Satellite Drag:
Thermosphere Observational Gaps

Eric Sutton
Senior Research Associate
Space Weather Technology, Research & Education Center (SWx TREC)
University of Colorado at Boulder

Grand Challenge
UNIVERSITY OF COLORADO **BOULDER**
SPACE WEATHER CENTER

SWx TREC

Orbiting Objects and Space Debris

We have launched, tracked, and cataloged over 45,000 objects in orbit around the Earth to date

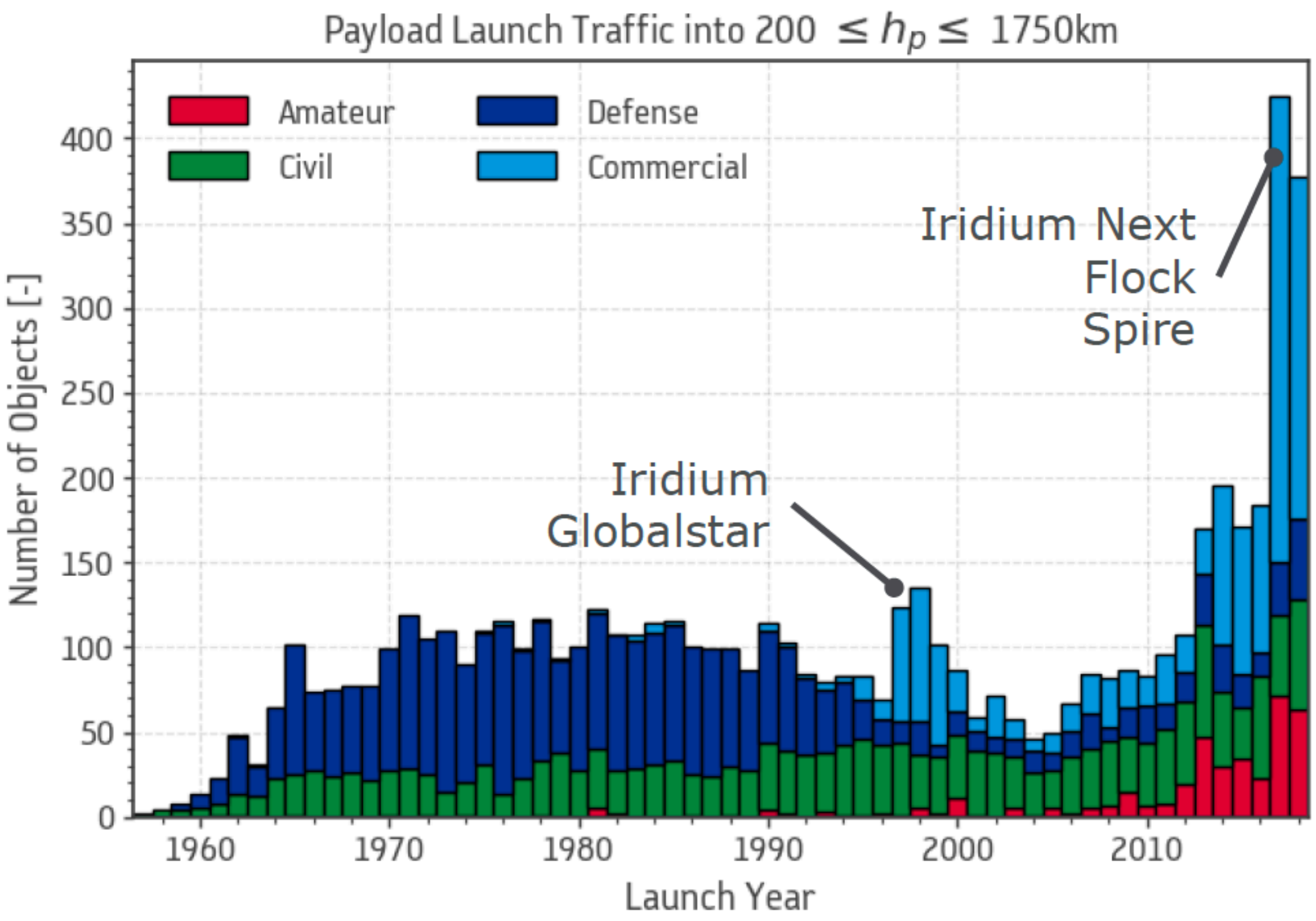
While many of these orbits have decayed, we currently track just over 20,000 objects in orbit around the Earth

Most of these, about 85%, reside in or transit Low-Earth Orbit (LEO, i.e., anything below 2,000 km)

These numbers continue to grow, on average, as we launch more and more satellite and improve tracking abilities

Payloads Launched into LEO

- Steady growth in the number of payloads launched over the last decade
- Commercial and Amateur show a marked uptick in 2017-2018
- Larger-satellite constellations such as the ~600 SpaceX/Starlink satellites now in orbit are not yet captured in this graphic

