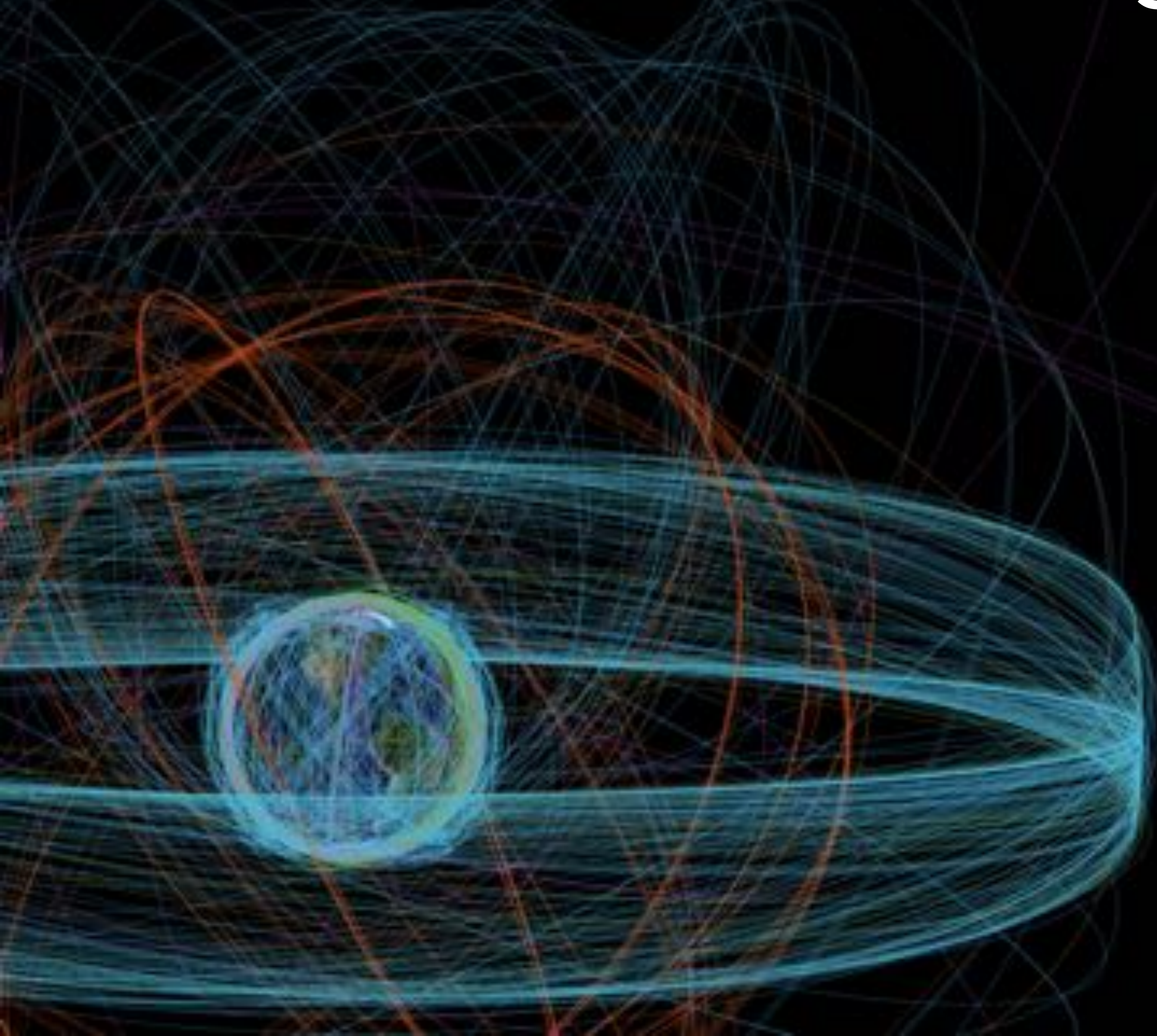
Leveraging Commercial Broadband LEO Constellations for Navigation



Tyler Reid, Andrew Neish, Todd Walter, & Per Enge
Stanford University GPS Lab

ION GNSS+ 2016
Portland, OR

September 16, 2016

Importance of GNSS

More Applications Coming

Drawbacks of GPS

- **Dependent:** We have become reliant on this now critical infrastructure for nearly all aspects of our lives.
- **Easy to Jam:** Can take out a city block with a 20 Watt GPS jammer.
- **Goal:** To increase GNSS resilience.

Changing Space

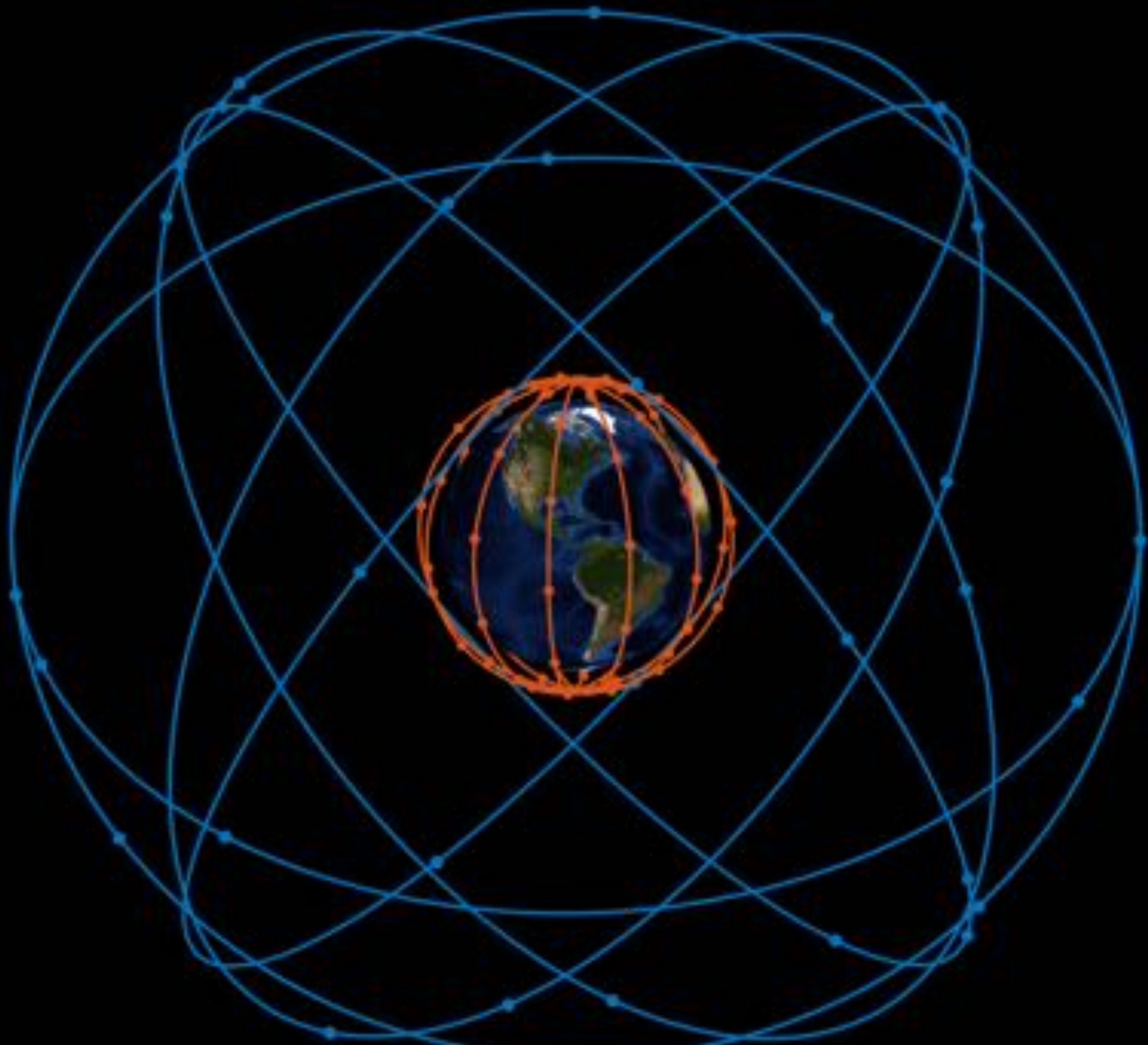
- There has been a resurgent interest in building large constellations of low Earth orbiting (LEO) satellites to deliver broadband internet to the world.
- Proposals have been announced by OneWeb with support from Virgin and Qualcomm, SpaceX with support from Google, Boeing, and Samsung.
- Can these be leveraged as a platform for navigation by piggybacking with a hosted navigation payload?

