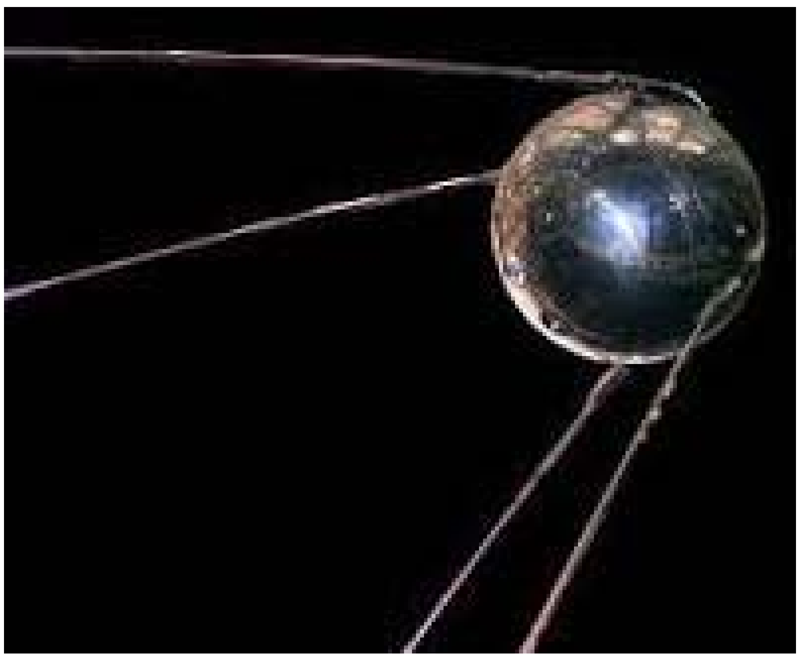
MECHANICAL ENGINEERING

Space Object Population and Tracking

It All Began with Sputnik

- Sputnik 1 was the first artificial Earth satellite
- Soviet Union launched it into an elliptical low Earth orbit on 4 October 1957
- U.S. launched its first satellite, Explorer 1, on January 31, 1958
- Earth-orbiting space object population has grown rapidly ever since



Sputnik

Explorer 1

Number & Types of Satellites

- Satellites serve many different purposes, including:
    - Remote sensing of Earth (terrain mapping, geology, soil conservation)
    - Remote sensing of space (i.e astronomy, space telescopes)
    - Communications (phone, TV, internet)
    - Other science (radiation, spectroscopy, gravity modeling)
    - Surveillance (primarily military)
    - Navigation (GPS)
- Total # of Earth-orbiting satellites launched worldwide since Sputnik is several thousand
- Of these, the # of satellites that are currently active is only a few thousand
- However, the # of total objects currently in Earth orbit is several times this amount…WHY?

Space Object Population

- There are numerous contributors to the space object population other than active satellites, including:
  - **Inactive satellites**: once-operational satellites that have reached end of life, either intentionally or unintentionally (e.g. equipment malfunction, communication failure)
  - **Rocket bodies**: transport operational satellites (i.e. payloads) to orbit, then burn out
  - **Debris**: can occur "one at a time" from a piece breaking off of a satellite (e.g. part of a solar panel) or coming loose (e.g. lens cap), OR "many at a time" from a catastrophic event (e.g. explosion or collision)
- While the first 2 categories of objects above are not technically debris, if they are not properly retired from space after serving their purpose, they effectively become debris as well → "space junk"
- We will discuss the debris issue in detail later in the term