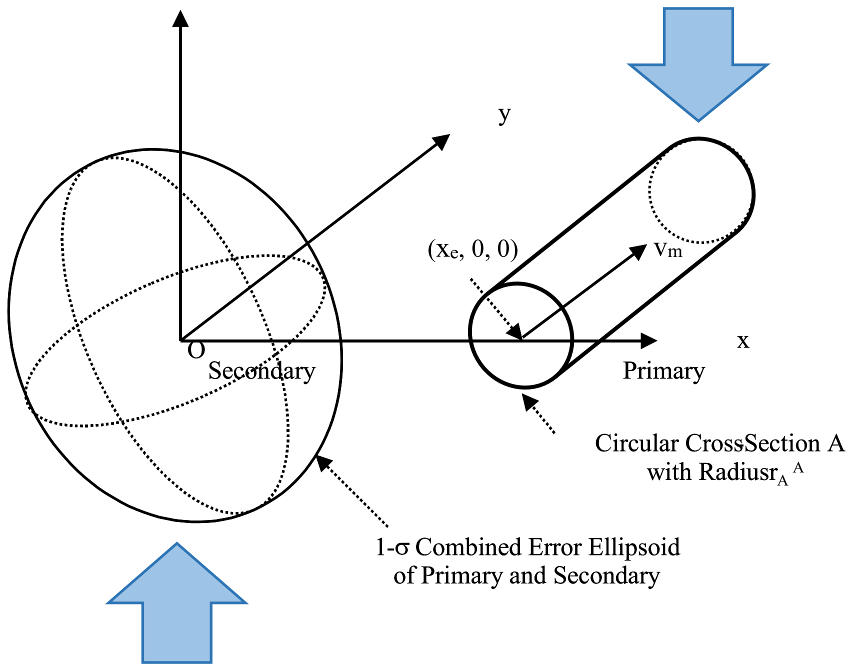


Credit: ESA Space Debris Office

LEO: On-Orbit Collisions

Collision Probability

10cm to few meters



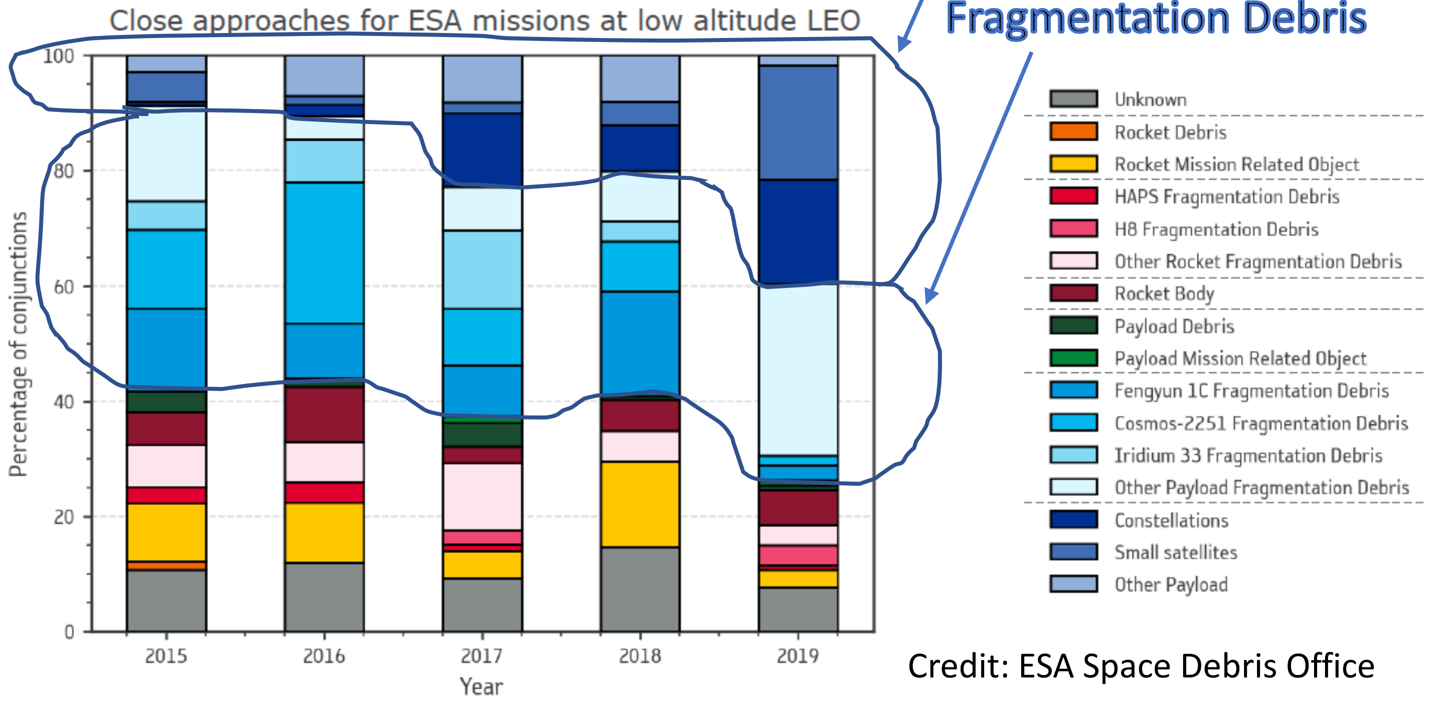
100's of meters to few km

$$Pc = \iiint_V \frac{1}{\sqrt{(2\pi)^3 |C|}} e^{-\frac{1}{2}\mathbf{r}^T C^{-1}\mathbf{r}} dx\,dy\,dz$$

Credit: Cerven (2015)

Constellations/SmallSats

Fragmentation Debris

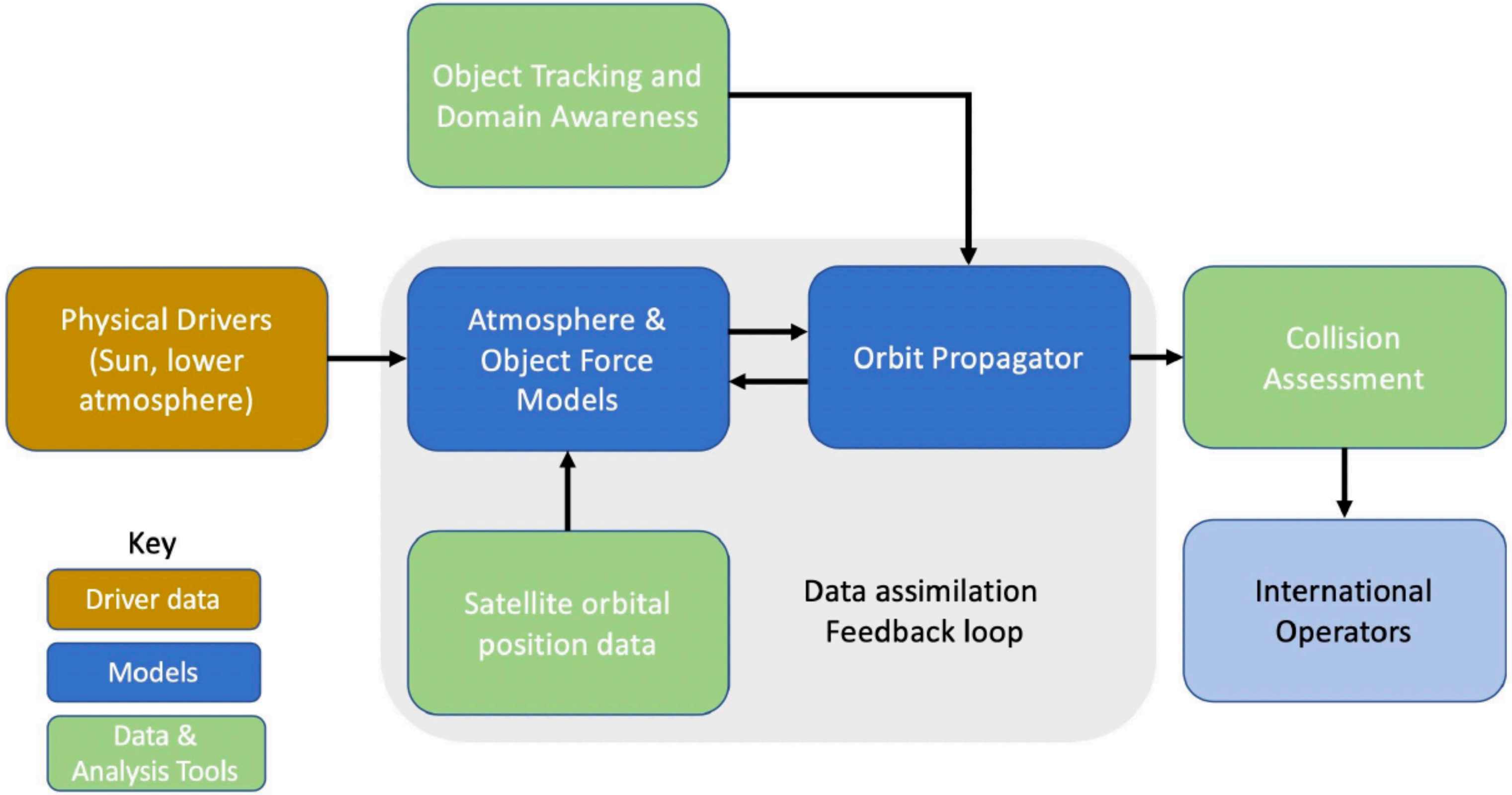


Credit: ESA Space Debris Office

Space Traffic Management in LEO

Infrastructure required for STM in LEO

- Some form of these components currently exist within the DOD
- In order to keep up with evolving requirements, most components will need updating…
- …and additional components will need to be added



The Dynamic LEO Environment

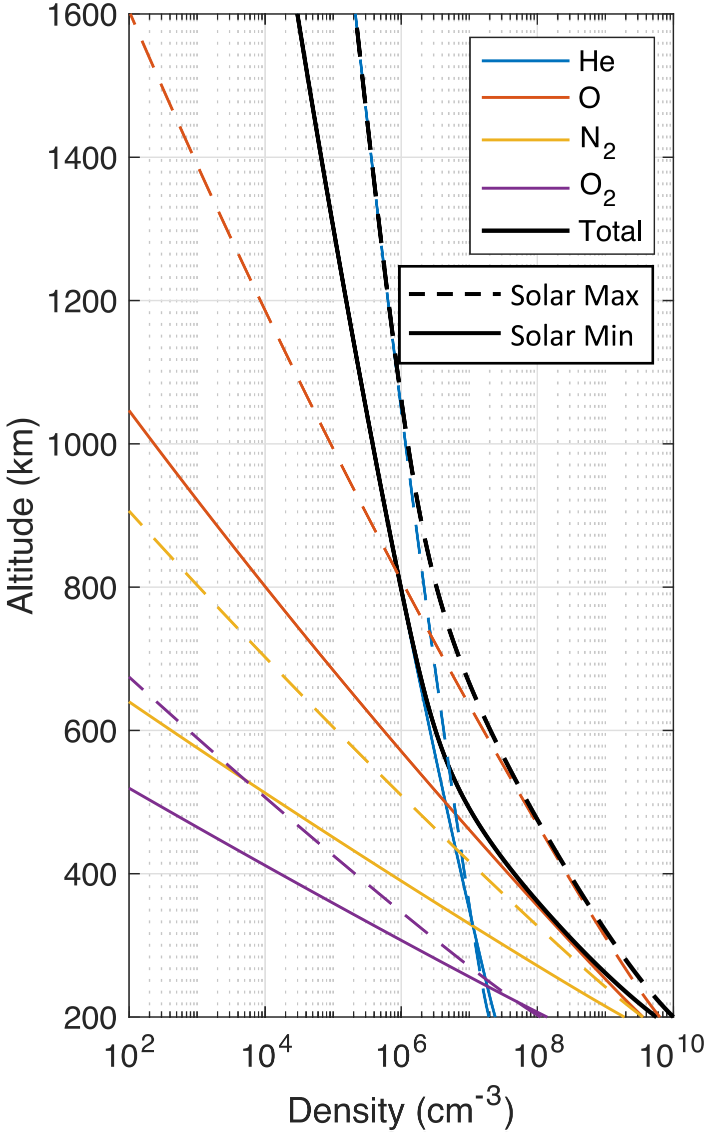
While SRP[1] is larger in magnitude, aerodynamic drag is the most variable force and the primary contribution to orbit errors