Hosted Payload

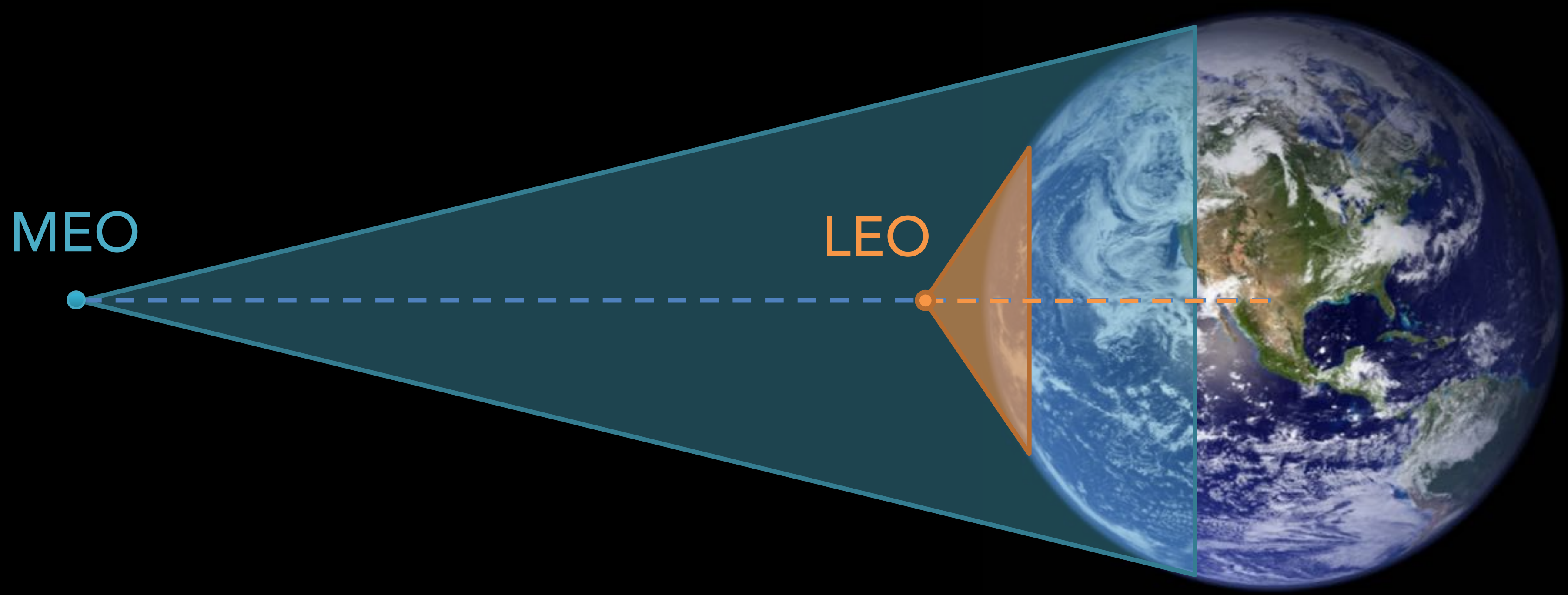
- WAAS is an FAA payload which has been hosted on a variety of commercial GEO satellites including Intelsat, Telesat, and Inmarsat.
- This shows WAAS on Intelsat's Galaxy 15, a GEO telecommunications satellite.

Source: Hosted Payload Alliance

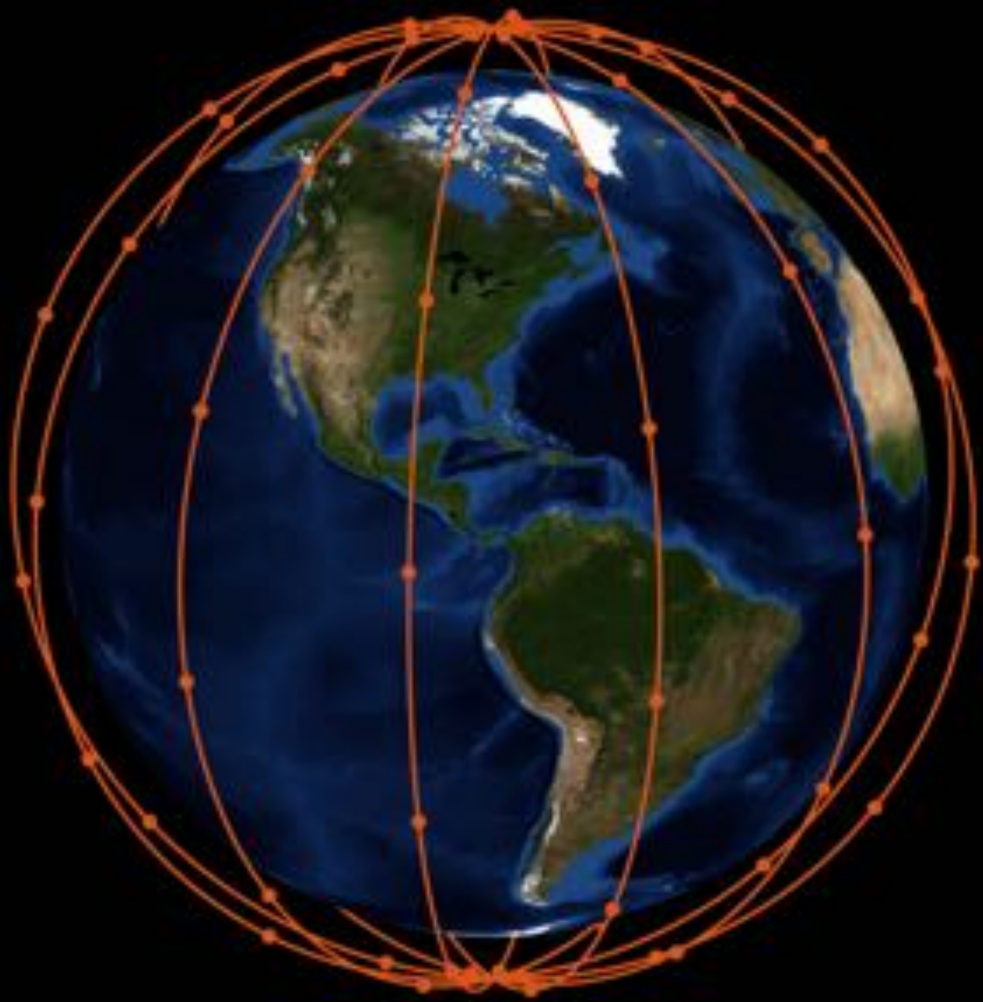
GPS (32) + Iridium (66)



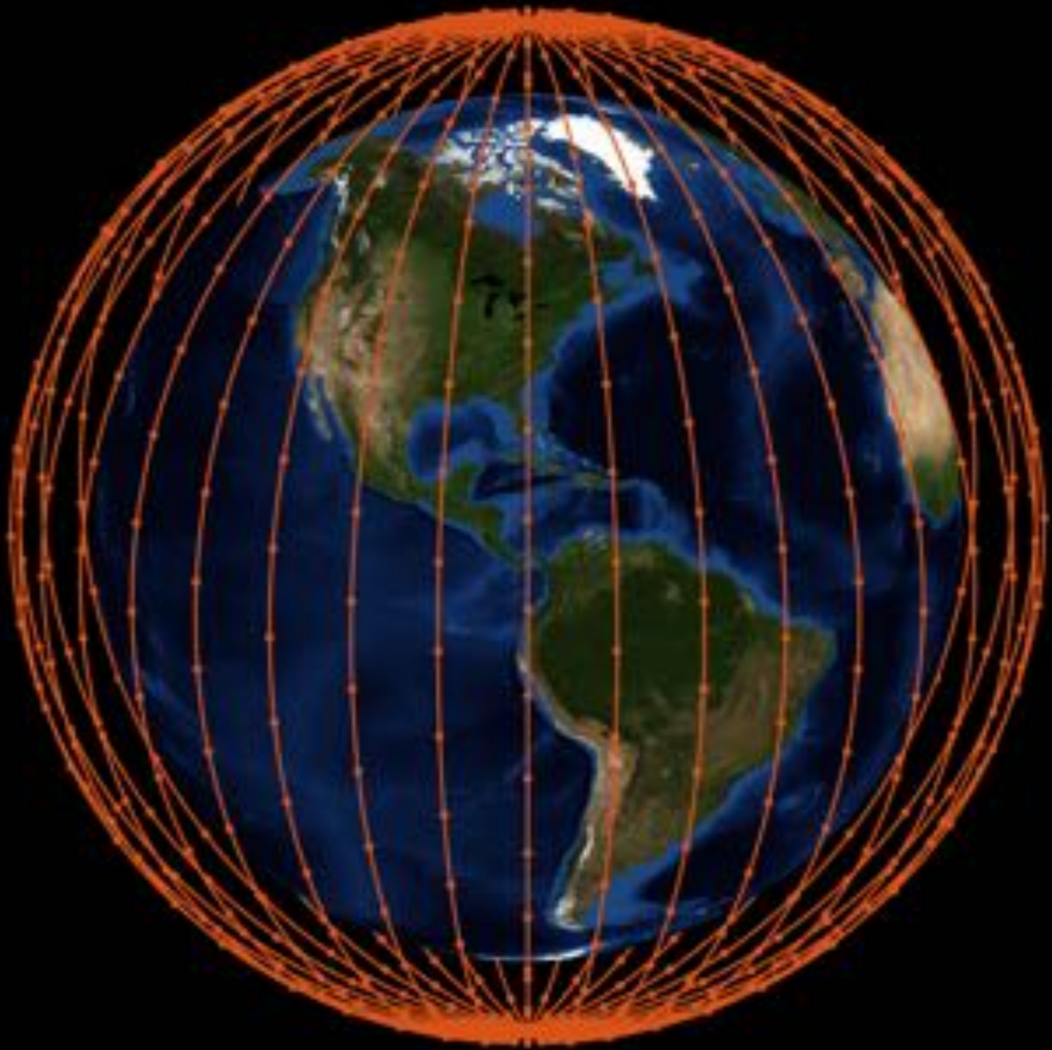
Satellite Footprint



Iridium (66)