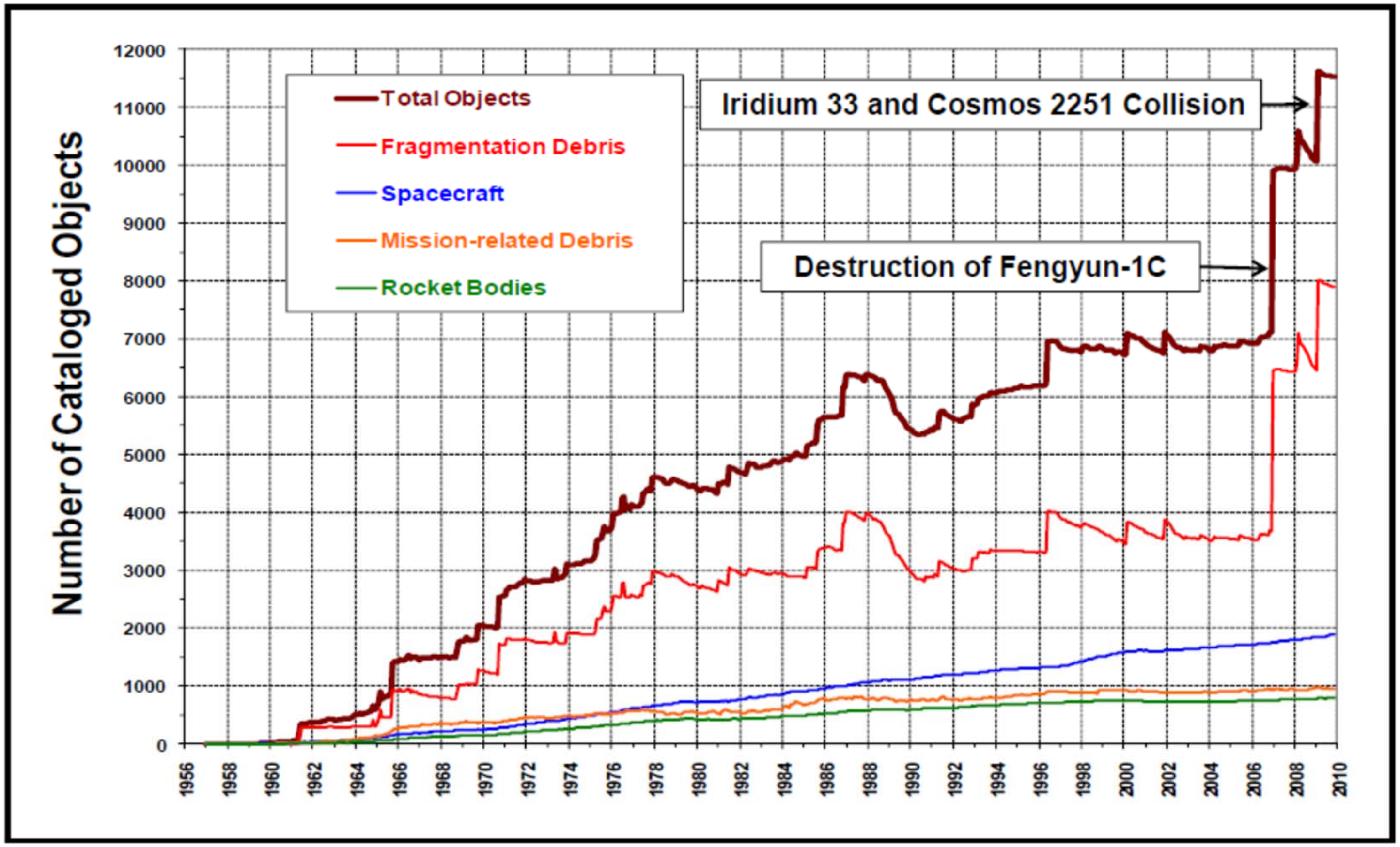
Retiring Inactive Satellites & Rocket Bodies

- Drag tends to de-orbit space objects over time, but this is a function of many variables:
  - Object altitude (density decreases quasi-exponentially as altitude increases)
  - Object size/frontal area
  - Object material properties (drag coefficient)
  - Solar cycle (density varies slowly over time)
- Bottom line is that different objects take different amounts of time to de-orbit
- De-orbit time for Low Earth orbit objects (LEO, approx. 400-900km altitude) usually on the order of years
- Objects in Geostationary Earth orbit (GEO, approx. 36,000km altitude) will essentially never de-orbit; best means to retire is to maneuver them to a higher non-intrusive orbit (the "GEO graveyard")
- Objects between LEO & GEO (e.g. GPS satellites) must either be maneuvered down to LEO or up to the GEO graveyard

