UPPER ATMOSPHERIC DENSITIES DERIVED FROM STARSHINE SPACECRAFT ORBITS

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- Motivation - \textit{improved density model for orbit tracking}
- Starshine Orbits - \textit{cycle 23 max}
- Spacecraft Drag - \textit{independent data for model validation}
- Starshine vs NRLMSIS – \textit{model density comparison}
drag acceleration = 0.5 \( \rho \ v^2 \ C_d \ A \ M \)

\( \rho \) atmospheric density
\( v \) velocity relative to local environment
\( C_d \) drag coefficient, \( M \) mass
\( A \) cross sectional area perpendicular to velocity vector

three Starshine Spacecraft with spherical geometry and known mass have been launched into circular low-Earth orbits

9,000 resident space objects larger than 15 cm

Knowles et al., GRL, 1999
### Properties of Starshine Spacecraft

<table>
<thead>
<tr>
<th>Starshine Spacecraft</th>
<th>Launch Date</th>
<th>Re-entry Date</th>
<th>Initial Altitude (km)</th>
<th>Eccentricity</th>
<th>Inclination (degree)</th>
<th>Mass (kg)</th>
<th>Diameter (cm)</th>
<th>$C_D$</th>
<th>Inverse Ballistic Coefficient (cm² gm⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1999-05-27</td>
<td>2000-02-18</td>
<td>385</td>
<td>0.001</td>
<td>51.6</td>
<td>39</td>
<td>48 (19”)</td>
<td>2.1</td>
<td>0.097</td>
</tr>
<tr>
<td>2</td>
<td>2001-12-05</td>
<td>2002-05-01</td>
<td>370</td>
<td>0.002</td>
<td>51.6</td>
<td>38</td>
<td>48 (19”)</td>
<td>2.1</td>
<td>0.100</td>
</tr>
<tr>
<td>3</td>
<td>2001-09-29</td>
<td>2003-01-21</td>
<td>475</td>
<td>0.001</td>
<td>67</td>
<td>90</td>
<td>94 (37”)</td>
<td>2.1</td>
<td>0.162</td>
</tr>
</tbody>
</table>

*Graph showing variations in $F_{10.7}$ and $A_p$. Note: $F_{10.7}$ and $A_p$ are indices used in solar-terrestrial relations.*
Solar Activity Alters Temperature and Composition at Starshine Altitudes

**Temperature**

**Primary Constituents**

- **solar min – dashed**
  \[ F_{10.7} = 70, \langle F_{10.7} \rangle_{81} = 70, Ap = 11 \]

- **solar max - solid**
  \[ F_{10.7} = 200, \langle F_{10.7} \rangle_{81} = 174, Ap = 11 \]
Starshine Two Line Element Sets

USSPACECOM orbit parameters derived from General Perturbation theory:

six Kozai mean elements
  • inclination
  • right ascension of ascending node
  • argument of perigee
  • eccentricity
  • mean motion
  • mean anomaly
  plus drag (Bstar)

provided by Dr T. Kelso, http://www.celestrak.com
Atmospheric Density Derived from TLEs

instantaneous change in mean motion with time

\[ dn = \frac{3}{2} n^{1/3} \mu^{-2/3} BF \rho v^3 dt \]

change in mean motion between two successive TLE epochs

\[ n_2 - n_1 \approx \frac{3}{2} n_E^{1/3} \mu^{-2/3} B \rho_E \int F v^3 dt \]

density average between two successive TLE epochs

\[ \rho_E = \frac{2/3 (n_2 - n_1)}{B n_E^{1/3}} \frac{\mu^{2/3}}{\int F v^3 dt} \]

where \( \rho_E \) and \( n_E \) are effective values between two successive TLE epochs:

\[ \rho_E = \frac{\int F \rho v^3 dt}{\int F v^3 dt} \]

\( n = \text{mean motion}, \quad t = \text{time} \)

\( \rho = \text{mass density} \)

\( B = \text{inverse ballistic coeff} = C_d A/M \)

\( \mu = GM, \text{gravitational parameter} \)

\( v = \text{spacecraft velocity} \)