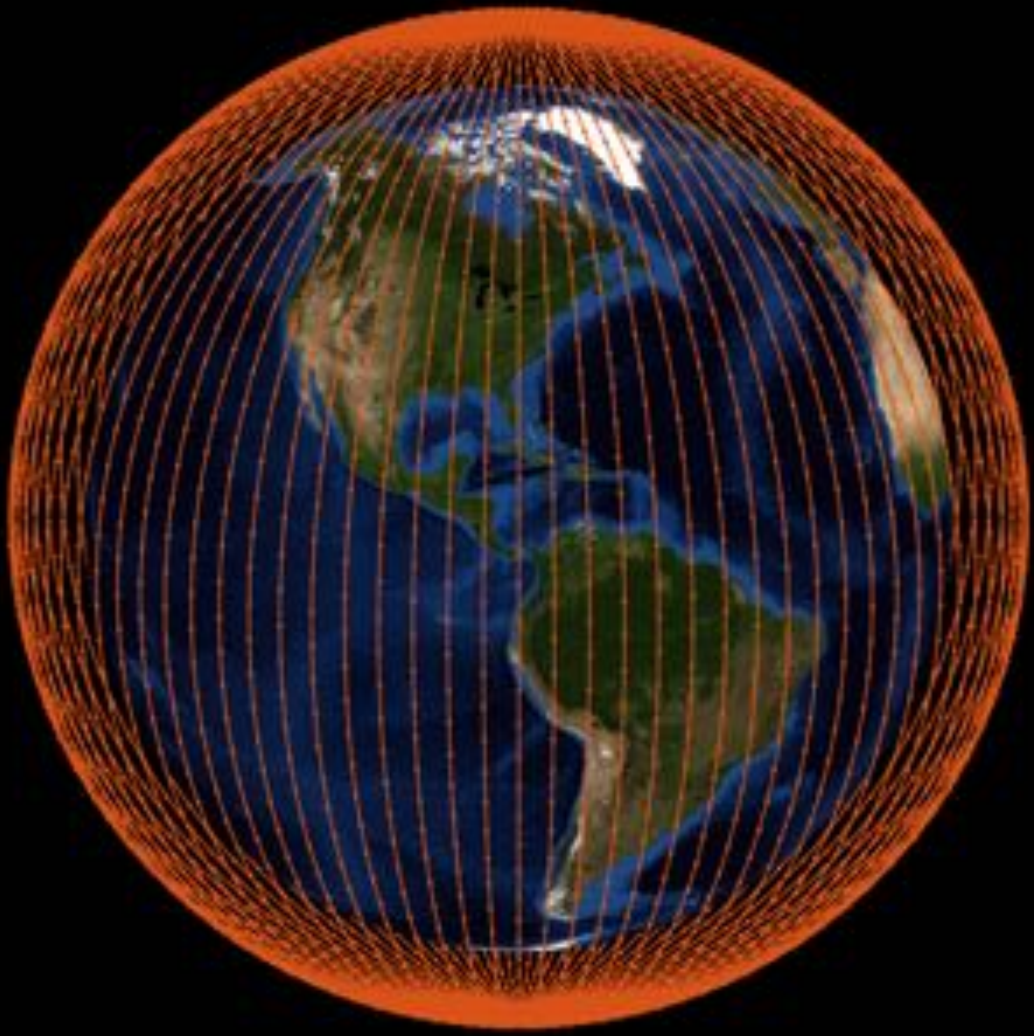


OneWeb (648)



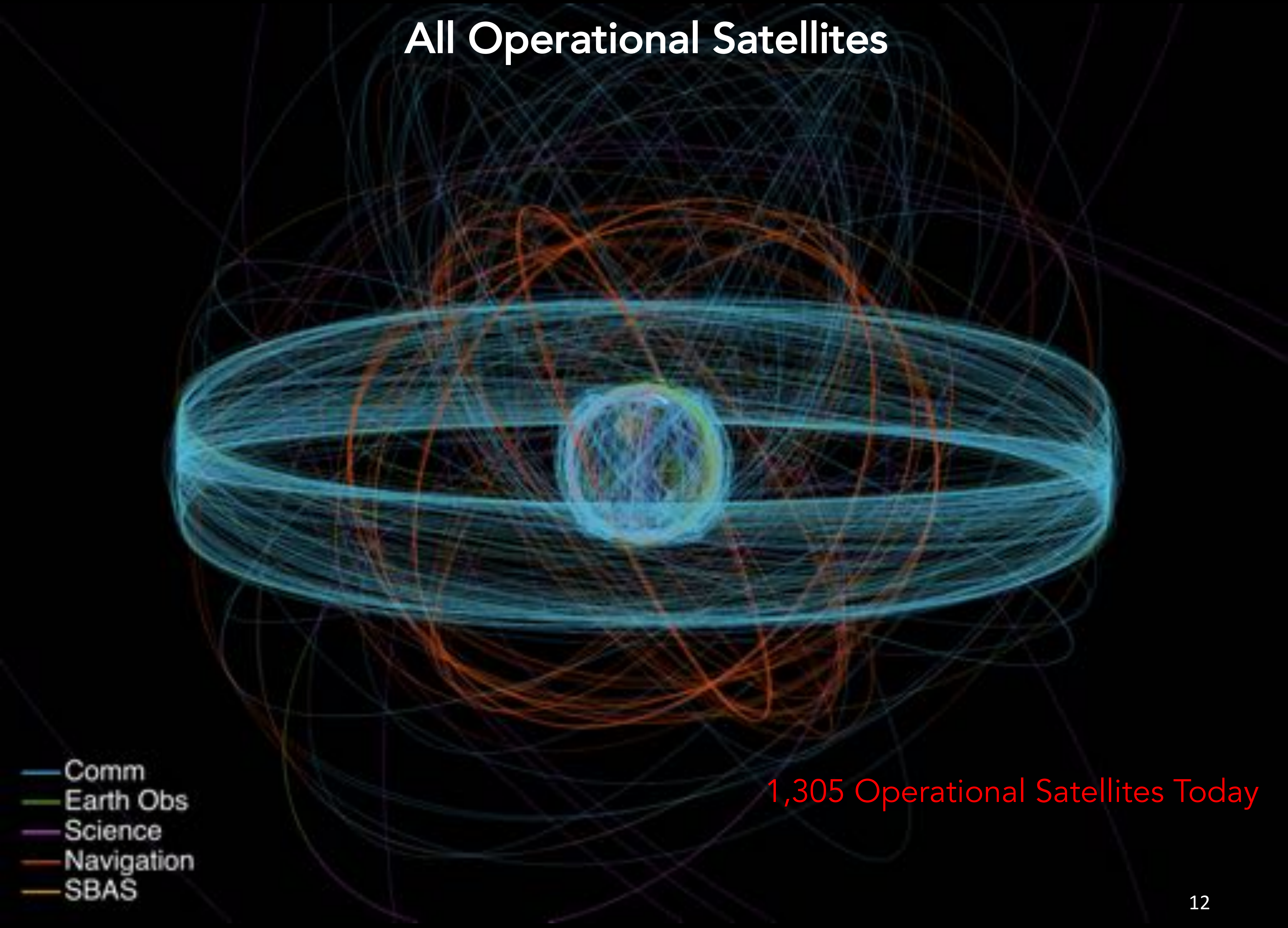
First launches 2017, initial operational capability 2019

SpaceX / Samsung (4000+)



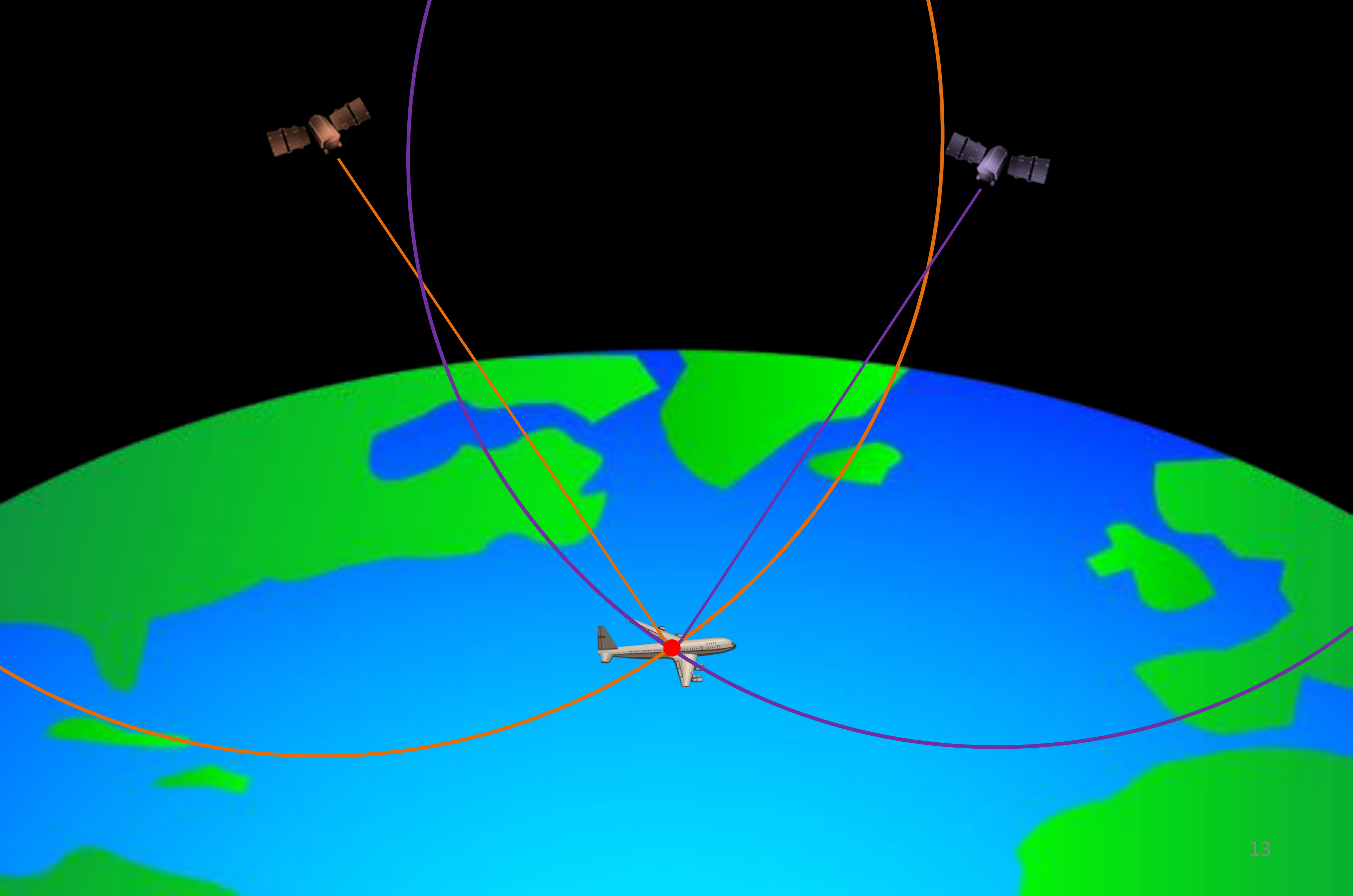
First launches 2016, initial operational capability 2020

