450 km (upper three curves in Fig. 11), all three orbital decay models yield nearly coincident values of decay to 405 km in 90 days. This analysis suggests that the simple orbital decay model [Eq. (14) using the average global density] is a good approximation for the ISS orbital decay.

The 100-day ISS orbital decay from initial altitudes of 400 and 450 km was computed using the simple orbital decay model [Eq. (14)] with inputs to the MET model of the 81-day prior-average solar flux, daily solar flux, and a_p at 6 h prior to the time of computation to compute the global maximum and minimum exospheric temperature [Eqs. (5) and (6)], and then the global average density was computed [Eq. (7)]. The results are shown in Fig. 12 (solid lines) for the years 1948 to 1994. In a similar manner, the 13-month smoothed solar flux and 13-month smoothed a_p were used in the MET model to compute the global average density. The daily solar flux was set equal to the 13-month smoothed solar flux. These results for 100 days' decay are shown as dots in Fig. 12. For initial altitudes of 400 and 450 km, there is good agreement between the two MET model inputs (81-day prior and 13-month smoothed) to the simple orbital decay model. For solar cycle 19 and an initial altitude of 400 km, the orbital decay in 100 days is so large that there is a risk indicated that the ISS will re-enter during high solar activity unless reboosted. In contrast, the orbital decay during low solar activity for the initial altitude of 400 km is approximately 10 km in 100 days. The variation in orbital decay for various initial altitudes and durations is an important consideration in planning reboost strategies for the ISS.

The ISS assembly is to be completed in the year 2002. Assuming that solar cycle 23 began near midyear 1996 places part of the ISS assembly period near the peak of the cycle when solar activity effects on orbital decay could be significant.

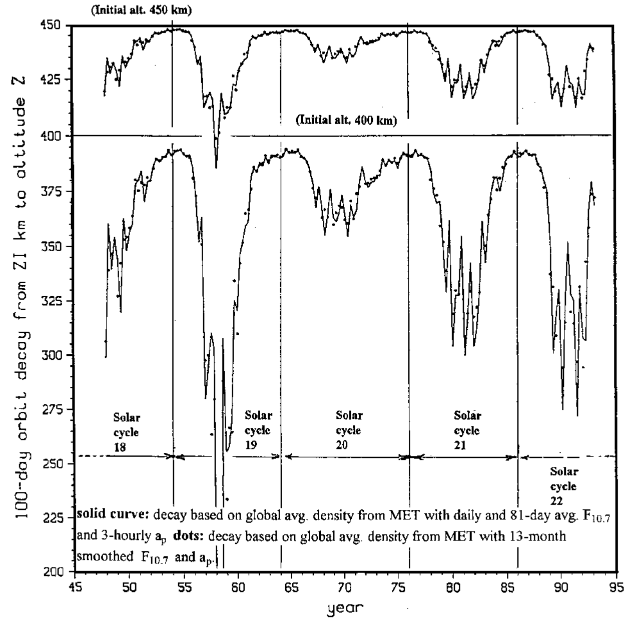


Fig. 12 ISS altitude after 100 days of orbital decay from initial altitudes of 400 and 450 km.

Appendix: Mass Density vs Altitude and Exospheric Temperature

Table A1 MET model neutral mass density (kg/m^3) as a function of altitude and exospheric temperature