Debris Problem

- While some owner/operators are diligent about properly retiring their inactive payloads &/or rocket bodies, many are not (or attempts at retirement are unsuccessful)
- These unretired objects, combined with objects in the aforementioned "debris" category, comprise the majority of the space object population
- One issue about breakup/collision events: when an object breaks apart into multiple objects, those objects will all possess slightly different orbits, in the vicinity of the original object's orbit → over time, these objects will likely spread out into a ring or constellation of debris
- Historically, most satellites have been launched into (1) LEO Sun-synchronous orbits or (2) the GEO belt
  - GEO objects' orbits are all roughly 36,000km altitude, circular, & equatorial
  - LEO Sun-synchronous objects are a bit more widely distributed: approx. 400-900km altitude & 95-99° inclination
- Thus, most space objects (of all categories) are located in these 2 regions

Historical Growth of the Space Object Population

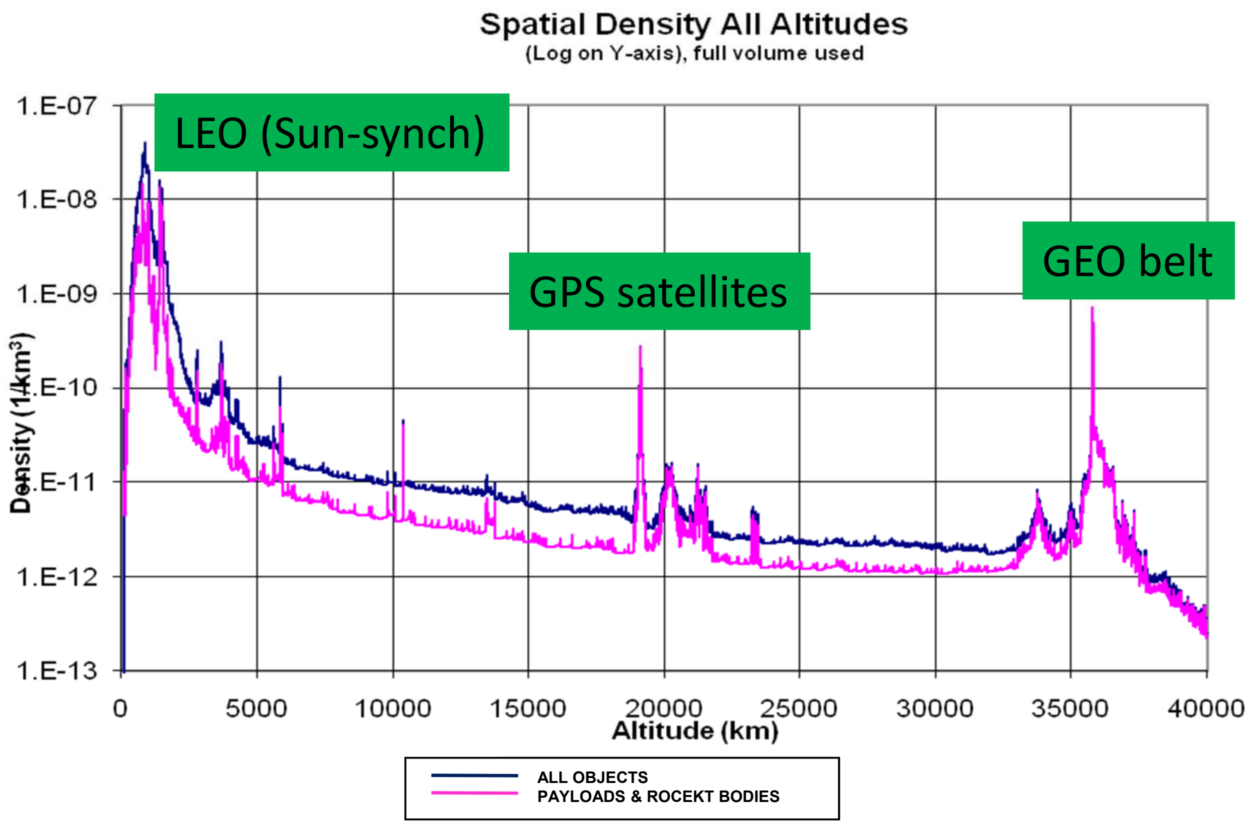


NASA Orbital Debris Quarterly News, vol. 14 issue 2, April 2010, p. 4

Two recent events added over 4,000 objects to the catalog:

- 17 January 2007: Chinese anti-satellite test (more about this later in the term)
- 17 February 2009: Iridium 33 collides with COSMOS 2251

Object Distribution by Altitude



Nicholas Johnson, NASA Orbital Debris Program Office

- GPS satellites (& resulting debris fragments thereof) account for comparable # of total objects to that found in LEO & GEO

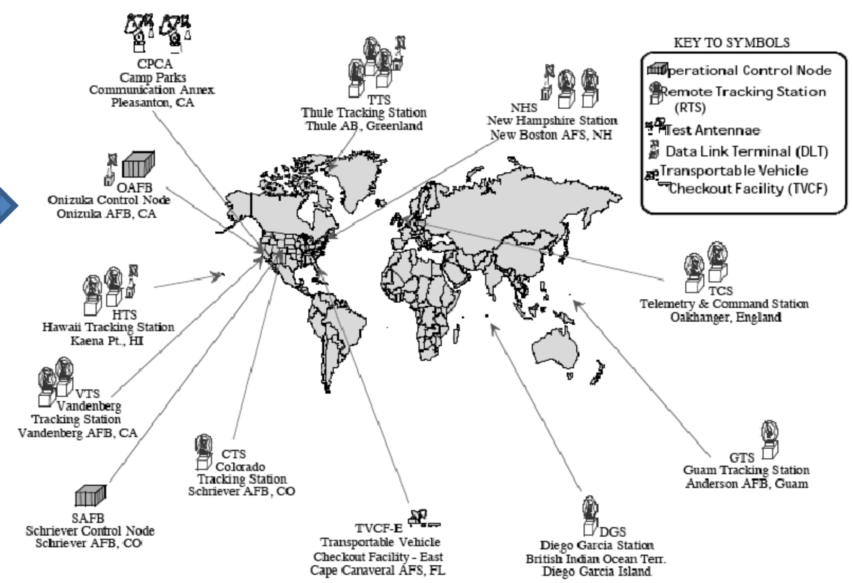
Object Size

- So how certain are we of these numbers of objects?
- Consider that a breakup/collision event likely results in fragments of varying size, including dust-sized particles
- For this reason, the actual # of objects orbiting Earth at any time is statistically uncountable
- Therefore, any estimate of the space object population should be qualified by the minimum size considered (e.g. "The # of objects orbiting Earth greater than 5cm in diameter is…")
- Most estimates pertain to those objects that can be tracked by sensors

Object Tracking

- Two basic means by which Earth-orbiting objects are tracked:
- Active tracking involves 2-way communication between an active satellite & its owner/operator
- Owner/operator sends commands up to the satellite; satellite sends down telemetry—a wide array of info generated on-board
  - Vehicle "state of health" (e.g. battery levels)
  - Navigation solution (both translational & attitude)
  - Images, spectroscopy, other science-related info

- Satellite & its owner/operator are connected via a network of ground stations; one example is the Air Force Satellite Control Network (AFSCN)
- This process is known as telemetry, tracking, & command (TT&C)
- Obviously only applicable to active satellites equipped with communication capability with the ground (e.g. RF transceivers)