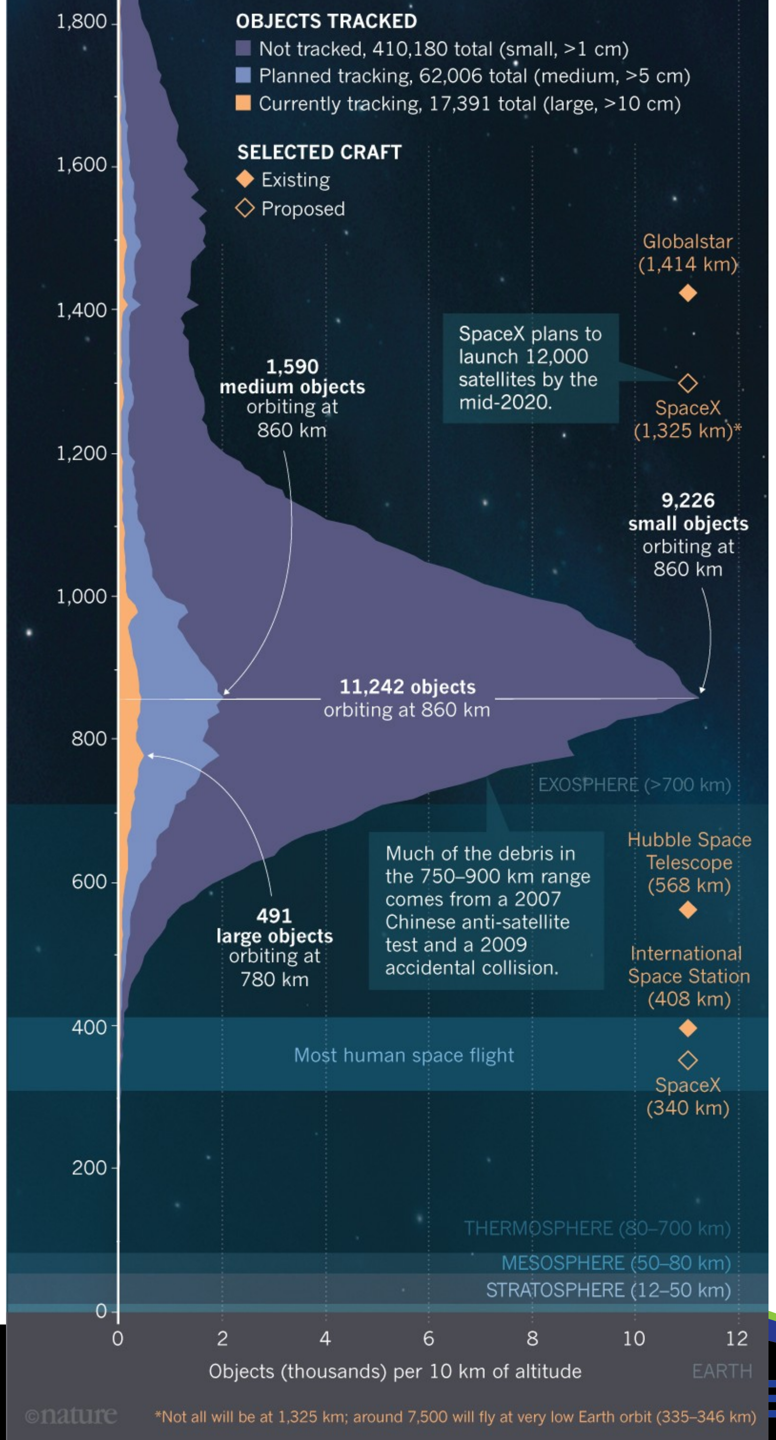
Drag is the dominant non-conservative force

free-molecular flow

composition and temp. drives gradual changes in C_D

re-entry, extreme C_D variability

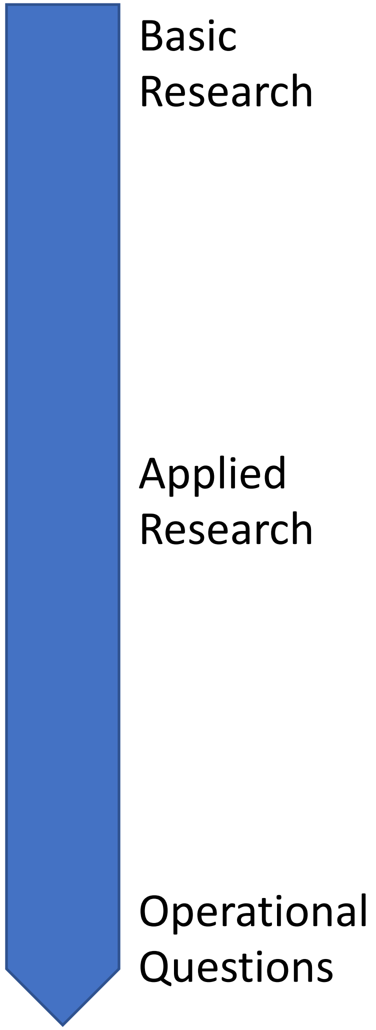




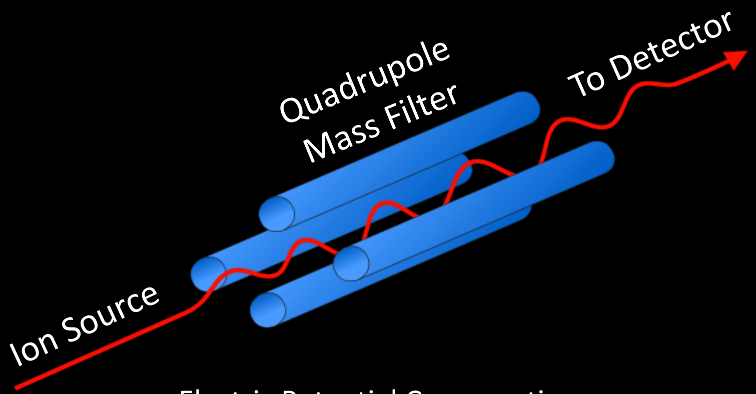
Open Questions in Thermosphere Research & Operations:

*not an exhaustive list

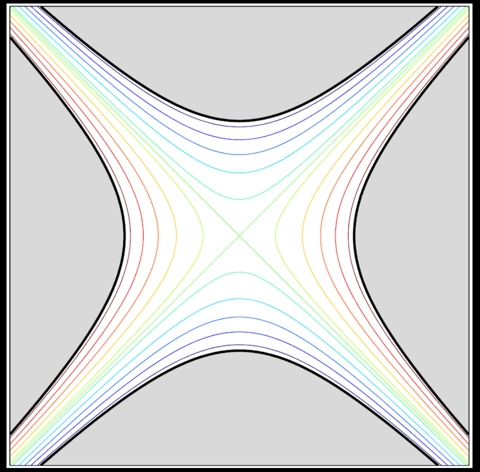
- How does the thermosphere transport and mediate energy from above and below?
- What are the mechanisms of mass transport?
- How does composition respond to variable energy sources?
- How does mass density respond to variable energy sources?
- How do neutral and plasma components interact?
- What is the average global distribution of density vs. location, local time, season, geophysical condition, phase in the solar cycle?
- How do variations in density influence the motion of orbiting objects?
- How can we nowcast mass density and forecast 18–72 hours in advance?
- What uncertainties to orbital motion and collision probabilities are imparted by geospace variability?