	Total density, kg/m^3, at exospheric temperature, K:								
z, km	600	800	1000	1200	1400	1600	1800	2000	2200
250	0.18483E-10	0.44060E-10	0.73248E-10	0.10047E-09	0.12326E-09	0.14131E-09	0.15528E-09	0.16607E-09	0.17454E-09
260	0.13158E-10	0.33150E-10	0.57155E-10	0.80505E-10	0.10075E-09	0.11726E-09	0.13035E-09	0.14068E-09	0.14889E-09
270	0.94599E-11	0.25175E-10	0.44972E-10	0.65006E-10	0.82965E-10	0.98035E-10	0.11028E-09	0.12013E-09	0.12810E-09
280	0.68587E-11	0.19279E-10	0.35654E-10	0.52856E-10	0.68775E-10	0.82503E-10	0.93924E-10	0.10330E-09	0.11100E-09
290	0.50090E-11	0.14875E-10	0.28461E-10	0.43246E-10	0.57348E-10	0.69832E-10	0.80455E-10	0.89343E-10	0.96764E-10
300	0.36812E-11	0.11553E-10	0.22861E-10	0.35584E-10	0.48074E-10	0.59409E-10	0.69265E-10	0.77667E-10	0.84794E-10
310	0.27202E-11	0.90271E-11	0.18466E-10	0.29431E-10	0.40492E-10	0.50771E-10	0.59897E-10	0.67816E-10	0.74637E-10
320	0.20199E-11	0.70906E-11	0.14993E-10	0.24457E-10	0.34254E-10	0.43567E-10	0.52000E-10	0.59445E-10	0.65953E-10
330	0.15064E-11	0.55958E-11	0.12230E-10	0.20412E-10	0.29092E-10	0.37524E-10	0.45305E-10	0.52288E-10	0.58479E-10
340	0.11279E-11	0.44349E-11	0.10019E-10	0.17103E-10	0.24799E-10	0.32429E-10	0.39598E-10	0.46135E-10	0.52009E-10
350	0.84770E-12	0.35281E-11	0.82392E-11	0.14384E-10	0.21211E-10	0.28114E-10	0.34712E-10	0.40820E-10	0.46381E-10
360	0.63945E-12	0.28163E-11	0.67997E-11	0.12138E-10	0.18199E-10	0.24444E-10	0.30511E-10	0.36210E-10	0.41464E-10
370	0.48413E-12	0.22551E-11	0.56298E-11	0.10275E-10	0.15660E-10	0.21309E-10	0.26886E-10	0.32196E-10	0.37151E-10
380	0.36791E-12	0.18108E-11	0.46751E-11	0.87228E-11	0.13513E-10	0.18624E-10	0.23746E-10	0.28689E-10	0.33356E-10
390	0.28069E-12	0.14579E-11	0.38927E-11	0.74252E-11	0.11689E-10	0.16315E-10	0.21019E-10	0.25616E-10	0.30005E-10
400	0.21506E-12	0.11766E-11	0.32494E-11	0.63365E-11	0.10136E-10	0.14324E-10	0.18642E-10	0.22915E-10	0.27039E-10
410	0.16555E-12	0.95181E-12	0.27186E-11	0.54200E-11	0.88081E-11	0.12602E-10	0.16567E-10	0.20536E-10	0.24407E-10
420	0.12808E-12	0.77167E-12	0.22794E-11	0.46460E-11	0.76706E-11	0.11109E-10	0.14749E-10	0.18435E-10	0.22065E-10
430	0.99660E-13	0.62699E-12	0.19150E-11	0.39906E-11	0.66931E-11	0.98110E-11	0.13153E-10	0.16575E-10	0.19978E-10
440	0.78036E-13	0.51052E-12	0.16118E-11	0.34341E-11	0.58509E-11	0.86798E-11	0.11749E-10	0.14925E-10	0.18113E-10
450	0.61535E-13	0.41657E-12	0.13589E-11	0.29604E-11	0.51237E-11	0.76918E-11	0.10512E-10	0.13459E-10	0.16445E-10
460	0.48899E-13	0.34066E-12	0.11477E-11	0.25563E-11	0.44941E-11	0.68270E-11	0.94181E-11	0.12154E-10	0.14949E-10
470	0.39189E-13	0.27921E-12	0.97078E-12	0.22107E-11	0.39480E-11	0.60685E-11	0.84504E-11	0.10989E-10	0.13606E-10
480	0.31695E-13	0.22938E-12	0.82241E-12	0.19147E-11	0.34733E-11	0.54019E-11	0.75922E-11	0.99492E-11	0.12398E-10
490	0.25886E-13	0.18891E-12	0.69774E-12	0.16606E-11	0.30600E-11	0.48150E-11	0.68300E-11	0.90183E-11	0.11311E-10
500	0.21359E-13	0.15598E-12	0.59282E-12	0.14421E-11	0.26993E-11	0.42973E-11	0.61519E-11	0.81840E-11	0.10329E-10

Conclusions

Based on the MET model for estimation of neutral mass density at ISS orbital altitudes for the entire period of record (1947–1994) for the model input variables that produced a calculated maximum value for exospheric temperature of 2152.2 K, the altitude above which the atmospheric-drag acceleration on the ISS would not have exceeded 1 μg is 397 km for no uncertainty in the MET model density and 422 km if the MET model underestimates the density by 20% (the worst-case uncertainty). These altitudes are reduced to 363 km (no uncertainty) and 380 km (worst-case 20% uncertainty) if the maximum exospheric temperature is less than 1700 K. The range of this critical altitude vs exospheric temperature (Fig. 6) for 1 μg has important implications for the ISS planning strategies.

For the ISS orbital decay up to 100 days for initial altitudes at 400 and 450 km, the use of the 13-month smoothed values for the 10.7-cm solar flux and the geomagnetic index a_p produces results that are comparable to those produced by the using the specified inputs to the MET model. For periods of high solar activity, as in solar cycle 19 (Fig. 12), this study suggests that the ISS could reenter the Earth's atmosphere within 100 days from an initial altitude of 400 km if not reboosted.

For development of reboost operational strategies and for real-time operations, the complete MET model with 81-day running means and daily values for 10.7-cm solar flux and 3-h values for a_p are required.

The variation in density within an ISS orbit is important information for the assessment of the capability of the ISS to meet the microgravity-experiment acceleration requirements and requirements for torque and attitude control by the control-moment gyros.

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I. D. Boyd
Associate Editor