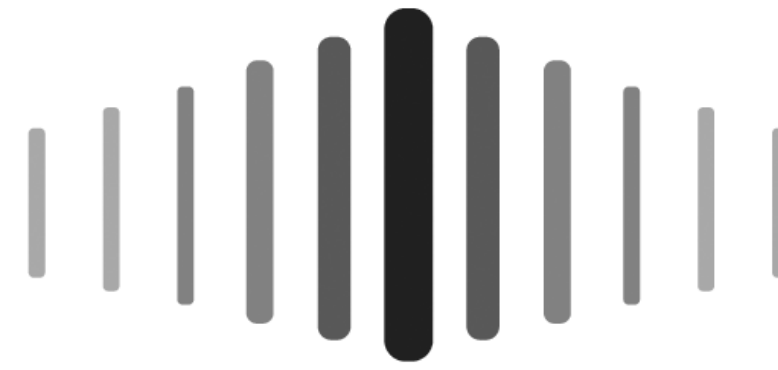
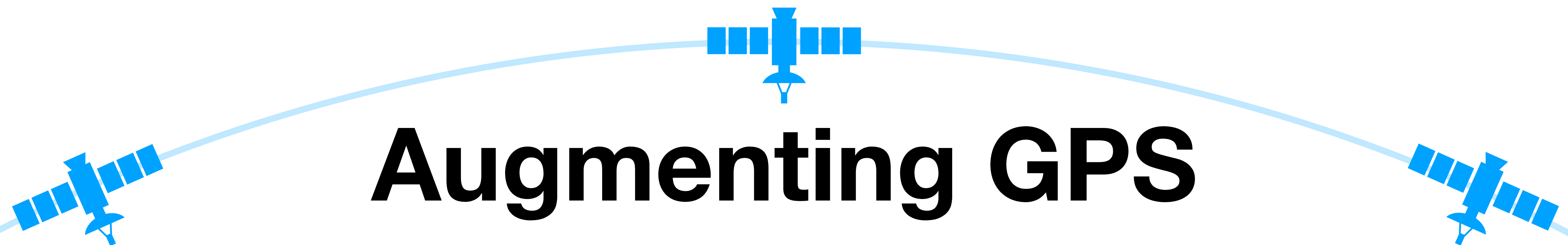


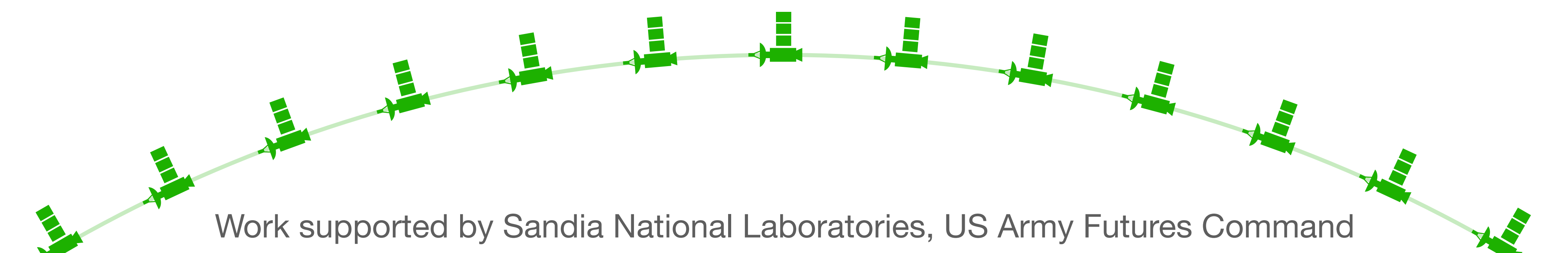


THE UNIVERSITY OF TEXAS AT AUSTIN
RADIONAVIGATION LABORATORY



Augmenting GPS with PNT from LEO

Peter Iannucci • Todd Humphreys
The University of Texas at Austin



Work supported by Sandia National Laboratories, US Army Futures Command

Call to Action for GPS

- Protect
- Toughen
- Augment



LEO

- DARPA: Blackjack
 - “Pivot to LEO”
 - Comms+PNT payloads (in phase 2)
 - Government-owned vehicles (\$4-15 million per SV)
- DLR + GFZ Potsdam: Kepler
 - Next-generation Galileo
 - Space-based atmosphere-free global synchronization + precision orbit determination