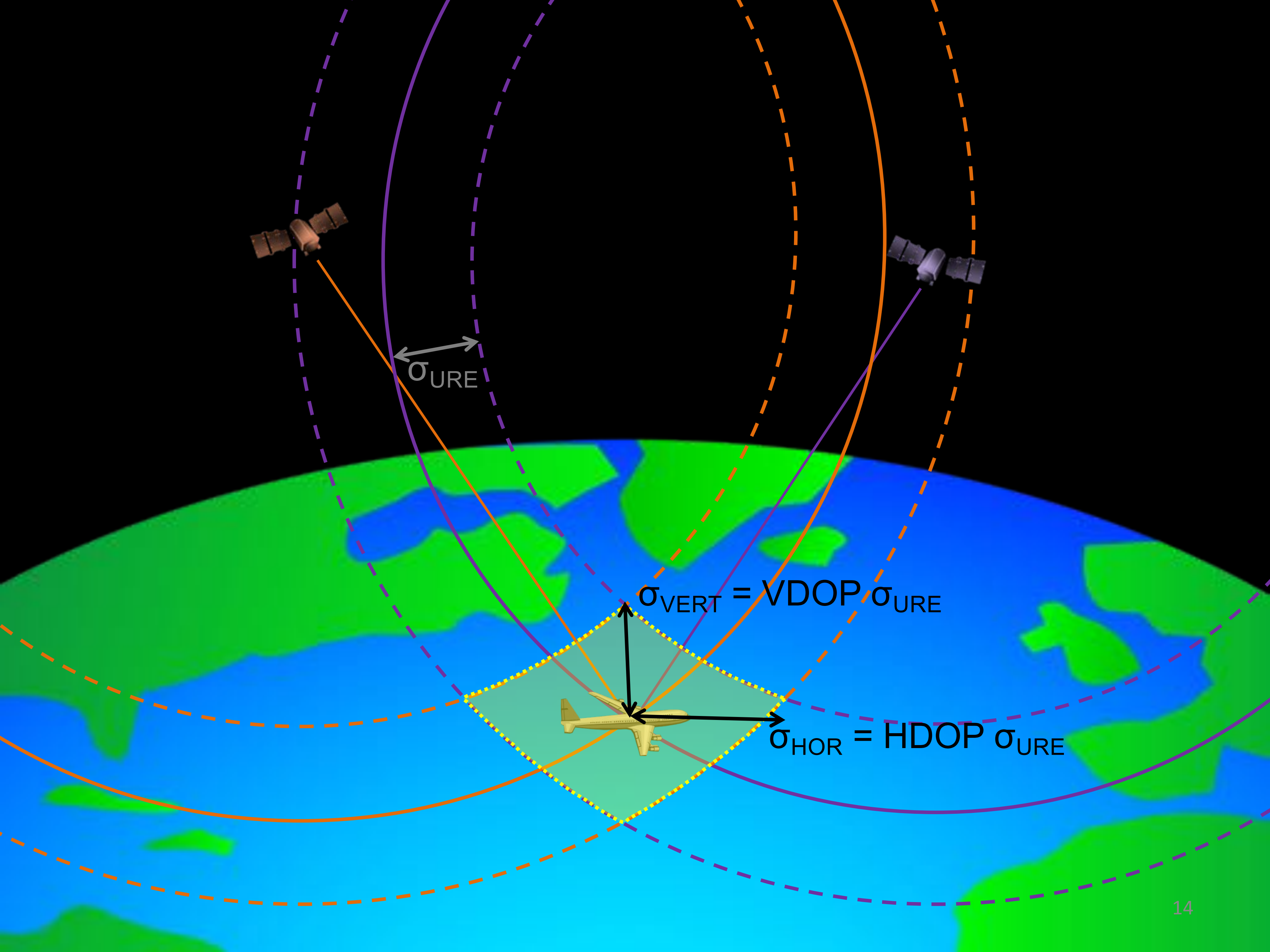
All Operational Satellites



1,305 Operational Satellites Today

Position Error





σ_{URE}
σ_{VERT} = VDOP σ_{URE}
σ_{HOR} = HDOP σ_{URE}

Error Budget

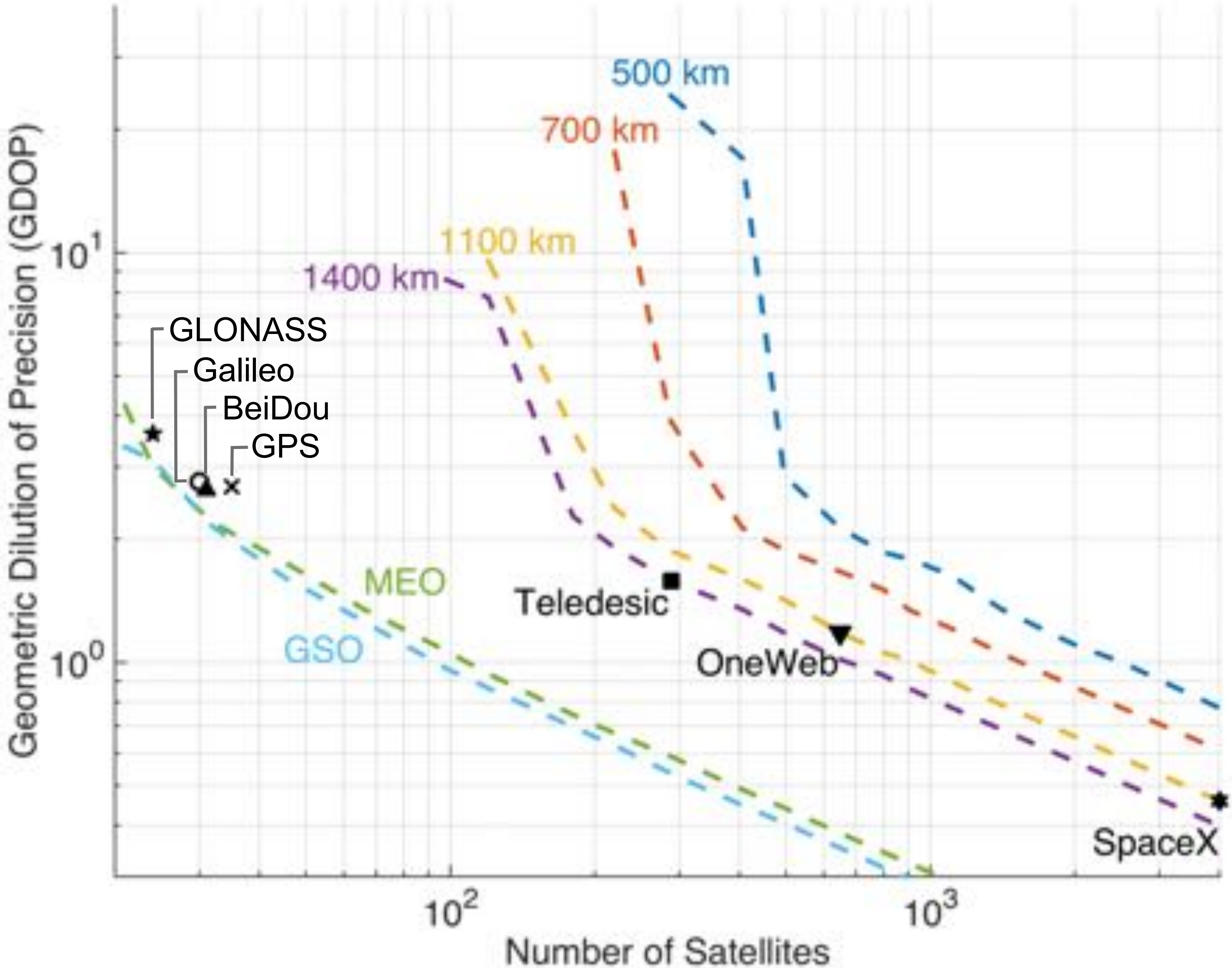
- What is our 3D position error?

$$\sigma_{URE} \times PDOP$$

User Range Error (σ_{URE})

Position Dilution of Precision (PDOP)

GDOP as a Function of Constellation Size



Error Budget

- What is our 3D position error?

$$\sigma_{URE} \times PDOP$$

User Range Error

Position Dilution of Precision

What Does URE Need to Be?

	Horizontal	Vertical	SIS URE
GPS Global DOPS / URE Analysis (95%)	3.309 m	4.860 m	0.8 m
OneWeb Global DOPS / URE Analysis (95%)	2.864 m	4.773 m	**3.0 m**

***A constellation like OneWeb could have a URE 3x worse and give comparable positioning performance.**

[1]William J. Hughes Technical Center Federal Aviation Administration GPS Product Team, *Global Positioning System (GPS) Standard Positioning Service (SPS) Performance Analysis Report, Report #86*, 2014.