Data: Satellite In Situ Measurements
Mass Spectrometers



Electric Potential Cross-section

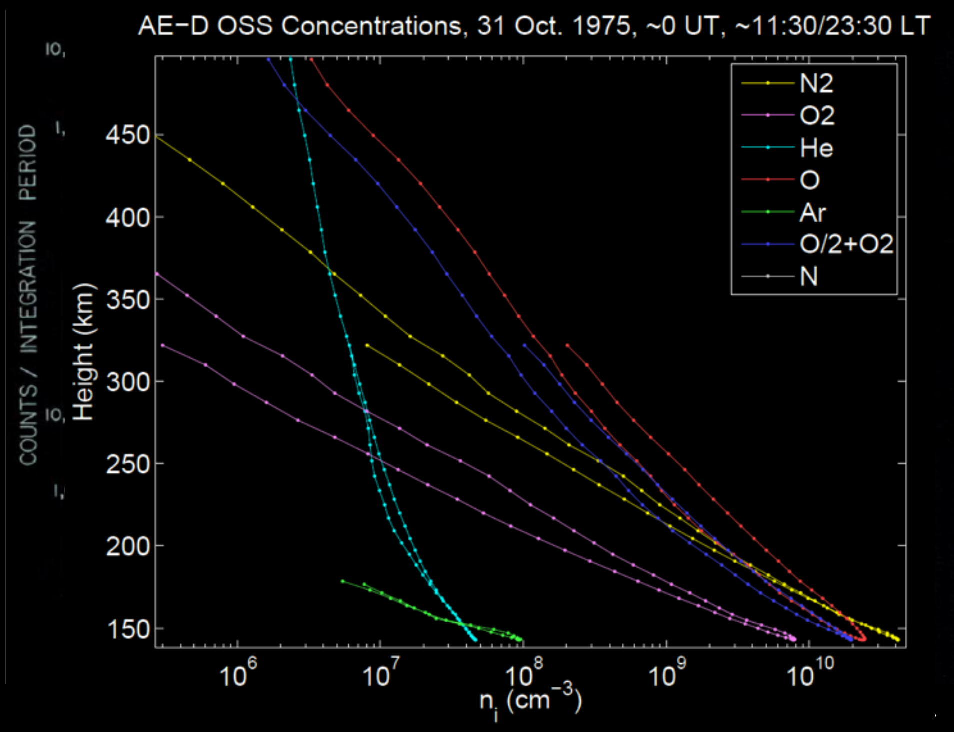


$$\phi = U + V\cos\omega t$$

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

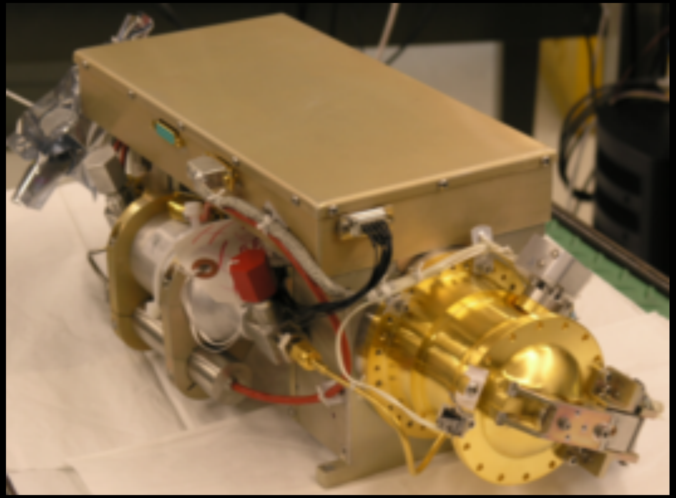
Satellite Missions:

- OGO-6 (1969 – 1971)
- AE-C, -D, and -E (1973 – 1981)
- DE-2 (1981 – 1983)
- Cassini (1997 – 2017)
- MAVEN (2015 – present)
- Very few at Earth since the ‘80s



Provides the densities of individual components (e.g. O_2, O, N_2, He, Ar).

Closed-Source Mass Spectrometer now in storage at AFRL



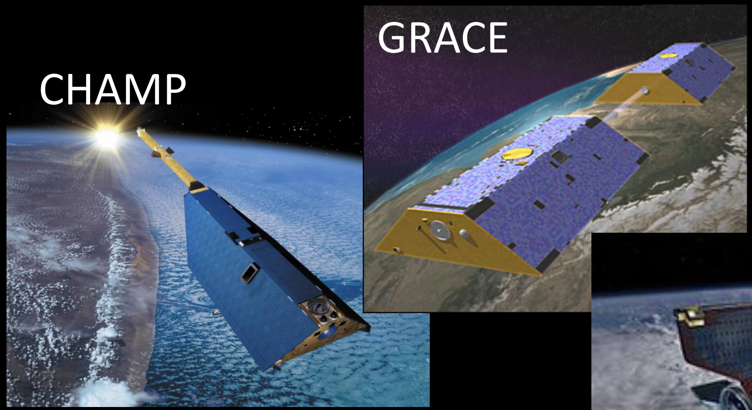
Grand Challenge
UNIVERSITY OF COLORADO BOULDER
SPACE WEATHER CENTER

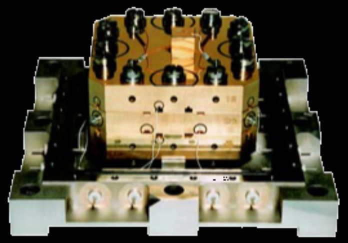
SWx TREC

Data: Satellite In Situ Measurements
Accelerometers

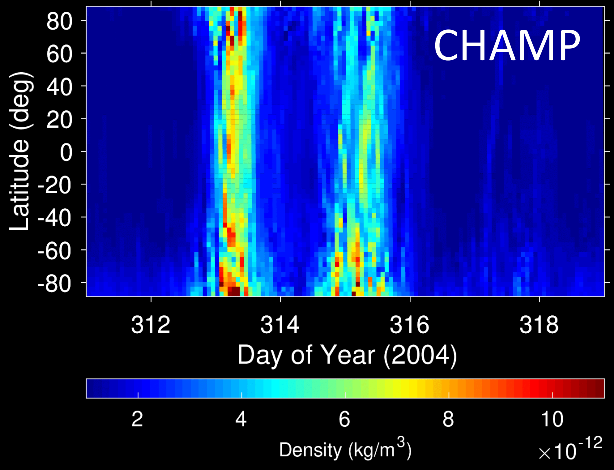
Total mass density derived from measurements of satellite acceleration

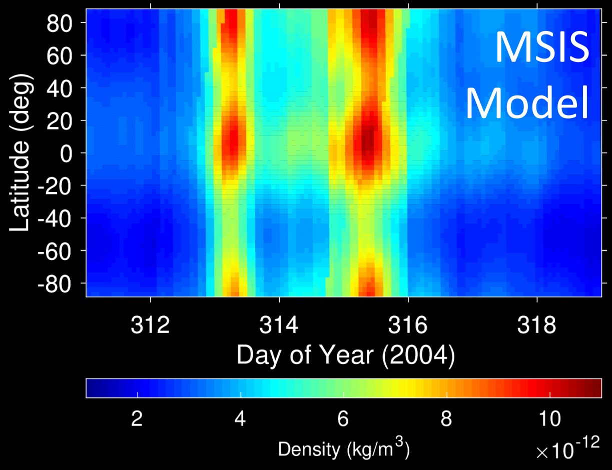
Recent Satellite Missions:
- CHAMP (2001 – 2010)
- GRACE (2002 – present)
- GOCE (2009 – 2012)
- Swarm (2014 – present, degraded)
- GRACE-FO (2018 – present)





High-Precision (~1 nano-G) Accelerometer





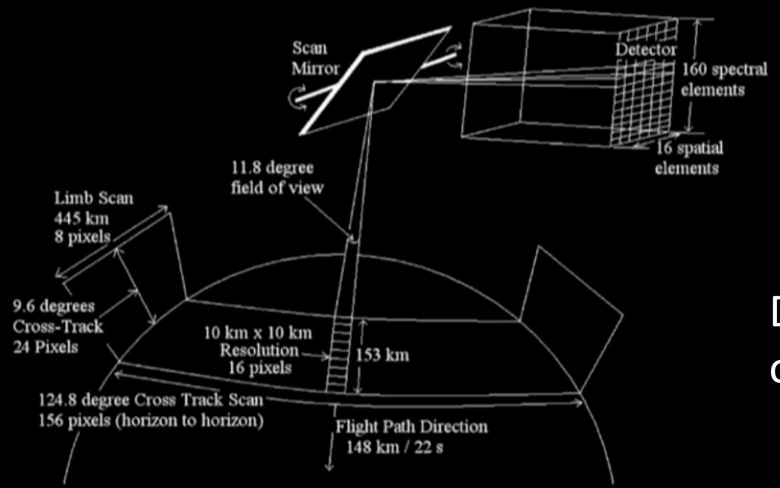
Grand Challenge
UNIVERSITY OF COLORADO BOULDER
SPACE WEATHER CENTER