\( F = \text{wind factor} \approx \left(1 - \frac{r \omega}{v} \cos(i)\right)^2 \)
Starshine Orbits are Assumed Circular

for circular orbits

\[
\int Fv^3 \, dt = Fv^3 (t_2 - t_1)
\]

density at TLE epoch

\[
\rho \approx \frac{2}{3} \frac{dn}{dt} \frac{\mu^{2/3}}{Bn^{1/3} v^3 F}
\]

height and speed are approximately constant during Starshine orbits so

\[
\int Fv^3 \, dt \approx Fv^3 (t_2 - t_1)
\]
Quantities for Drag Calculations

Quantities obtained from TLE’s directly:

- Mean Motion
- Derivative of Mean Motion
- Speed
- Atmospheric Wind Factor

Quantities obtained from SPG4 with TLE inputs:

- Mean Motion
- Derivative of Mean Motion
- Speed

Quantities obtained from SPG4 and TLE’s:

- Mean Motion
- Derivative of Mean Motion
- Speed
- Atmospheric Wind Factor
Total Mass Densities Derived from Drag on Starshine Spacecraft

- **a. Altitude**
- **b. Density**

**Starshine 1**

- Day after 19990101

**Starshine 2**

- Day after 20010101

**Starshine 3**

- Day after 20010101

Graphs showing changes in altitude and density over time for each Starshine spacecraft.

Densities from Starshine drag:
- higher than USSA76 at altitudes above 200 km
- lower than USSA76 at altitudes below 200 km

Starshine 1, 2, & 3 orbits occurred during overall high solar activity
NRL’s Time-Dependent Upper Atmosphere Density Specification Model

calculates upper atmosphere total mass density, composition and temperature, for specified altitude, latitude, longitude, local time, day of year and solar activity

NRLMSIS-00
Naval Research Laboratory
Mass Spectrometer and Incoherent Scatter Model (2000)

- enhanced, revised model within MSIS framework
- extended database for model formulation
  - total mass densities from satellite - excluding Starshine
    accelerometers and orbit determinations
  - temperatures from incoherent scatter radar
  - O₂ densities from solar UV occultation
- solar/geomagnetic inputs
  - F₁₀.₇, F₁₀.₇ A, Ap

Picone et al., Phys. Chem. of Earth, 2000
Comparison of Starshine and NRLMSIS Total Mass Densities

- NRLMSIS model is evaluated around one complete Starshine orbit
- Orbit-average model density is compared with Starshine drag value

Starshine 2 & 3 show similar differences with NRLMSIS
NRLMSIS Total Mass Density Variations During Single Starshine Orbits

Starshine location around orbit input to NRLMSIS model, with specified day-of-year and solar activity
density calculated by NRLMSIS model
when NRLMSIS densities lead Starshine densities, F10.7 coronal index leads chromospheric index (derived from ratios of core-to-wing emission in solar Ca II K and Mg II h&k Fraunhofer lines)

differences between NRLMSIS and Starshine densities track differences between F10.7 and chromospheric indices
Reformulating NRLMSIS Upper Atmosphere Density Model

Current Version: NRLMSIS-00

\(F_{10.7}, [F_{10.7}]_{81}\)  -- proxies for EUV radiation
\(A_P\)  -- proxy for geomagnetic effect of solar wind


Future Version: NRLMSIS-SOLC

\(I_{\text{CHROM}}, [I_{\text{CHROM}}]_{81}\)  -- proxies for EUV radiation
\(A_P\)  -- proxy for geomagnetic effect of solar wind

NRLMSIS has been reformulated using a new solar irradiance index - improvements will be assessed by comparisons with Starshine drag
mass densities at 130-470 km derived from USSPACECOM TLEs along Starshine 1,2,3 orbits

densities have solar EUV induced 27-day variations superimposed on exponential fall-off with altitude

Starshine and NRLMSIS-00 densities agree to within 20%

… differences between chromospheric and $F_{10.7}$ proxies may account for some of the differences

NRLMSIS has been reformulated with a new solar EUV proxy

… NRLMSIS-SOLC

Starshine 4, 5 are in progress

… model validation during 11-year solar cycle
… comparisons with TIMED irradiance & density
Starshine Spacecraft Series

Starshine 1, STS-96, mid-1999, 385 km, 39 kg

Starshine 2, STS-108, Dec 2001, 387 km, 38 kg

Starshine 3, Kodiak, Sept 2001, 471 km, 90 kg

Starshine 4,5, TBD

TIMED: GUVI atmospheric densities
SEE solar EUV irradiances

tracking the 11-year solar activity cycle