How do We Get That URE

- **Clocks**
  - Need to use clocks that get comparable performance to GPS.
- **Orbit**
  - Orbit ephemeris.
  - Constellation-wide orbit determination.
- **Cost**
  - How can this be done at a lower than traditional cost? We want this to make sense for a hosted payload in LEO.

Clocks

- Each GPS satellite has 4 atomic clocks onboard.
- Each costs millions of dollars and consume ~40 Watts.
- They are too costly in terms of $'s and power for low cost LEO.

Chip Scale Atomic Clock (CSAC)

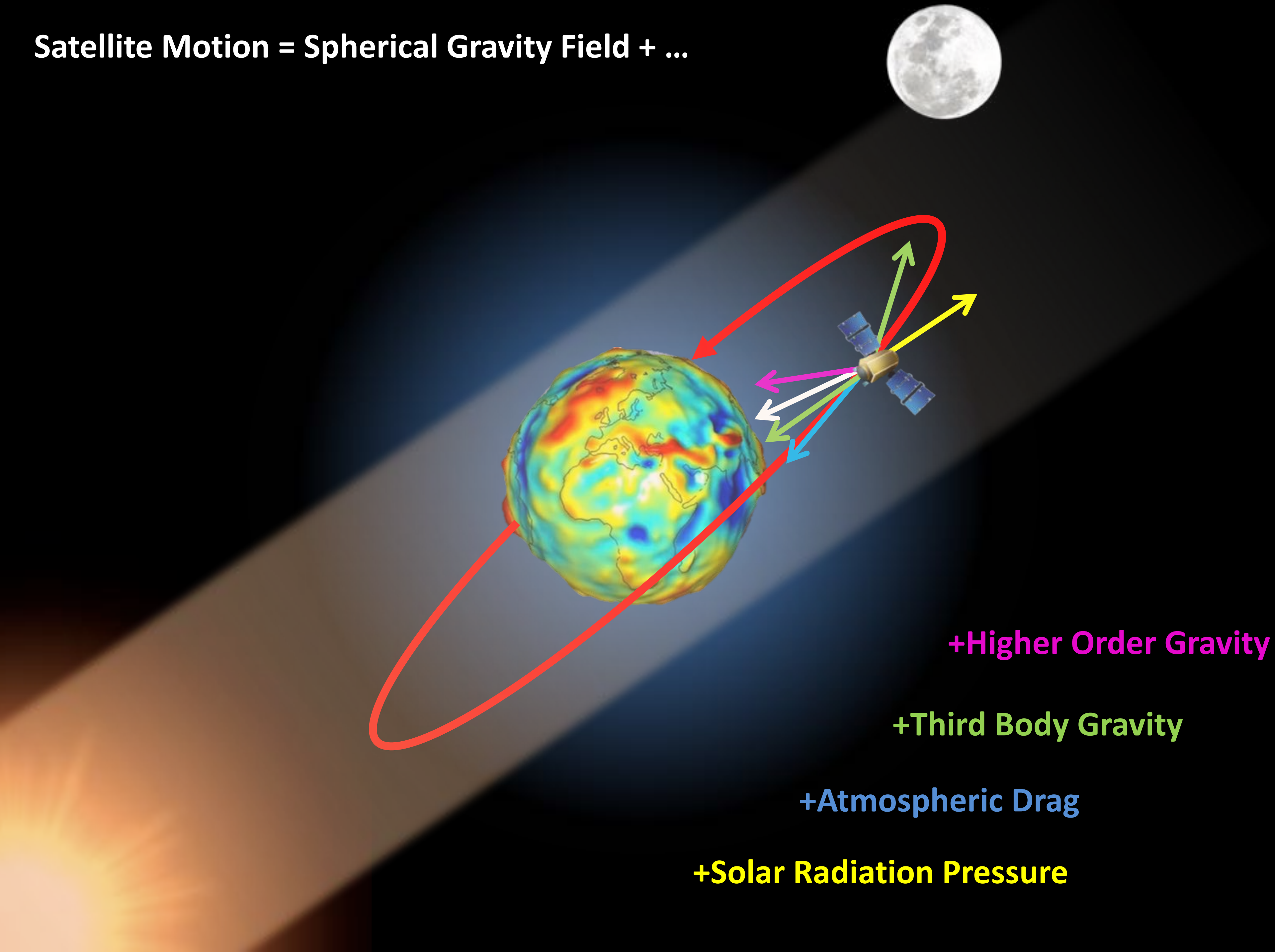
- **Low Power**: <120mW
- **Small Size**: 17 cc volume, 1.6"x1.4"x0.5"
- **Low Cost**: ~1000$, projected to be ~$300 in coming years.
- **Trade off**: ~100x worse at one day compared to GPS clocks.
- Can get comparable performance if you update once per orbit (100 minutes) instead of once per day.

Source: Symmetricom

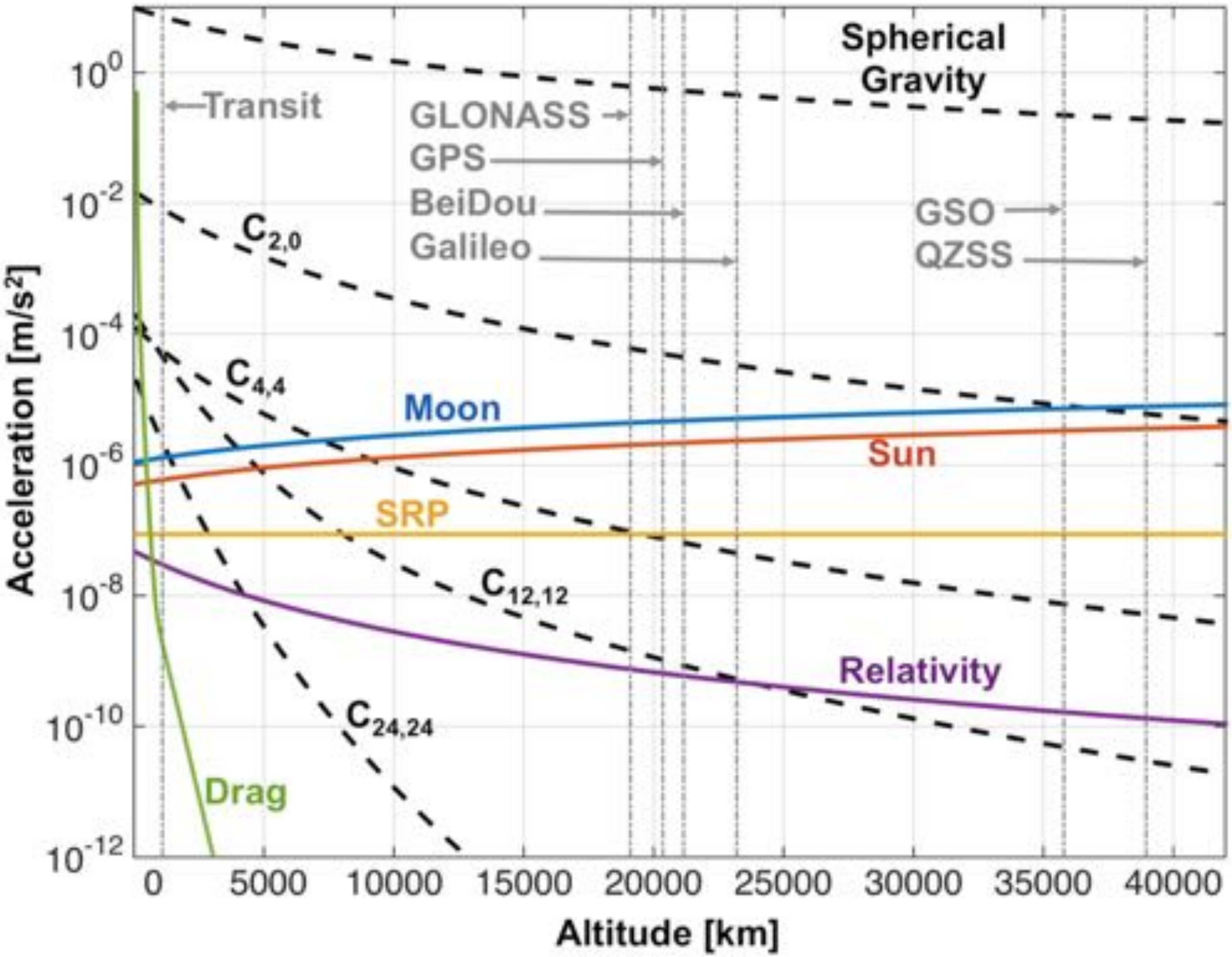
Orbits

- With the CSAC, we need to know the orbit within a 3D RMS position of 5 meters (~3 meters in along track, cross track, and radial directions – all equally important in LEO).
- Ephemeris accuracy will be largely based on the orbit determination, prediction, and parametrization.

Satellite Motion = Spherical Gravity Field + ...



