ASEN-5519-007,008
Space Weather Overview:
The Thermosphere and Satellite Drag

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Wednesday, March 22nd, 2023
Outline

• Societal Relevance
• The Upper Atmosphere
• Satellite / Atmosphere Interactions
• Measurements of Satellite Drag
• Early and Recent Discoveries
Reentry
Operating in LEO

FEBRUARY 8, 2022

GEOMAGNETIC STORM AND RECENTLY DEPLOYED STARLINK SATELLITES

Loss of VLEO Assets

Day-to-Day Conjunction Assessment
Orbital Crowdedness

LEO Tracked Objects (data from Space-Track.org)

2010

2019

2023
Collisions and the Kepler Syndrome
Atmospheric Layers
By Temperature

Credit: Prölls (2004)
*Physics of the Earth’s Space Environment*
Atmospheric Layers
By Various Phenomena

From Prölss (2004)
*Physics of the Earth’s Space Environment*
Chemical Makeup

**Thermosphere**

\[ H = \frac{kT}{m_i g} \]

**Lower Exosphere**

\[ H = \frac{kT}{m_i g} \]

Credit: Emmert et al., 2020

From Prölls (2004)  
*Physics of the Earth’s Space Environment*
Energy Sources for the I-T

- Electric Fields
  - Joule & Particle Heating
- Upper Atmosphere
- Lower/Middle Atmospheric Waves & Tides
- Magnetosphere
- Solar Wind
- Irradiance
- Heating/Photochemistry

Adapted from Prölss, 2011
Solar Radiation

Credit: Machol et al., 2020
doi: 10.1016/B978-0-12-814327-8.00019-6
Magnetosphere-Ionosphere-Thermosphere System

Adapted from Potemra, 1983
Solar Wind and Magnetic Clouds

![Diagram showing plasma density and radial velocity](image)
Current Closure in the Ionosphere

Credit: Le et al., 2010. doi: 10.1029/2009JA014979
Waves and Tides

Credit: ARISE Project
Infrared Cooling of the Thermosphere

\[
\begin{align*}
\text{NO} & \rightarrow 5.3 \, \mu m \\
\text{CO}_2 & \rightarrow 15 \, \mu m \\
\text{O}^{(3P)} & \rightarrow 63 \, \mu m
\end{align*}
\]
WACCM-X Movie
St. Patrick’s Day Storm, 2015

Credit: WACCM-X Team, NCAR
Visualization: Eelco Doornbos
Non-Conservative Accelerations
Contributions vs. Altitude

Drag Acceleration:
\[ \mathbf{a}_D = -\frac{1}{2} \frac{c_D A_{proj}}{m} \rho |\mathbf{v}_{rel}|^2 \mathbf{v}_{rel} \]

Solar Radiation Pressure (SRP) Acceleration:
\[ \mathbf{a}_{SRP} = -\frac{R A \cos(\phi_{inc})}{m c} \times \left( 2 \left( \frac{c_{rd}}{3} + c_{rs} \cos(\phi_{inc}) \right) \mathbf{n} + (1 - c_{rs}) \mathbf{s} \right) \]

While SRP\(^1\) is larger in magnitude, aerodynamic drag is the most variable force and the primary contribution to orbit errors.

Drag is the dominant non-conservative force.
Drag Coefficient Sensitivities

Thermal to bulk velocity ratio

Energy exchange with surface (Energy-Accommodation)

Spacecraft velocity

Composition

Attitude

Shape

L / D = 3 unless otherwise stated

Credit: Marcin Pilinski
Satellite Drag Measurements

**Traditional:** e.g., Ground-Based Satellite/Object Tracking

**Dedicated NASA Missions:**
e.g., GOLD O/N₂ & Temperatures, CHAMP/GRACE/GOCE densities

**Signals of Opportunity:**
e.g., New Constellations of GNSS-Equipped Small-Sats and CubeSats
High-Precision Accelerometers

Total mass density derived from measurements of satellite acceleration

Recent Satellite Missions:
- GRACE (2002 – present)
- GOCE (2009 – 2012)
- Swarm (2014 – present, degraded)
- GRACE-FO (2018 – present)
Mass Spectrometers

Satellite Missions:
- OGO-6 (1969 – 1971)
- MAVEN (2015 – present)
- GDC mission in development (x6 sats)

Provides densities of individual components (e.g. O₂, O, N₂, He, Ar).

Scanning of various mass-to-charge ratios is done by holding ω constant, and sweeping through V while U is kept as a constant fraction of V.

AE+D OSS Concentrations, 31 Oct. 1975, ~0 UT, ~11:30/23:30 LT

Closed-Source Mass Spectrometer
Remote Sensing of FUV

Provide daytime measurements of:
- $\Sigma O/N_2$: Ratio of column-integrated atomic oxygen to molecular nitrogen content
- Column-integrated temperature

Satellite Missions:
- TIMED/GUVI (2001 – present)
- DMSP/SSUSI (2003 – present)
- GOLD (2018 – present)
Constraining Models

High-Accuracy Satellite Drag Model (HASDM)

Feedback loop performed using ~75-90 “Calibration Satellites”

- Estimate Spherical Harmonic Corrections to Temperature
- Compare Predicted Ephemeris with Observations
- Observed Satellite Ephemeris: $t = \text{now} - \Delta t$
- Semi-Empirical Thermosphere Model
- Satellite Force Model
- Satellite Orbit Propagator
- Satellite Ephemeris: $t = \text{now}$
- Initial condition
- Solar/Geophysical Drivers
- Update

Example:
- Adjusted/unadjusted model vs. observations for several orbits
- Day 300, 2003
- Approx. altitude = 400 km
- Note: these observations are measured by a satellite accelerometer -- data from the normal “calibration satellites” is much less frequent (i.e. 1 per several orbits to 1 per day)
Early Discoveries:
Solar Flux Signatures

Credit: Jacchia and Slowey, 1972
Early Discoveries:

Geomagnetic Influences

More recently, from the CHAMP Satellite

Credit: Jacchia, 1959

Credit: Sutton, 2008
Early Discoveries:
Annual / Semi-Annual Variation

Paetzold and Zschorner, 1961

Jacchia and Slowey, 1972
Seasonal Dependencies

Composition

Credit: Qian et al., 2022
High-Speed SW Streams and Co-Rotating Interaction Regions (CIRs)

Credit: Thayer et al., 2008
CO₂ Cooling

Credit: Emmert, 2015

Credit: Roble and Dickinson, 1989
Traveling Atmospheric Disturbances

Credit: Bruinsma and Forbes, 2007
doi: 10.1029/2007GL030243
Helium Winter Bulge

Over an order of magnitude @ 300 km

Credit: Cageao & Kerr, 1984 – AE-D Satellite

Credit: Sutton et al., 2015