Object Tracking

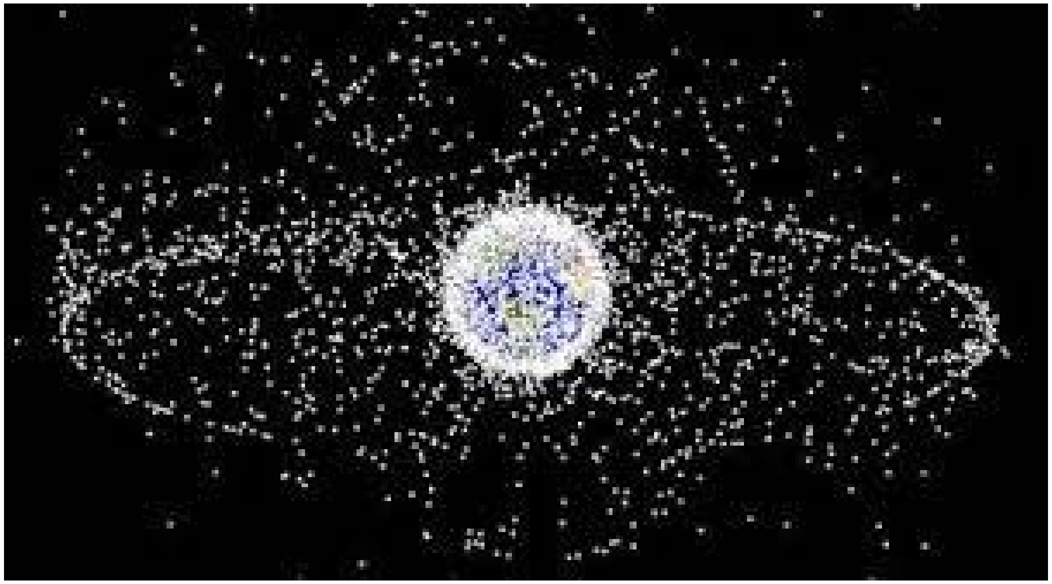
- Passive tracking involves 1-way sensing of objects through electromagnetic means
- Primary sensing modes are RF (e.g. radars) & optical (e.g. telescopes)
- Most passive sensors are terrestrial, although some are in space
- Most terrestrial sensors are fixed on the ground, although some are mobile—some sensors have even been maintained aboard ships!
- Applicable to all satellites that can be "seen" by sensors
- We'll discuss sensors in more detail later in the term

Object Tracking

- Passive tracking doesn't require any communication with the object being sensed
- Therefore, this type of tracking can be performed by anyone with a sensor & knowledge of where to "look" for objects
- Passive tracking efforts range from amateur individuals/groups to nat'l/internat'l agencies owning large networks of sensors
    - U.S. Air Force Joint Space Operations Center (JSpOC) operates the Space Surveillance Network (SSN)
    - Russia operates the International Scientific Optical Network (ISON)
- Passive sensing of Earth-orbiting objects is analogous to passive sensing of deep-space objects, i.e. astronomy
- Astronomy has a much longer history than Earth-orbiting object tracking, but technologies are similar
    - Informal efforts (amateur individuals/groups)
    - Formal efforts (observatories, arrays)
- Passive tracking is the type of tracking we'll focus on in this course (as opposed to active tracking)

SSA & the Space Catalog

- The goal of most large-scale passive tracking efforts is space situational awareness (SSA)
- This can be defined as the knowledge of the location of as many Earth-orbiting objects as possible
- Because objects' locations constantly vary with time, SSA can be more specifically defined as knowledge of the orbits of the objects
- SSA essentially began decades ago, with the profusion of satellites being launched into Earth orbit from multiple countries
- Eventually the concept of the Space Catalog evolved