Commercial LEO

OneWeb  Satellites

A **OneWeb** and **Airbus** joint venture

2,000 satellites

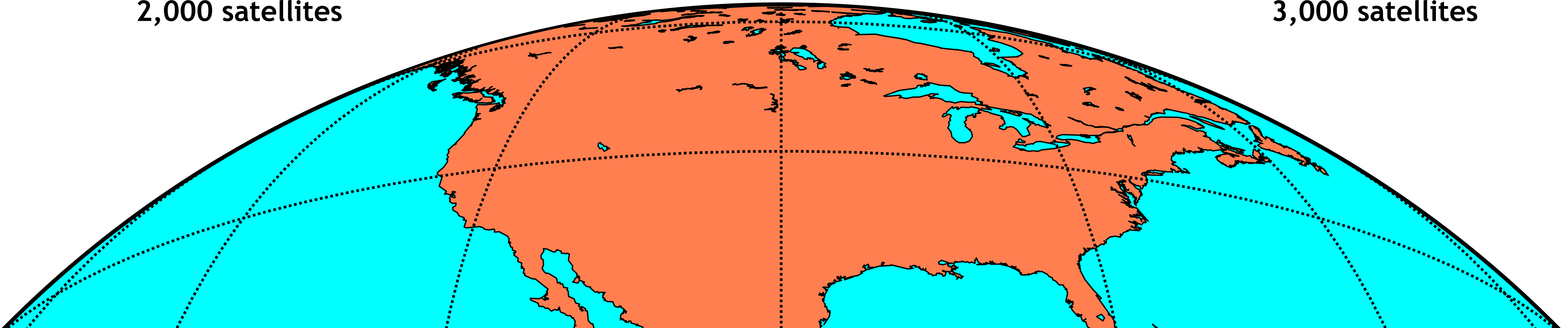


STARLINK

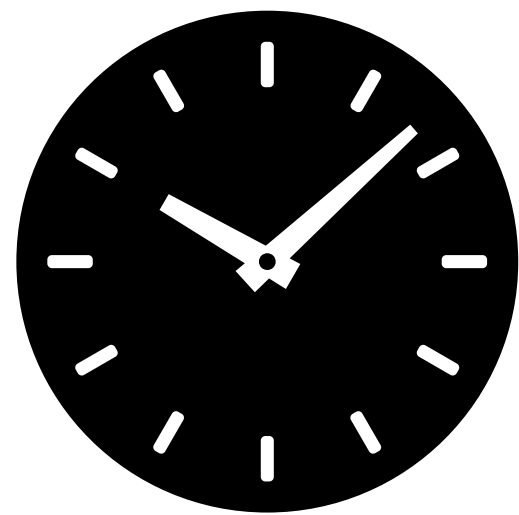
12,000-30,000 satellites

Kuiper Systems
amazon

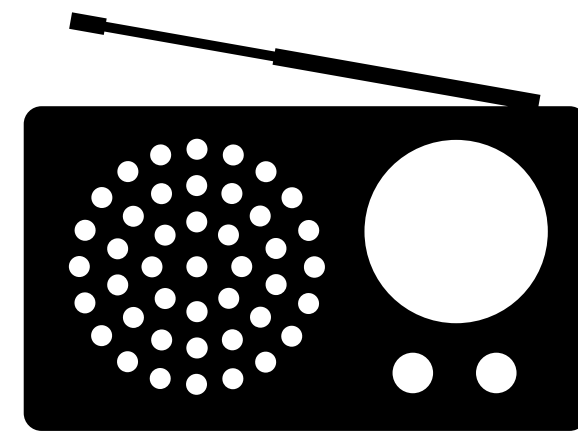
3,000 satellites



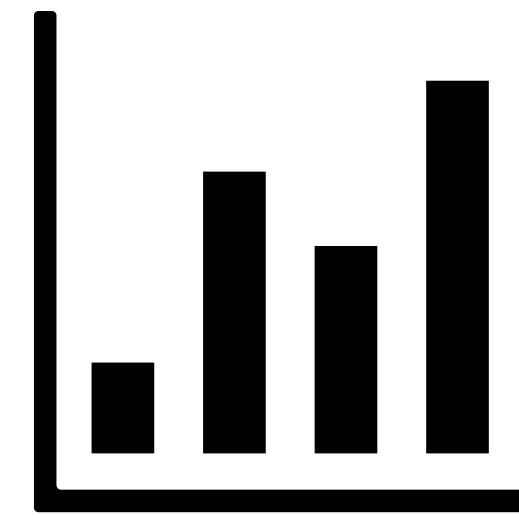
Elements of Fused PNT



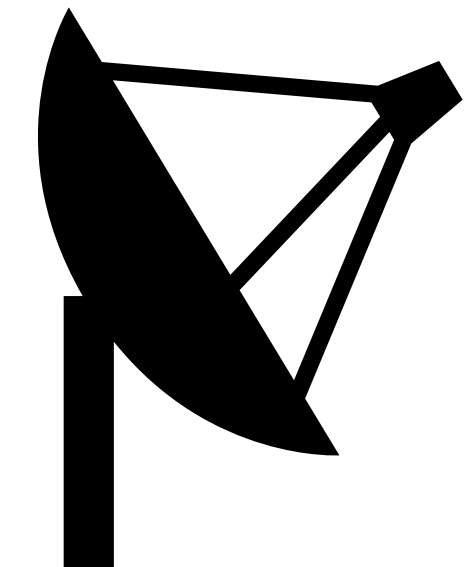
Clock



Radio



Spectrum



Antenna

Already present ... just not purpose-built!