SWx TREC

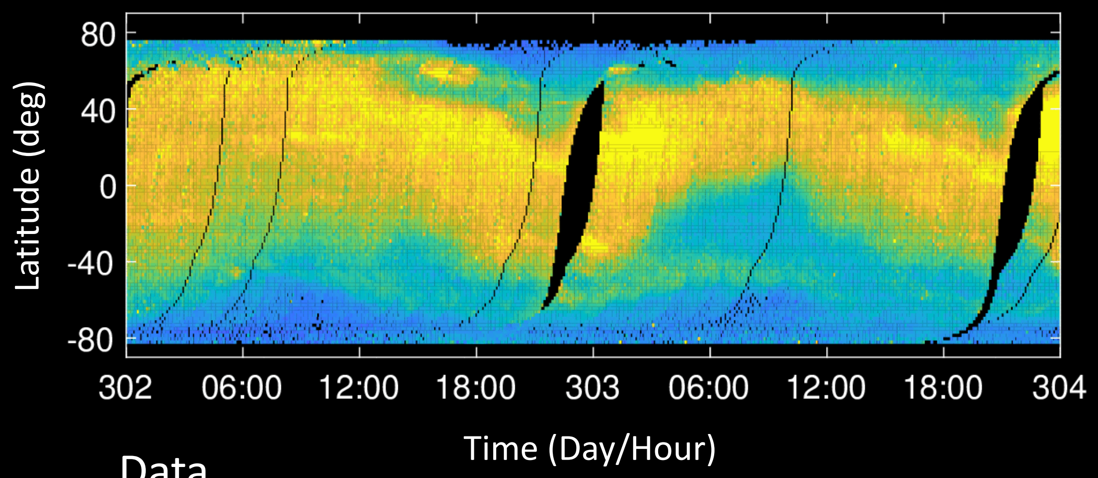
Data: Satellite Remote Sensing Measurements
Far-Ultraviolet Spectrographic Imagers

Ratio of the column content of **atomic oxygen** to **molecular nitrogen** derived from spectral measurements:
- OI (135.6nm)
- N_2 LBH Bands (~155 – 170nm)

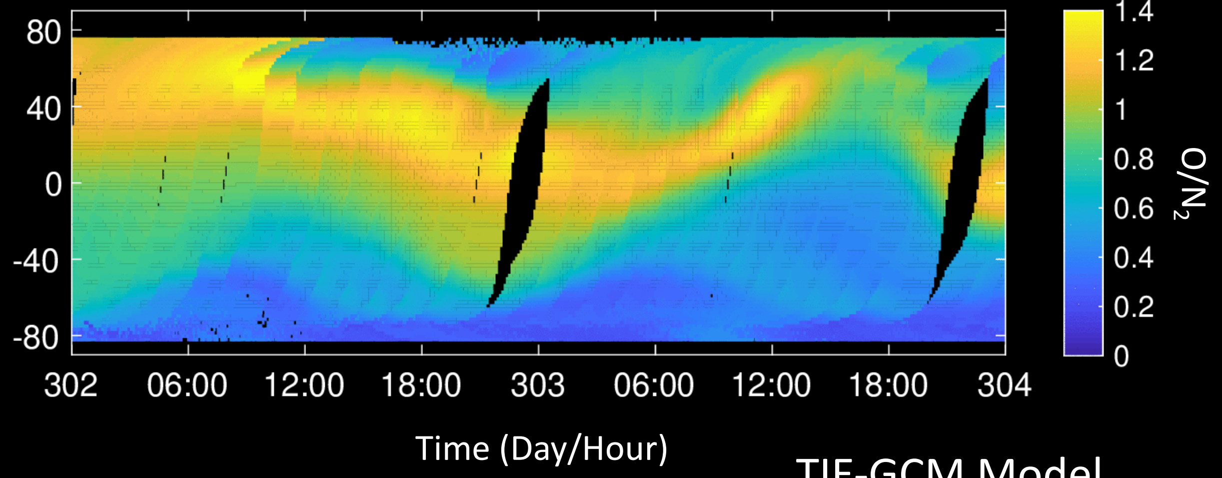
Satellite Missions:
- TIMED/GUVI (2001 – present)
- DMSP/SSUSI (2003 – present)
- GOLD (2018 – present)



