NRLMSIS Atmosphere Temperature and Composition Model

- Arguments: Position, time, solar irradiance, geomagnetic activity
- Output: $T(z)$, $T_{ex}$ (K); $N_2$, $O_2$, O, He, H, N, Ar (cm$^{-3}$); $\rho$ (g cm$^{-3}$)
- Physical constraints: Approximate hydrostatic equilibrium; diffusive equilibrium above $\sim$200 km
- Formulation: Bates/spline vertical temperature profile; spherical and temporal harmonic expansion; polynomial in F10.7 and Ap heating function
- Major overhaul in progress

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Space Science Division, Naval Research Lab

Mike Picone
Department of Physics and Astronomy, George Mason University

Acknowledgement: This work was supported by the Chief of Naval Research
NRLMSIS History

- The Mass Spectrometer and Incoherent Scatter radar model (MSIS®) was created in 1977 by Alan Hedin at Goddard Space Flight Center, based in large part on Atmospheric Explorer data.
- It grew out of a 1974 statistical model of Ogo 6 mass spectrometer data.
- MSIS originally represented the upper thermosphere. Upgrades followed:
  - 1983: Rocket data, extended to lower thermosphere
  - 1986: DE-2 data, atomic nitrogen added, expanded formulation
  - 1990: Extended to ground
- After Alan Hedin retired from NASA in 1995, Mike Picone of NRL’s Space Science Division continued development of the model with Alan’s assistance.
- The current version, NRLMSISE-00, added mass density from satellite drag, O₂ data from solar occultation, and a new “anomalous O” species above 500 km.
NRLMSISE-00 Physical Constraints

\[ \ln n_i = \ln n_{i,0} - (1 + \alpha) \ln \frac{T}{T_0} - \frac{m_i g_0}{k} \int_{\zeta_0}^{\zeta} \frac{1}{T(\zeta')} d\zeta' \]

- \( n_i = \) Species number density, \( T = \) Temperature
- \( m_i = \) Species mass, \( \zeta = \) Geopotential height,
- \( \alpha = \) Thermal Diffusion

\[ \ln n = \ln n_0 - \ln \frac{T}{T_0} - \frac{m g_0}{k} \int_{\zeta_0}^{\zeta} \frac{1}{T(\zeta')} d\zeta' \]

- \( n = \) Total number density, \( \bar{m} = \) Mean mass

- Asymptotic temperature profile defined by exospheric temperature
- Fully mixed hydrostatic equilibrium below \( \sim 100 \) km
- Diffusive equilibrium (\( \sim \)species hydrostatic equilibrium ) above \( \sim 200 \) km
- Approximate hydrostatic equilibrium between 100 and 200 km
- Temperature profile constructed so that the integral can be computed in closed-form
NRLMSISE-00 Formulation

- **Vertical temperature profile (17 parameters)**
  - Cubic splines in $1/T$ below 120 km (14 parameters)
  - Bates profile above 120 km ($T_{ex}, T_{120}, \sigma$)

- **Species density parameters (8 per species)**
  - Reference density (1)
  - Mixing ratio relative to $N_2$ (1)
  - Turbopause height (1)
  - Corrections for dynamic flow and chemistry (5)

- **Expansion of vertical parameters (up to ~140 per param.)**
  - Associated Legendre fns in latitude (up to degree 6)
  - Polynomials in daily and 81-day average solar activity ($F10.7$) up to order 2
  - Intra-annual harmonics up to semiannual
  - Local time harmonics up to terdiurnal (migrating tides)
  - Time history of geomagnetic activity (ap index) via heating function
  - Longitude harmonics up to order 1
  - Universal Time harmonics up to order 1

- **Total number of nonzero model parameters:** ~1280

- **Limitation:** Important nonmigrating tides not included – use CTMT

\[
T_{ex} - (T_{ex} - T_{120}) \exp\left[-\sigma (\zeta - \zeta_{120})\right]
\]
\[
\sigma = T'_{120} / (T_{ex} - T_{120}) \quad \text{Shape factor}
\]
NRLMSIS Data

New Data for NRLMSIS-17:
Orbit, accelerometer, ISR, and:

Satellite Drag:
Orbit-derived, accelerometer ($\rho$)

Altitude (km)


Mass Spectrometer ($T, n_i$)

Incoherent Scatter Radar ($T$)

Occultation ($O_2$)

MAP tables (~CIRA-86)

ISR ($T$)

Occultation ($T$)

ISR ($T$)

Reanalysis ($T, P$)

Ultraviolet ($T, n_i$)

Microwave ($T$)

Infrared ($T, n_i$)

Lidar ($T$)
## NRLMSISE-00 Operation

GTD7 - Gets Temperature and Density:

\[
\text{GTD7}(\text{IYD}, \text{SEC}, \text{ALT}, \text{GLAT}, \text{GLONG}, \text{STL}, \text{F107A}, \text{F107}, \text{AP}, \text{MASS}, \text{D}, \text{T})
\]

### Input:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>IYD</td>
<td>YEAR AND DAY AS YYDDD (day of year from 1 to 365 or 366; year ignored)</td>
</tr>
<tr>
<td>SEC</td>
<td>UNIVERSAL TIME (s); should be consistent with GLONG and STL</td>
</tr>
<tr>
<td>ALT</td>
<td>GEODETIC ALTITUDE (km)</td>
</tr>
<tr>
<td>GLAT</td>
<td>GEODETIC LATITUDE (degrees)</td>
</tr>
<tr>
<td>GLONG</td>
<td>GEODETIC LONGITUDE (degrees)</td>
</tr>
<tr>
<td>STL</td>
<td>LOCAL APPARENT SOLAR TIME (hours)</td>
</tr>
<tr>
<td>F107A</td>
<td>81 day AVERAGE OF F10.7 FLUX (centered on day DDD)</td>
</tr>
<tr>
<td>F107</td>
<td>DAILY F10.7 FLUX FOR PREVIOUS DAY</td>
</tr>
<tr>
<td>AP</td>
<td>7-element array: Daily Ap, ap(t), ap(t-3h), ap(t-6h), ap(t-9h), Ap(12-33h), Ap(36-57h) First element used when SW(9) = 1, all elements used when SW(9) = -1</td>
</tr>
<tr>
<td>MASS</td>
<td>MASS NUMBER; 48 for all, 0, for temperature, 1 for H, 2 for He, 14 for N, etc.</td>
</tr>
</tbody>
</table>

### Output:

<table>
<thead>
<tr>
<th>D = Number Density (cm(^{-3}))</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>He</td>
<td>He</td>
<td>O</td>
<td>N(_2)</td>
<td>O(_2)</td>
<td>Ar</td>
<td>(\rho)</td>
<td>H</td>
<td>N</td>
<td>Hot O</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>T = Temperature</th>
<th>(T_{\text{ex}})</th>
<th>T(z)</th>
</tr>
</thead>
</table>

\(\rho\) in g/cm\(^3\)
**NRLMSISE-00 Operation**

**GHP7** -- Gets height of specified pressure level:  
**GHP7**(IYD, SEC, ALT, GLAT, GLONG, STL, F107A, F107, AP, D, T, PRESS)  