Perturbation Forces as a Function of Altitude



GPS Ephemeris

6 Keplerian Orbital Elements

Correction to orbital rate

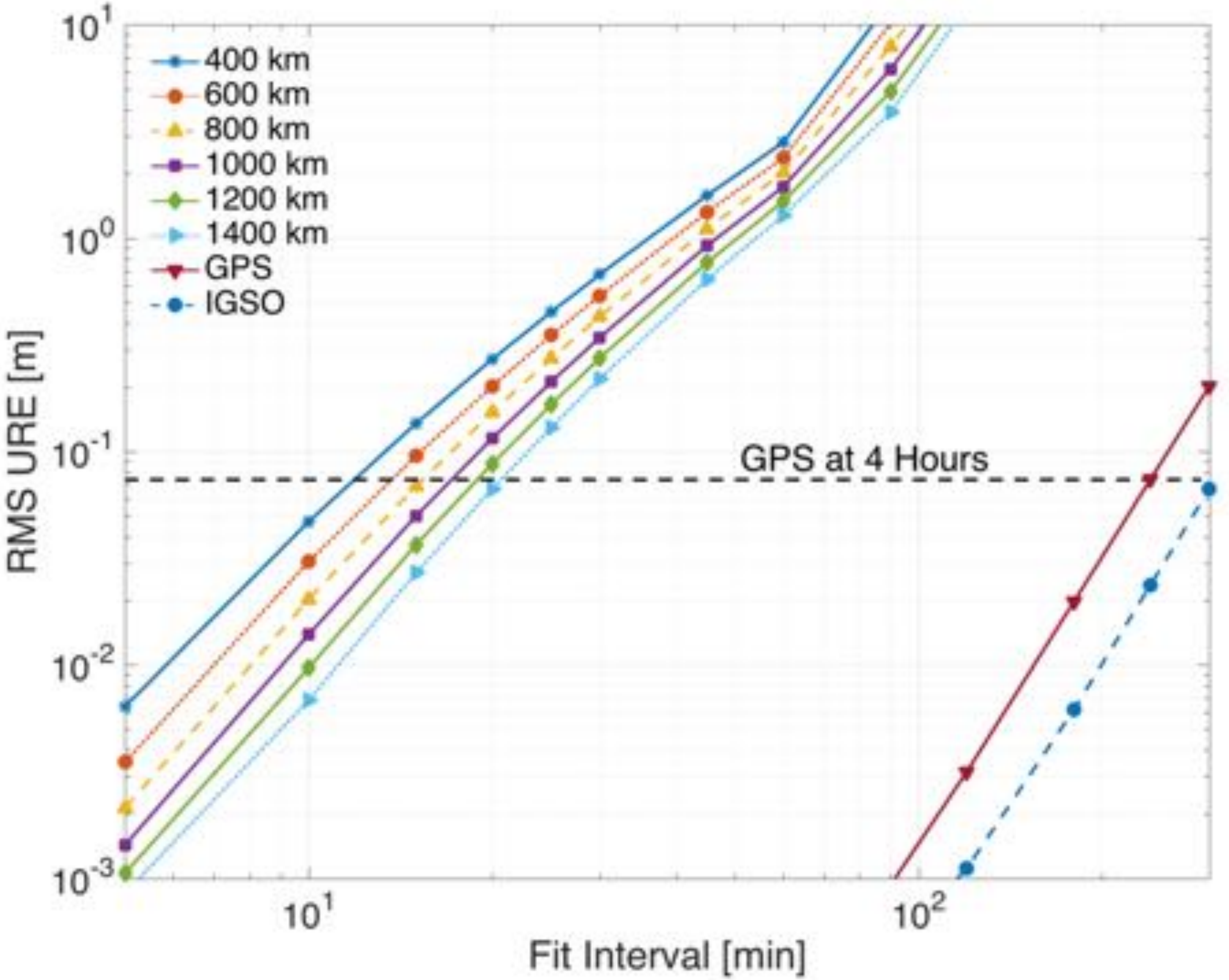
Account for orbit precession

Account for J_2 harmonic in radial, along-track, & cross-track

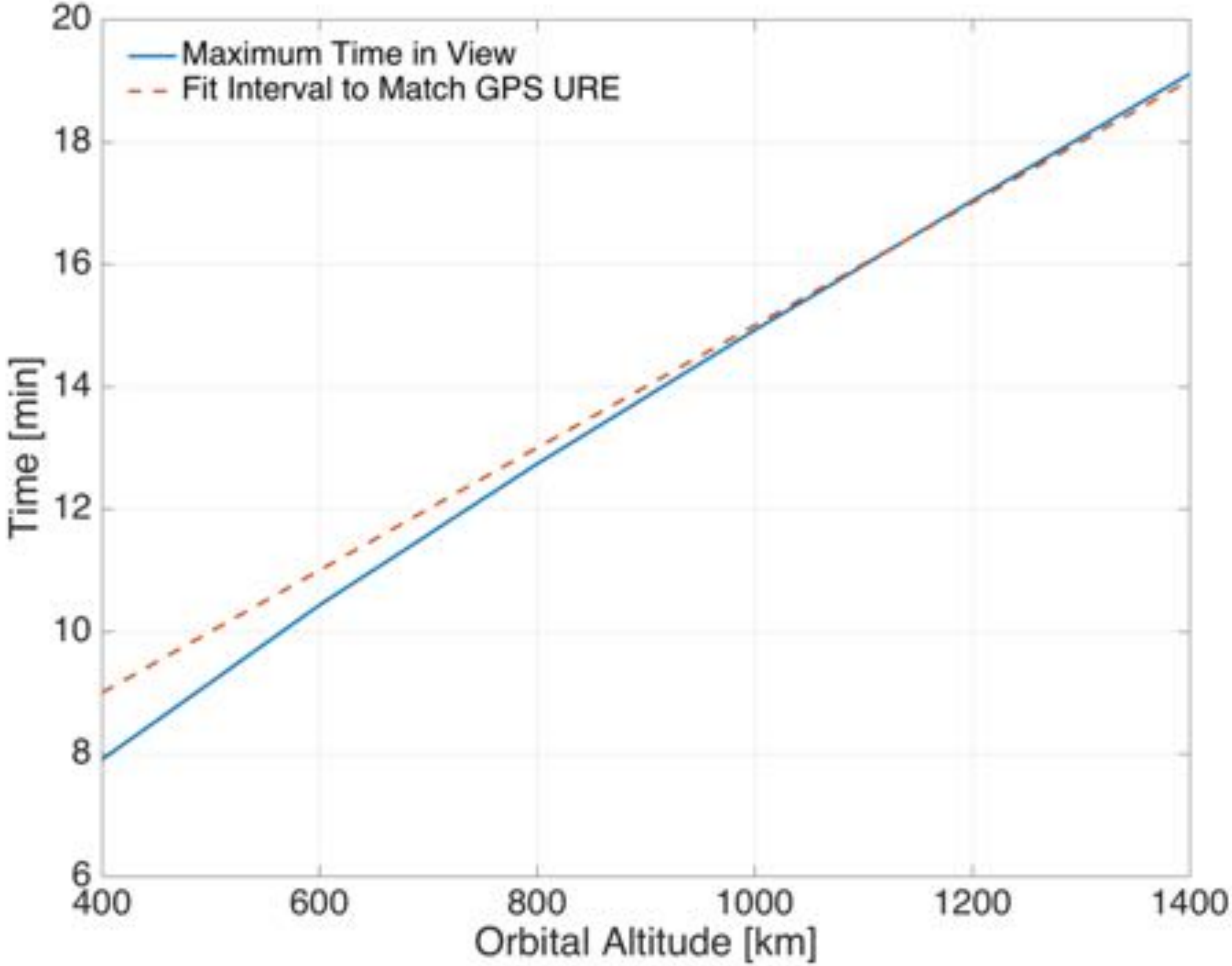
Table 20-II. Ephemeris Data Definitions

M_0	Mean Anomaly at Reference Time
Δn	Mean Motion Difference From Computed Value
e	Eccentricity
$\sqrt{A}$	Square Root of the Semi-Major Axis
Ω_0	Longitude of Ascending Node of Orbit Plane at Weekly Epoch
i_0	Inclination Angle at Reference Time
ω	Argument of Perigee
$\dot{\Omega}$	Rate of Right Ascension
IDOT	Rate of Inclination Angle
C_{uc}	Amplitude of the Cosine Harmonic Correction Term to the Argument of Latitude
C_{us}	Amplitude of the Sine Harmonic Correction Term to the Argument of Latitude
C_{rc}	Amplitude of the Cosine Harmonic Correction Term to the Orbit Radius
C_{rs}	Amplitude of the Sine Harmonic Correction Term to the Orbit Radius
C_{ic}	Amplitude of the Cosine Harmonic Correction Term to the Angle of Inclination
C_{is}	Amplitude of the Sine Harmonic Correction Term to the Angle of Inclination
t_{oe}	Reference Time Ephemeris (reference paragraph 20.3.4.5)
IODE	Issue of Data (Ephemeris)