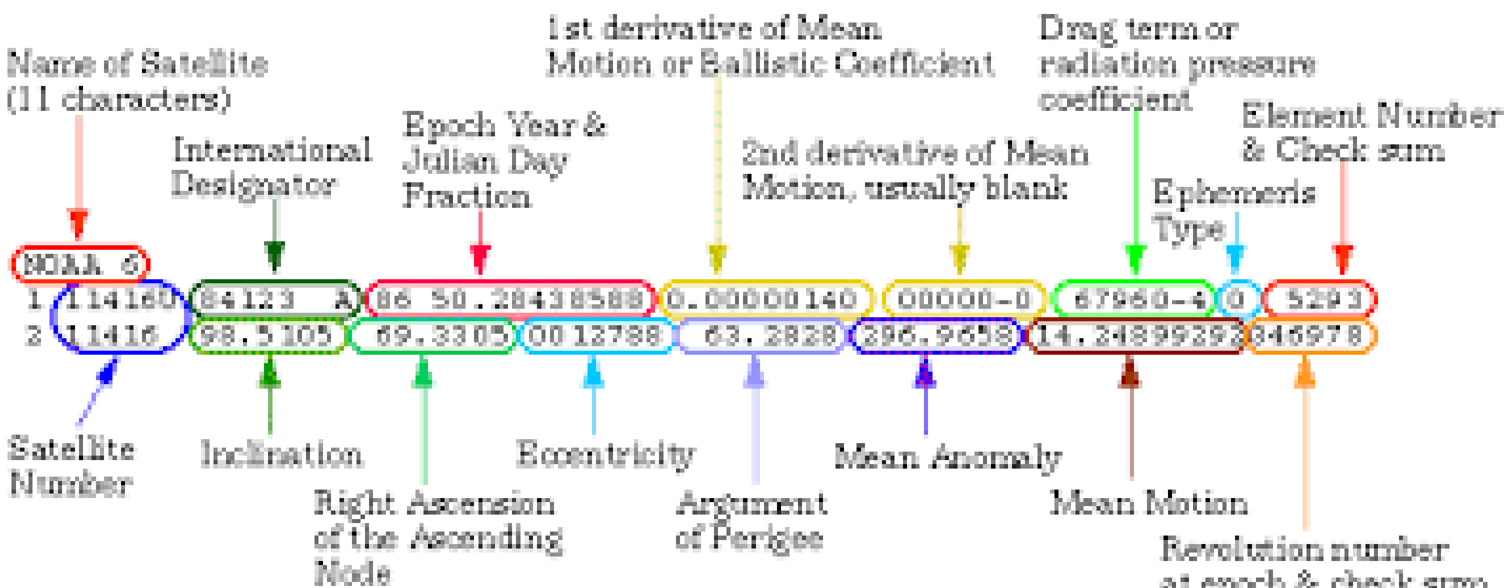


SSA & the Space Catalog

- A space catalog can be broadly defined as a listing of objects & their orbits
- While a single such listing is an instantaneous “snapshot” of the SSA picture, any useful catalog must be frequently updated
  - Subtractions to the catalog due to de-orbiting or objects being “lost”
  - Additions to the catalog due to new launches or objects being “found”
- There is no single, universally accepted version of the catalog, but the most widely accepted is that maintained by the JSpOC, a public version of which is made available on space-track.org
- Maintaining a space catalog of thousands of objects is a tremendous task; two major challenges are:
  - Sensor tasking: directing each sensor where to “look” & take data
  - Data association (or observation assignment): telescope images often capture multiple objects in a frame; correct orbit determination of objects requires them to be properly distinguished

TLEs/3LEs

- Each entry in the JSpOC space catalog is a two-line element set (TLE or ELSET)
- Contains info describing an object's orbit, with some metadata
- An extra line is often included indicating the name of the object → three-line element set (3LE)
- While this format is somewhat archaic, still widely accepted in the SSA community