**TSELEC** – Sets model switches: 0 = off, 1 = on, 2 = main effects off but cross terms on  
**TSELEC**(SW)

<table>
<thead>
<tr>
<th>Expansion Parameters</th>
<th>Vertical Profile Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>SW(1) Solar activity (F10.7)</td>
<td>SW(15) Departures from diffusive equilibrium</td>
</tr>
<tr>
<td>SW(2) Latitude dependence</td>
<td>SW(16) All $T_{ex}$ variations</td>
</tr>
<tr>
<td>SW(3) Hemispherically symmetric annual oscill.</td>
<td>SW(17) All $T$ variations at 120 km</td>
</tr>
<tr>
<td>SW(4) Symmetric semiannual</td>
<td>SW(18) All $T$ variations between 72.5 and 120 km</td>
</tr>
<tr>
<td>SW(5) Asymmetric annual (seasonal)</td>
<td>SW(19) All shape factor $(\sigma)$ variations</td>
</tr>
<tr>
<td>SW(6) Asymmetric semiannual</td>
<td>SW(20) All $T$ variations between 32.5 and 72.5</td>
</tr>
<tr>
<td>SW(7) Diurnal oscillations</td>
<td>SW(21) All species density variations at 120 km</td>
</tr>
<tr>
<td>SW(8) Semidiurnal oscillations</td>
<td>SW(22) All $T$ variations between 0 and 32.5 km</td>
</tr>
<tr>
<td>SW(9) Magnetic Activity (-1 for storm mode)</td>
<td>SW(23) All turbopause scale height variations</td>
</tr>
<tr>
<td>SW(10) All UT/Longitude</td>
<td>SW(24) Not used</td>
</tr>
<tr>
<td>SW(11) Longitude terms</td>
<td>SW(25) Not used</td>
</tr>
<tr>
<td>SW(12) UT and mixed UT/Longitude</td>
<td></td>
</tr>
<tr>
<td>SW(13) Mixed Ap/UT/Longitude</td>
<td></td>
</tr>
<tr>
<td>SW(14) Terdiurnal oscillations</td>
<td></td>
</tr>
</tbody>
</table>
## Other Thermosphere Temperature and Density Models

<table>
<thead>
<tr>
<th></th>
<th>NRLMSISE-00</th>
<th>DTM-2015</th>
<th>JB2008</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reference</strong></td>
<td>Picone et al., 2002</td>
<td>Bruinsma, 2015</td>
<td>Bowman et al., 2008</td>
</tr>
<tr>
<td><strong>Lower Boundary</strong></td>
<td>0 km</td>
<td>120 km</td>
<td>90 km</td>
</tr>
<tr>
<td><strong>Mesopause Density and Temperature</strong></td>
<td>Variable</td>
<td>Variable at 120 km</td>
<td>Fixed</td>
</tr>
<tr>
<td><strong>Temperature Profile</strong></td>
<td>Bates exponential profile above 120 km. Cubic splines below 120 km.</td>
<td>Bates exponential profile.</td>
<td>Arctangent above 125 km, plus height-dependent local time and latitude corrections to $T_{ex}$. Polynomial below 125 km.</td>
</tr>
<tr>
<td><strong>Solar Activity Variation</strong></td>
<td>Temperature and density parameters depend quadratically on $F_{10.7}$*</td>
<td>Temperature and density parameters depend quadratically on $F_{30*}$ the solar radio flux at 30 cm. wavelength</td>
<td>$T_{ex}$ is linear function of 4 solar indices.</td>
</tr>
<tr>
<td><strong>Local Time &amp; Latitude Variation</strong></td>
<td>Spherical harmonics (up to terdiurnal and latitudinal order 6) of temperature and density parameters, modulated by $F_{10.7}$*</td>
<td>Spherical harmonics (up to terdiurnal and latitudinal order 6) of temperature and density parameters, modulated by $F_{30*}$</td>
<td>Trigonometric function of local time, latitude, and solar declination applied to $T_{ex}$ only, plus a correction above 200 km dependent on local time, height, latitude, and $F_{10.7*}$.</td>
</tr>
<tr>
<td><strong>Intra-annual Variation</strong></td>
<td>Annual and semiannual harmonics of temperature and density parameters, modulated by latitude (up to order 3). No explicit dependence on solar activity.</td>
<td>Annual and semiannual harmonics of temperature and density parameters, modulated by latitude (up to order 5), local time, and $F_{30*}$</td>
<td>Mass density variation only; annual and semiannual harmonics, with net amplitude dependent on altitude (quadratic polynomial) and modulated by three solar indices.</td>
</tr>
<tr>
<td><strong>Geomagnetic Activity Variation</strong></td>
<td>Temperature and density parameters are a function of either 3-hr ap history or daily Ap. Modulated by latitude and UT.</td>
<td>Parameters are a quadratic (density) or linear (temperature) function of the km index, modulated by latitude.</td>
<td>$T_{ex}$ is a nonlinear function of the Dst history during storms, and of the 3-hr ap when a storm is not detected in Dst.</td>
</tr>
<tr>
<td><strong>Longitude/UT Variation</strong></td>
<td>Spherical harmonics up to wavenumber 2 in longitude, and diurnal UT terms. Modulated by geomagnetic activity.</td>
<td>None</td>
<td>None</td>
</tr>
</tbody>
</table>