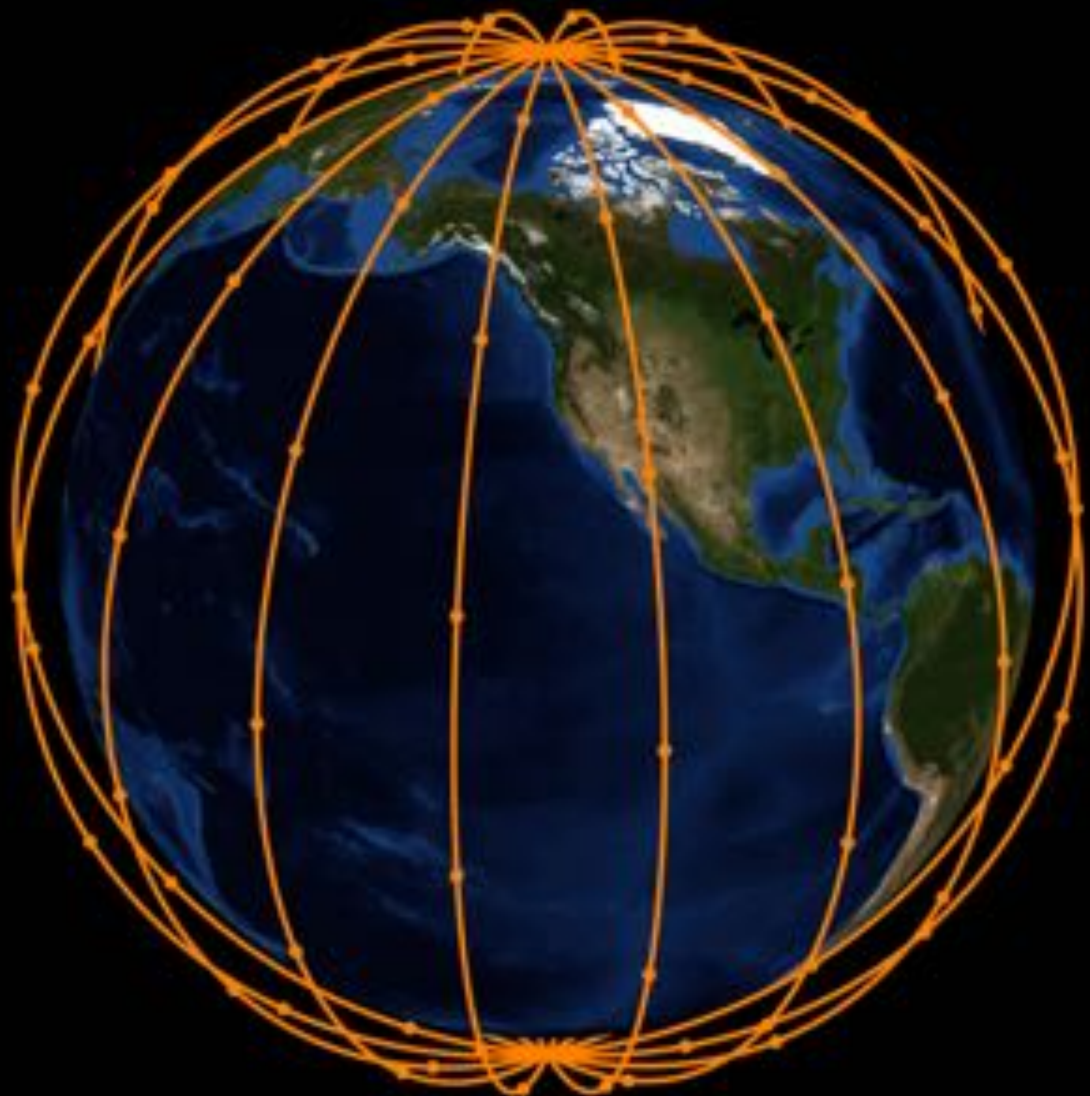
GPS Ephemeris Message Representation URE



LEO Fit Interval to Match GPS URE Performance

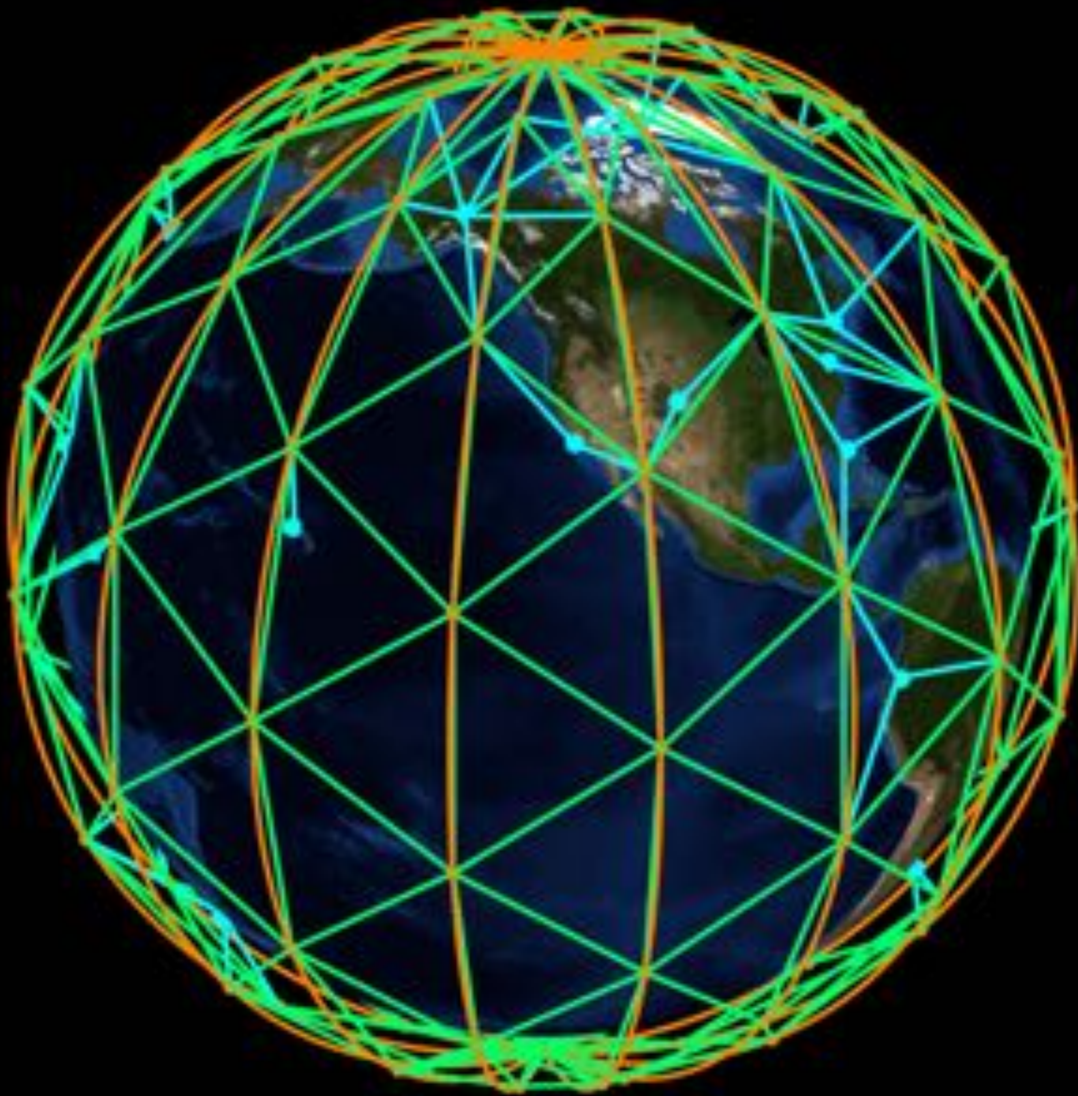


Orbit Determination?