Daytime only



Data

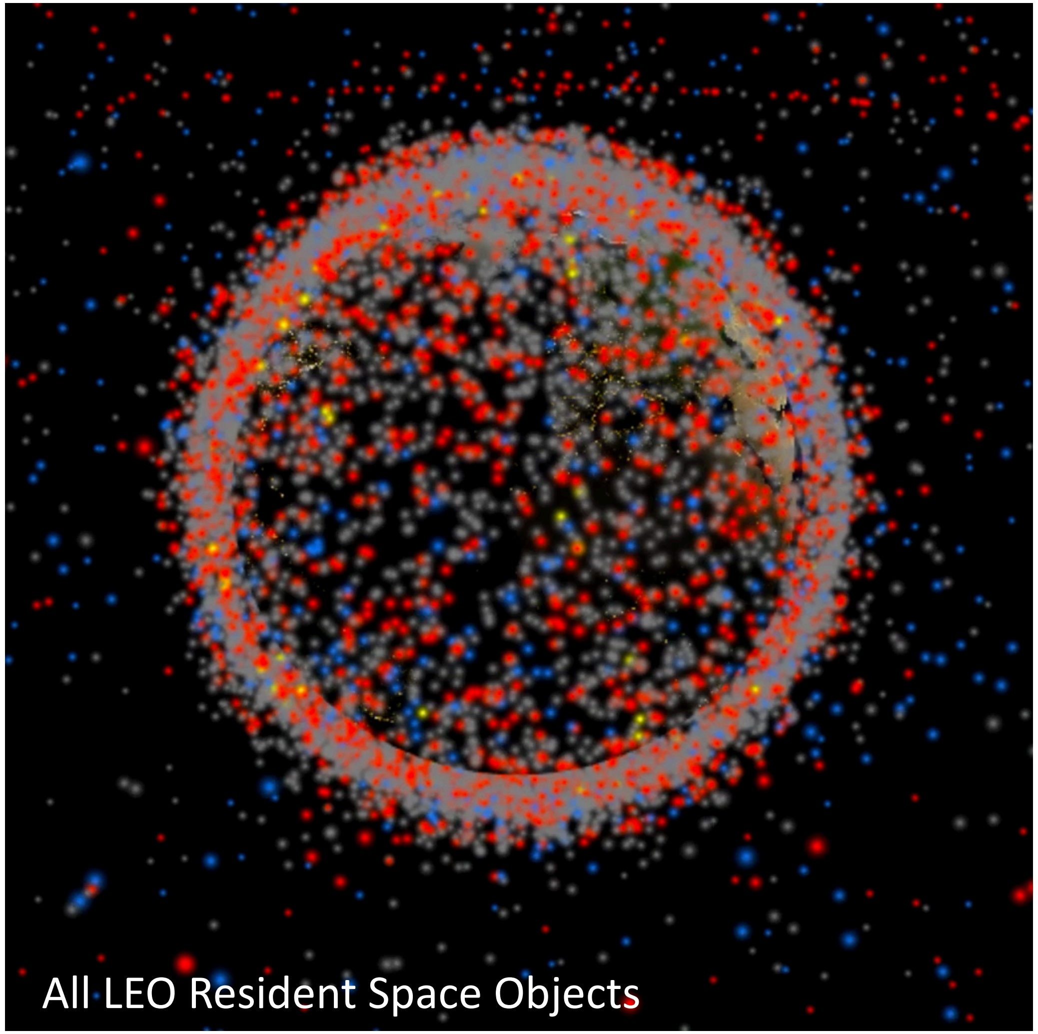


TIE-GCM Model

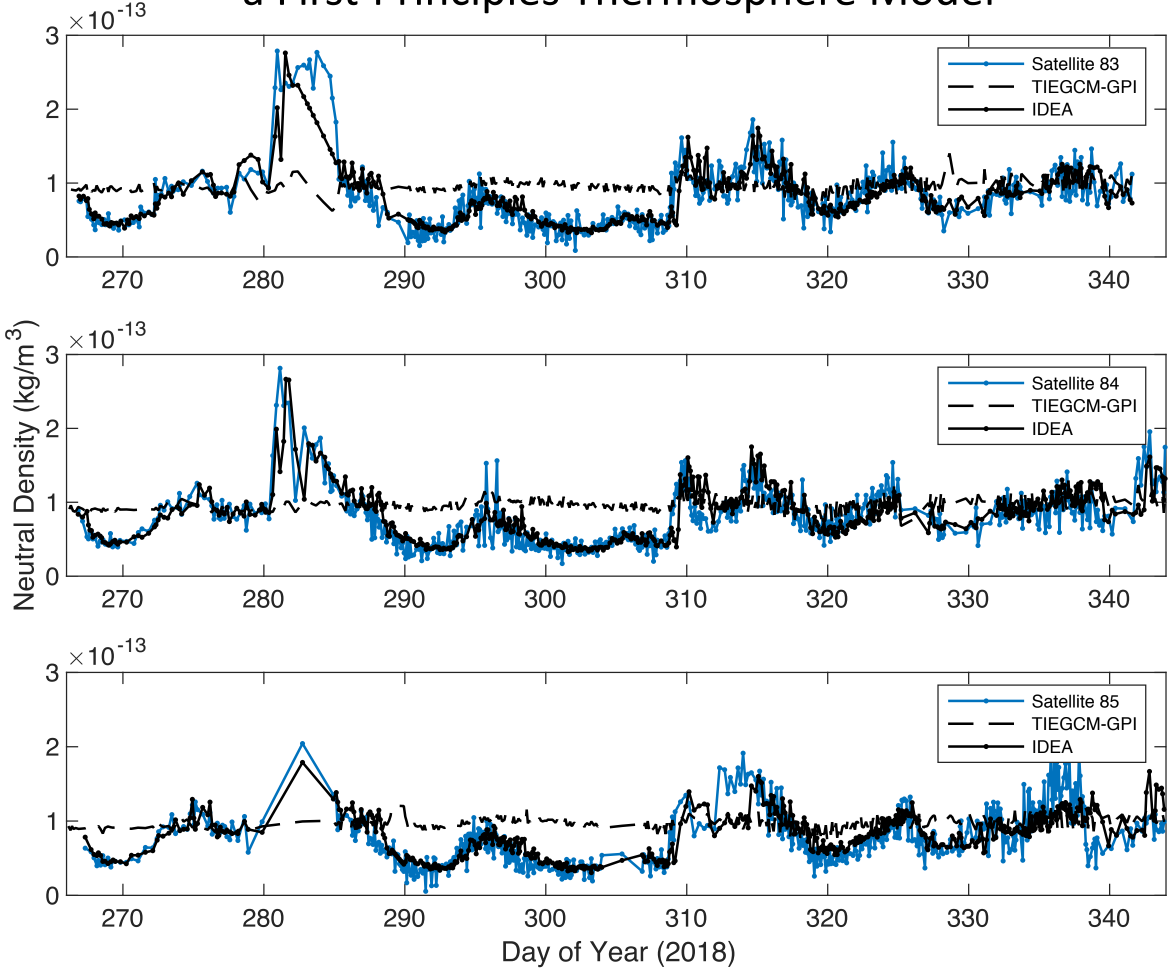
Grand Challenge
UNIVERSITY OF COLORADO BOULDER
SPACE WEATHER CENTER

SWx TREC

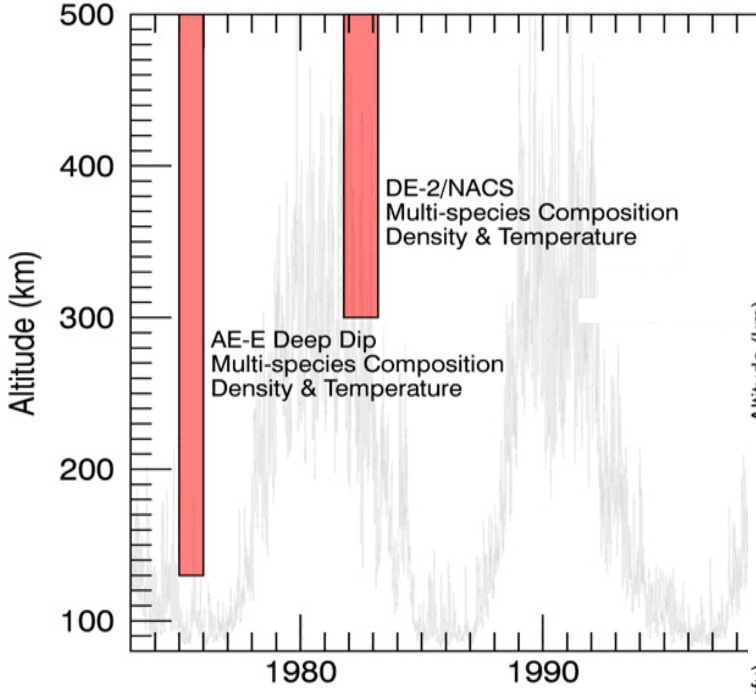
Data Sets of Opportunity:
GNSS-Equipped Satellites and SmallSats



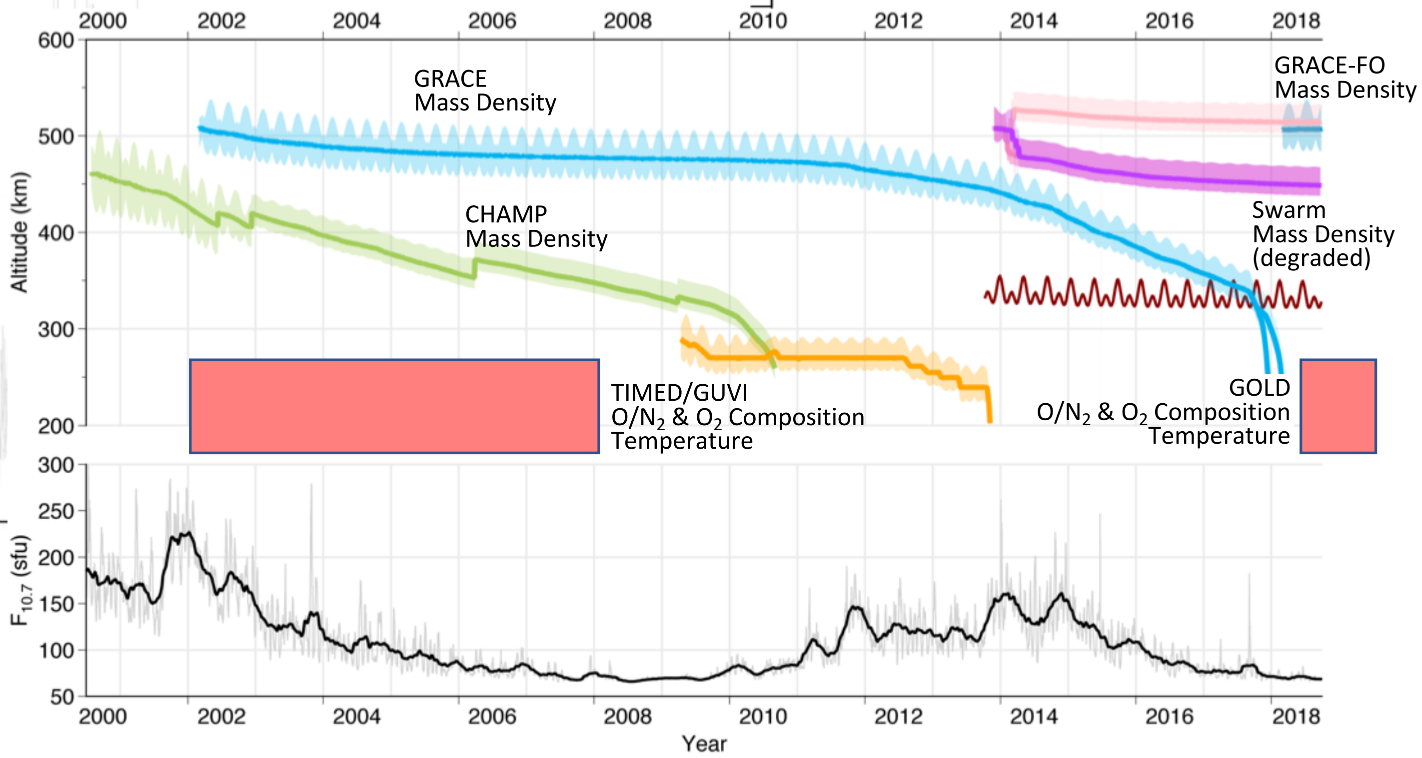
POD Data from 3 Satellites Assimilated into a First-Principles Thermosphere Model