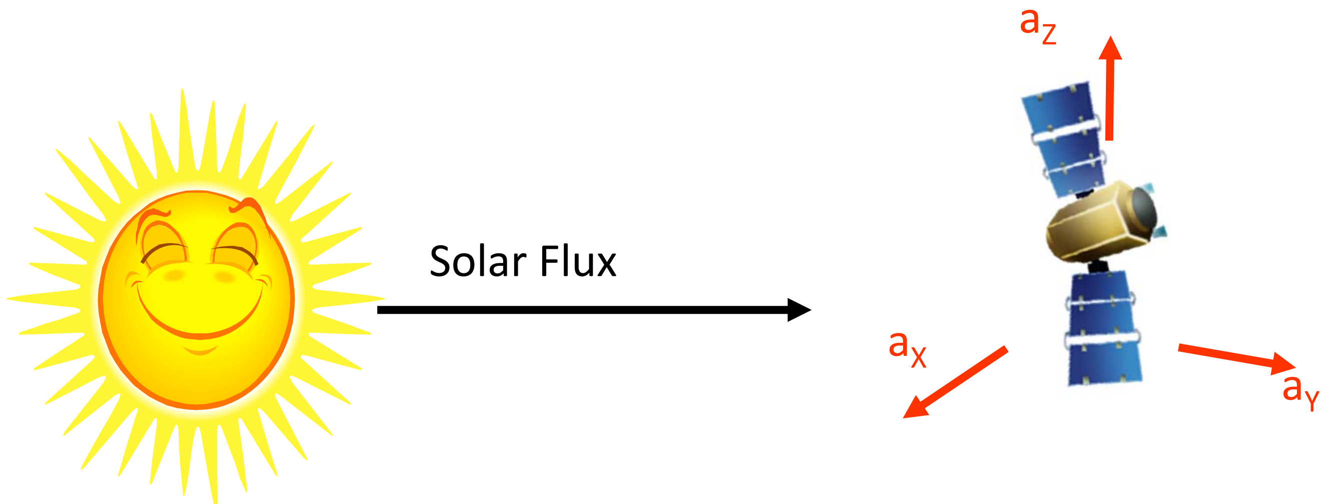
Space Weather

- Major force acting on an Earth-orbiting object is of course gravity from the Earth
- 2nd most dominant force on LEO objects is drag, driven largely by thermospheric density (in this case, not of air, but of other molecular particles)
- Drag is a dissipative perturbation that causes slow deceleration → de-orbit
- The field of Space Weather includes the modeling/prediction of density, solar particle hazards, & orbital lifetime
- After years of research, these phenomena are still extremely difficult to predict

Space weather effects stem from solar phenomena (radiation, flares, CMEs)

Space Weather

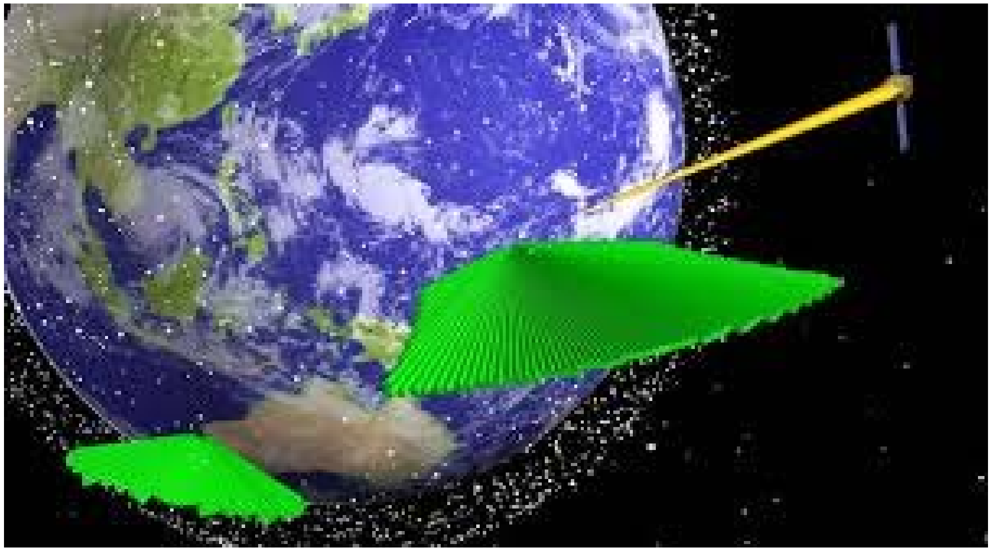
- For GEO objects, drag is essentially non-existent, solar radiation pressure (SRP) is significant → driven by solar flux/photons
- Unlike drag which acts in the negative velocity direction, SRP acts along the Earth-Sun line direction
- Whereas drag always dissipates an object's energy, SRP can increase or decrease energy, at different points in the orbit



Space weather effects can significantly affect space objects' motion, greatly complicating the determination/prediction of their orbits! (& therefore catalog accuracy)

Why SSA?

- What is the fundamental purpose of SSA?
- From a general perspective, it is collision avoidance: monitoring threats to active spacecraft from free-floating debris, predicting the probability of these threats, & planning collision avoidance maneuvers if necessary
- From a military perspective, it involves monitoring of active spacecraft as well—characterizing their type, size/geometry, purpose/intent, etc
- What is the future of SSA?
    - The space fence, a USAF S-band radar system, is projected to sense up to 200,000 objects (over 10 times the # of objects currently catalogued)
    - Potentially huge game-changing SSA capability, but will incur tremendous computational challenges



In this course, we will focus on many of the finer details of SSA which we have broadly touched on here