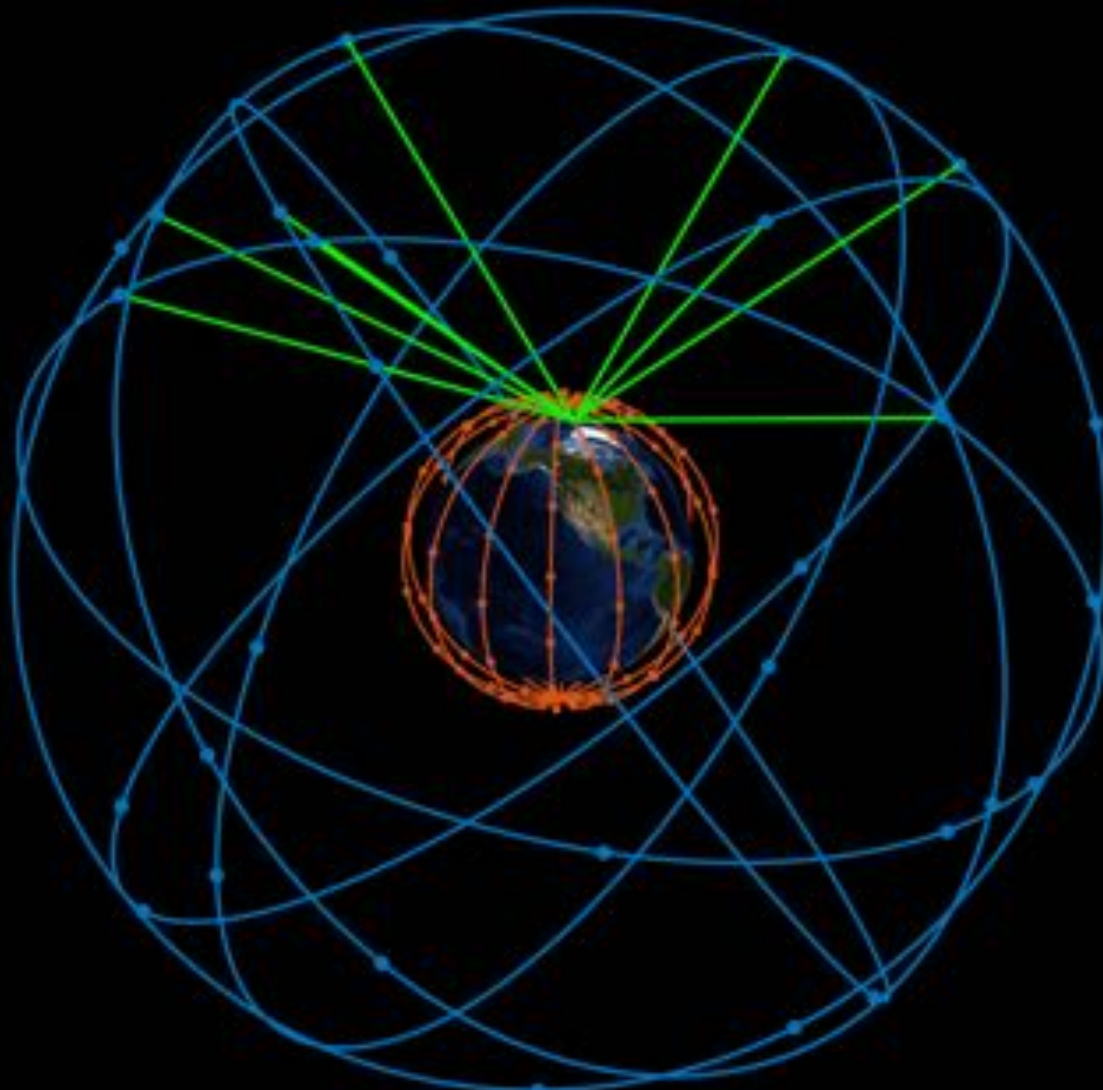


Ground Station Constraints

Ground Station + Crosslink Constraints

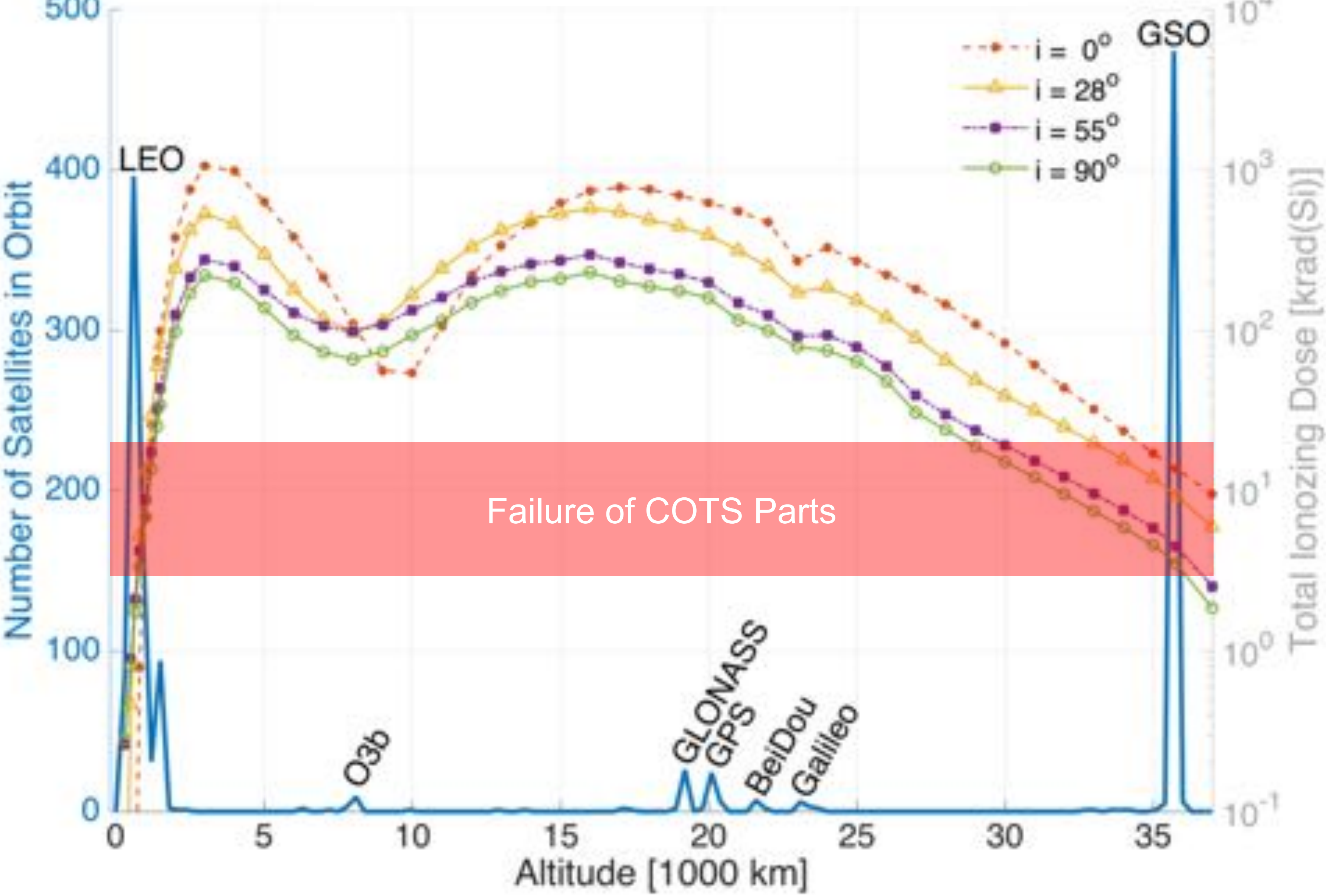


Use GPS Above



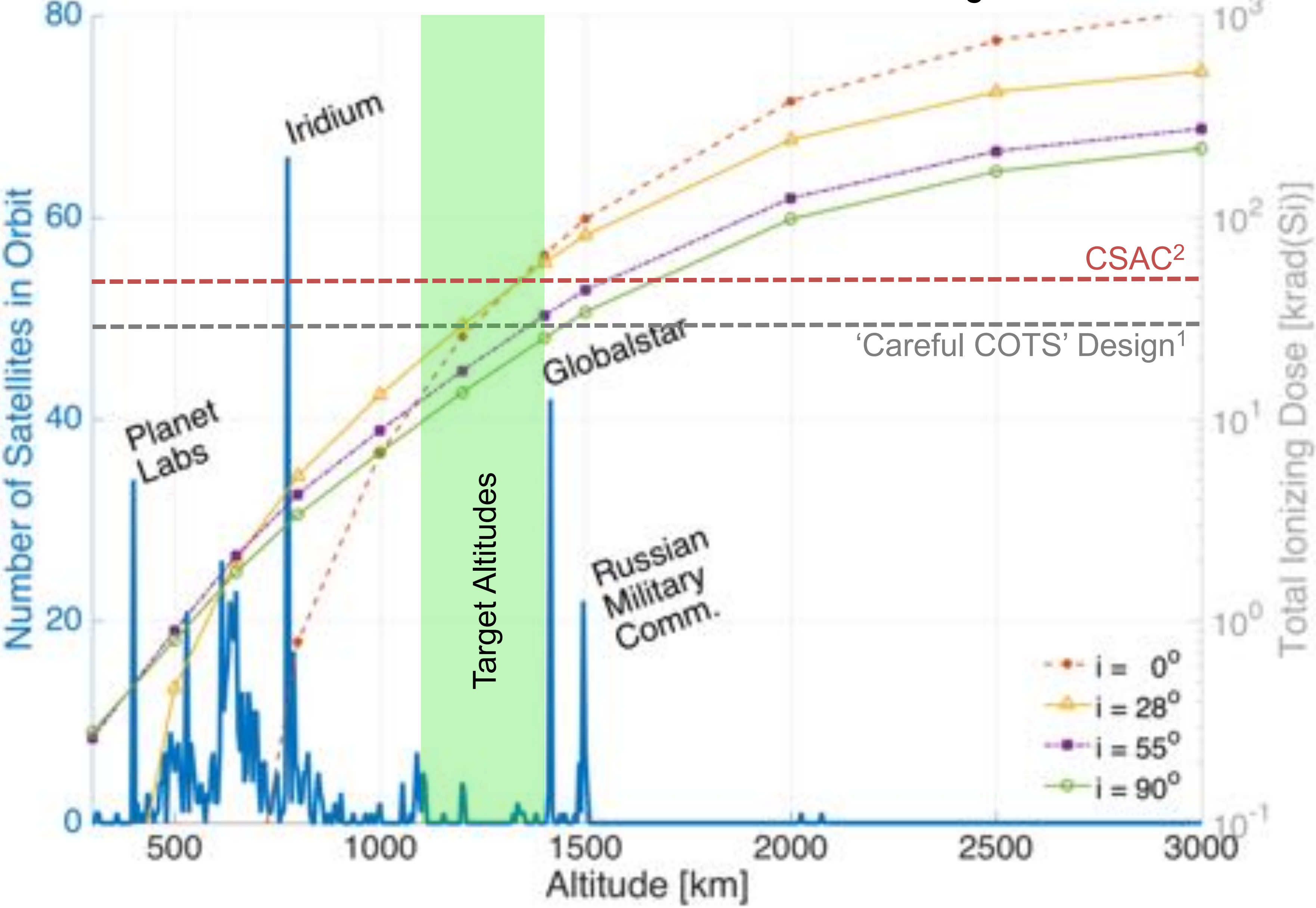
Total Ionizing Radiation Dose

For a 5 Year Mission with 5 mm Aluminum Shielding



Total Ionizing Radiation Dose

For a 5 Year Mission with 5 mm Aluminum Shielding



[1] D. Sinclair and J. Dyer, "Radiation Effects and COTS Parts in SmallSats," in *Proceedings of the 27th AIAA/USU Conference on Small Satellites*, Logan, UT, 2013.
[2] P. C. M. Stanczyk, M. Silveira, "Space CSAC: Chip- Scale Atomic Clock for Low Earth Orbit Applications," presented at the Proceedings of the 45th Annual Precise Time and Time Interval Systems and Applications Meeting, Bellevue, WA, 2013.

Conclusions

- Navigation from LEO:
  - Strength in numbers: more satellites and better geometry allows looser constraints on the URE (Orbit + Clock).
  - Less harsh radiation environment allows for ‘careful’ COTS design.
- Potential Benefits:
  - Closer satellites can mean stronger signals and resistance to jamming.
  - Geometric diversity: LEOs move across the sky faster than MEOs, giving some multipath rejection.
  - Constellation is more robust to single satellite failures.