Observational Coverage of the Thermosphere
To Date



Credit: Ed Thiemann, CU/LASP



*not an exhaustive list,
but these are the major missions

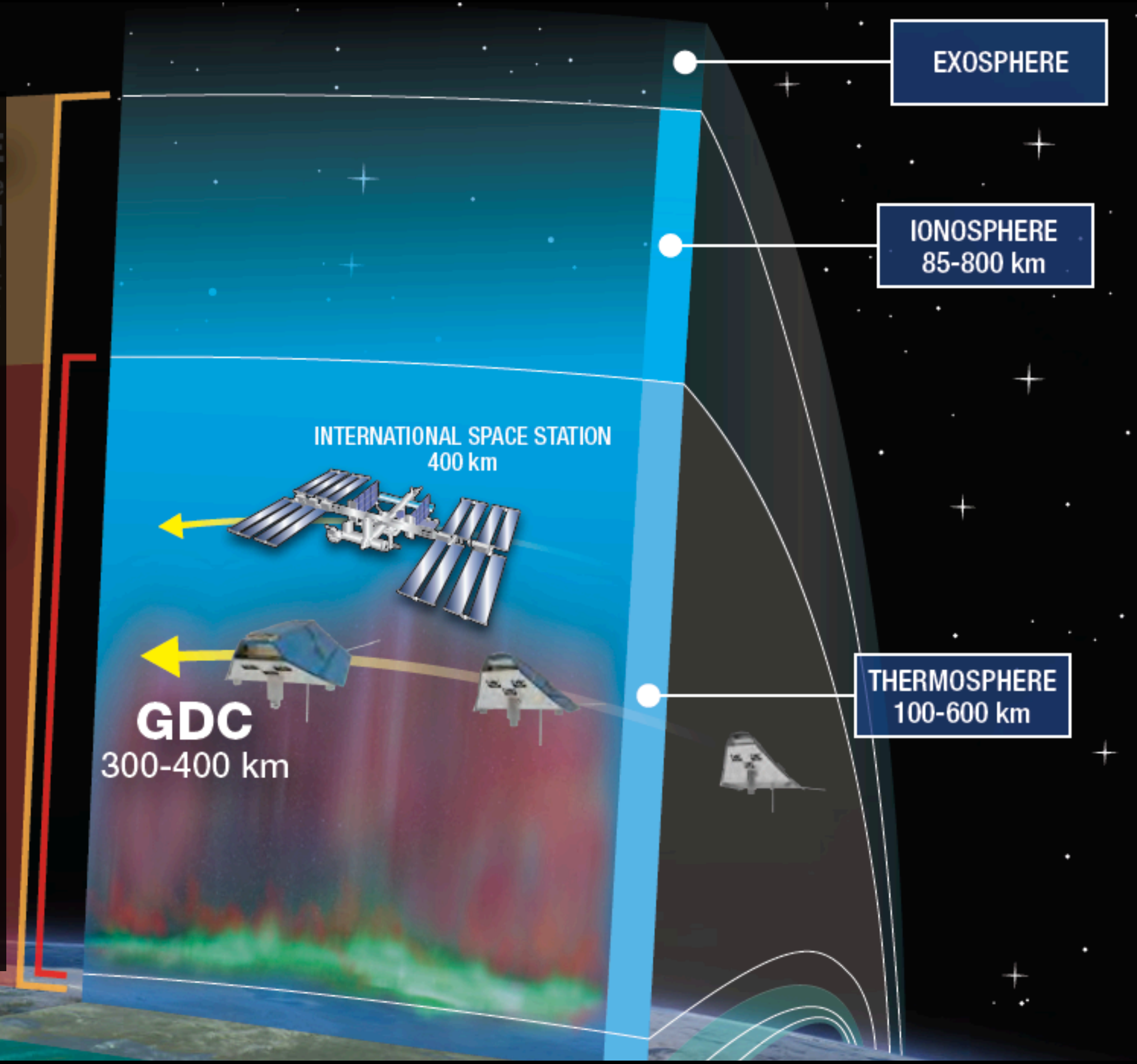
Credit: Christian Siemes, TU Delft

NASA’s Geospace Dynamics Constellation (GDC)

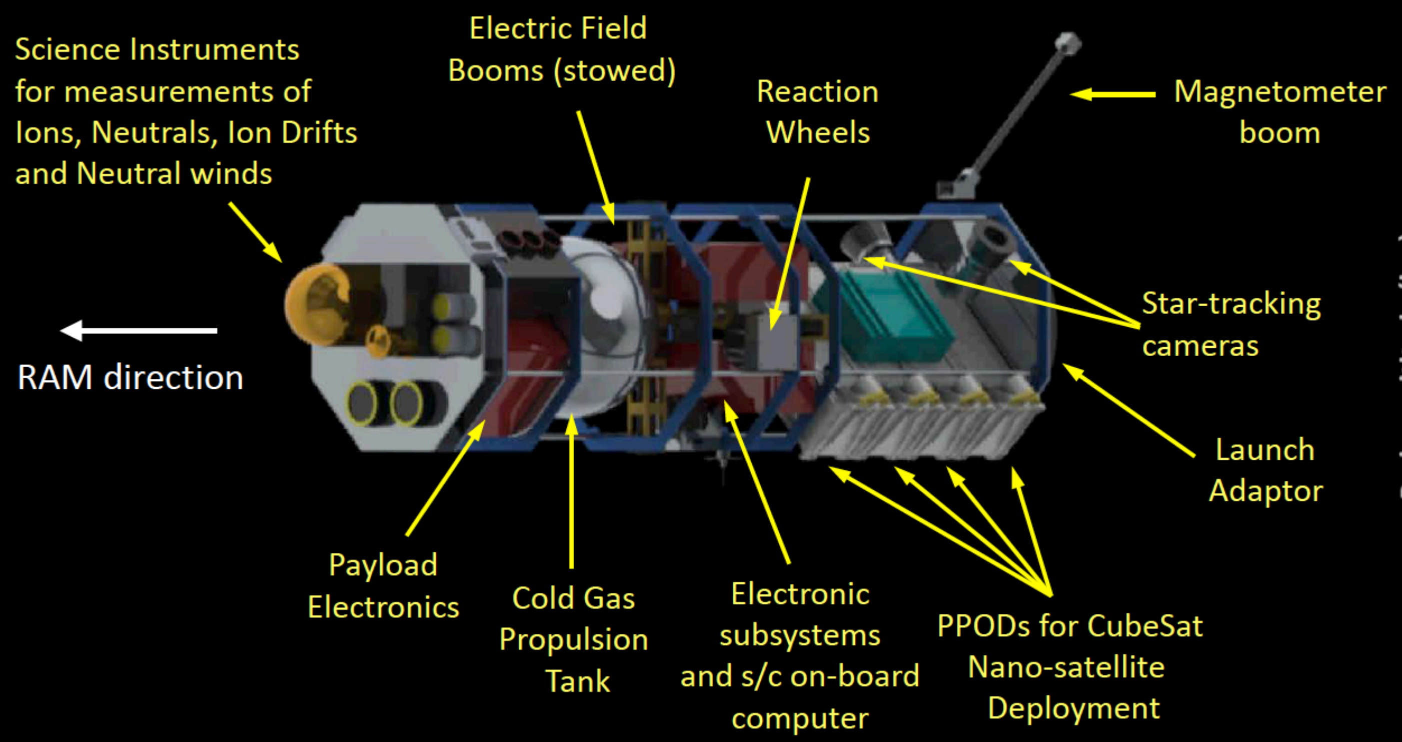
A NASA mission to “…meet critical observational needs of the complex IT system by employing a multi-satellite architecture sufficient to cover the relevant temporal and spatial scales, thereby transforming our understanding of this critically undersampled region.”