* $F_{10.7}$ is a proxy for solar radio flux at 10.7 cm wavelength.
NRLMSIS Upgrade

- **New Data**
  - NOAA meteorological reanalysis data in the troposphere and stratosphere.
  - Extensive new temperature and composition data in the mesosphere and lower thermosphere (incl. TIMED/SABER, Aura/MLS, ACE, AIM/Sofie, Odin/OSIRIS, Lidar).
  - Extensive new orbit-derived accelerometer densities, UV remote sensing data, and ground-based FPI temperatures in the thermosphere.

- **Major Changes to Formulation**
  - Seamless transition from fully mixed to species hydrostatic equilibrium using variable effective mass (current model: nonphysical interpolation)
  - O profile: Splines below 80 km, modified Chapman layer near peak, species hydrostatic equilibrium above 200 km.
  - Solar EUV irradiance input (backward compatible with F10.7).
  - Overhaul of expansion of vertical profile parameters.
  - Use geopotential $\Phi(z,\phi)$ internally (current model uses $\Delta \Phi(z_1,z_2;\phi)$).

- **Progress**
  - New temperature model complete up to 80 km.
  - Full model to be completed in 2017.
NRLMSIS Upgrade: Test fits of O profile
(5° N, Day of year 150)

-- NRLMSISE-00
-- SABER Climatology
-- Fit with MSIS above 120 km, SABER below 80 km

Daytime (14 LT)

Nighttime (2 LT)

Species Hydrostatic Equilibrium with Variable Mass:

Modified Chapman Layer:

Cubic B Splines (decoupled from T)

\[
\ln n = \ln n_0 - \frac{g_0}{k} \int_{\zeta_0}^{\zeta} \frac{M(\zeta')}{T(\zeta')} d\zeta' - \ln \frac{T(\zeta)}{T(\zeta_0)} - C \exp \left[ \frac{-(\zeta - \zeta_C)}{H_C} \right]
\]
NRLMSIS Upgrade: Mesosphere Temperature Residuals

**NRLMSISE-00** vs. **New**

- **75-80 km altitude**

Graphs show temperature residuals over different time periods (LST: 6-12 and 12-18) and geographic latitudes (GLAT: 30-60, 0-30, -30-0, -60-90) for various stations and instruments.

- STA_INST = UARS_HALOE
- STA_INST = TIMED_SABER
- STA_INST = ODIN_OSIRIS
- STA_INST = LO_LIDAR
- STA_INST = FC_LIDAR
- STA_INST = BO_LIDAR
- STA_INST = AURA_MLS
- STA_INST = AN_LiDAR
- STA_INST = AL_LiDAR
- STA_INST = AIM_SOFIE
- STA_INST = ACE_FTS
NRLMSISE-00 Summary

- **Arguments**: Position, time, solar irradiance, geomagnetic activity
- **Output**: $T(z)$, $T_{e_x}$ (K); $N_2$, $O_2$, O, He, H, N, Ar (cm$^{-3}$); $\rho$ (g cm$^{-3}$)
- **Domain**: Ground to exosphere

### Physical constraints:
- Asymptotic exospheric temperature
- Approximate Hydrostatic equilibrium
- Diffusive equilibrium above ~200 km

### Data:
- Thermosphere: Mass spectrometers, incoherent scatter radars, accelerometers, orbit-derived mass density, solar occultation spectra
- Troposphere, stratosphere, mesosphere: Rocket-based measurements, tabulated lower atmospheric climatology

### Formulation:
- Bates/spline vertical temperature profile
- Spherical and temporal harmonic expansion
- Polynomial in $F_{10.7}$ and $Ap$ heating function

### Major overhaul in progress:
- Extensive new data
- New formulation, including seamless transition from mixed to diffusive separation
- Temperature model complete up to 80 km; full model expected 2017