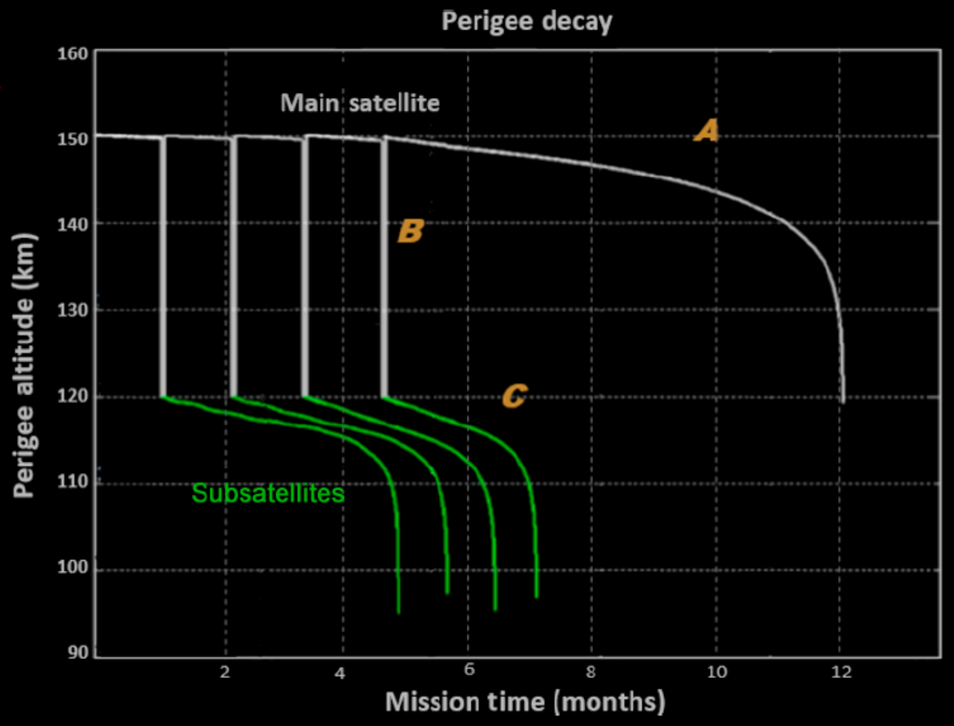
Related STDT Findings (Oct. 2019):

- Neutral composition, density, and wind measurements are required in order to address every Science Goal and Objective of the mission
- Neutral temperature measurements underly 9 of 10 Science Objectives



ESA's Daedalus Mission





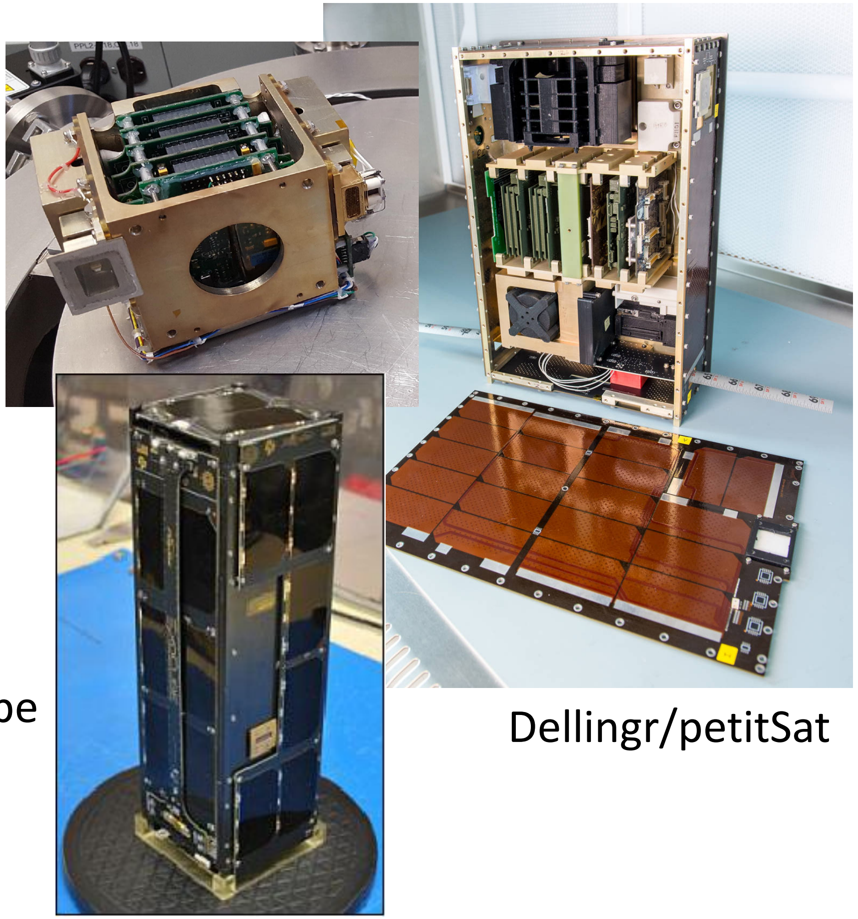
A Low-Flying Spacecraft for the Exploration of the Lower Thermosphere–Ionosphere

- Currently 1 of 3 missions in Phase-0 competition for ESA's 10th Earth Explorer
- Mission options include phased release of CubeSats from "Mother" satellite

Recent & Future SmallSat Mission Concepts

Ion/Neutral Mass Spectrometer (INMS) Missions:

INMS

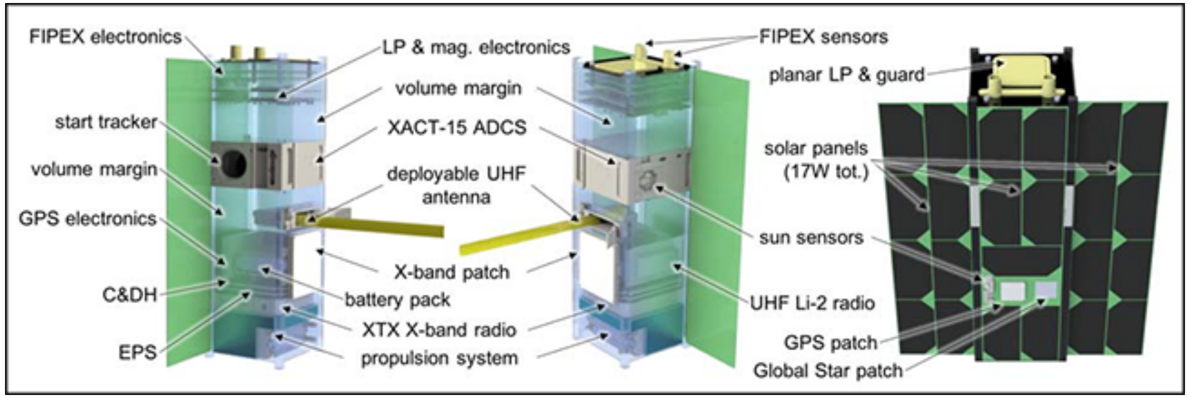


ExoCube

Dellingr/petitSat

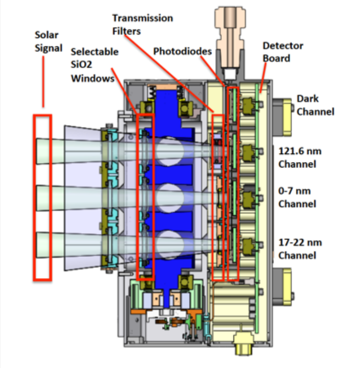
FIPEX Atomic Oxygen Sensor Missions:

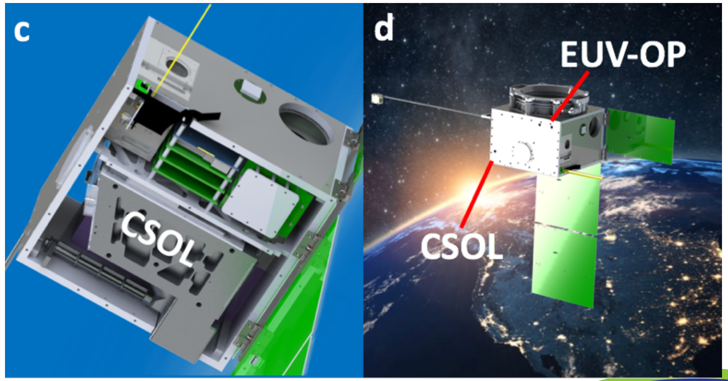
SWARM-EX



Occultation Wave Limb Sounder (OWLS) Missions:

INSPIRESat-3





Summary:

- Thermosphere observations for satellite drag currently consist of ground-based radar tracking of (<100) space debris objects
  - Information inferred from these is coarse, both spatially and temporally
- The operational satellite drag model relying on these data will be put to the test in the coming years as the LEO catalog is expected to see unprecedented growth
- Accelerometers, UV spectrometers and POD-derived density are extremely useful and/or promising, but they are not an unambiguous measurement of the thermosphere
- Atomic oxygen and helium have not been measured in the thermosphere since the early ‘80s
- Hydrogen has never been measured directly in the thermosphere
- Mass spectrometers are not a silver bullet, but can go a long way toward validating and refining the assumptions underlying other data sets as well as our sophisticated nowcast/forecast models