Q: Can we compromise on clock quality?

A: Yes. Discipline to GPS and update frequently. (e.g. 50s)

Q: Can we compromise on signal structure?

A: Yes. High SNR, wide bandwidth.

Q: Can we share spectrum, time, and antennas with (primary) data customers?

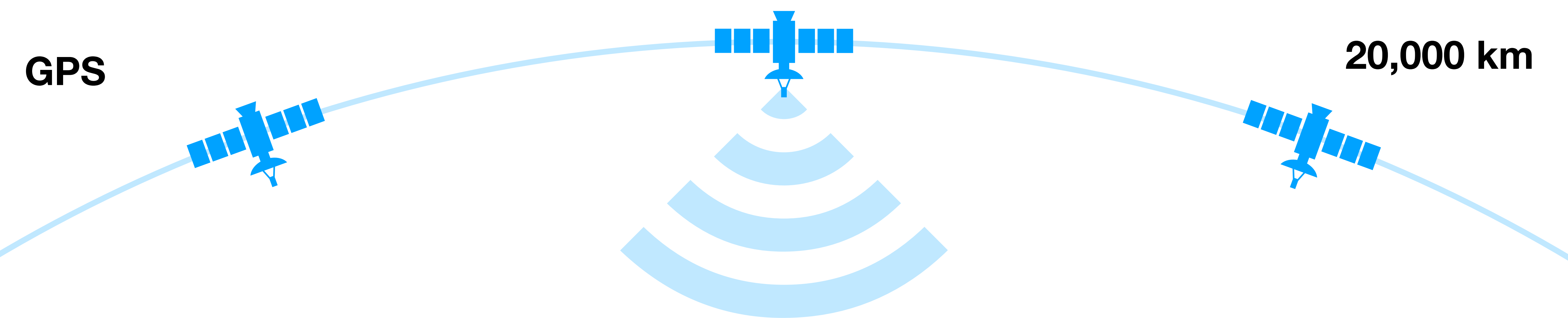
A: Yes. TDMA+FDMA, high SNR. Service cost per 20km spot beam $\approx$ cost of 1 MB/s downlink bandwidth

Prior work

- High-Integrity GPS program (Iridium, Boeing, Coherent Navigation, 2007-2011)
 - Now Satelles
 - Not single-epoch (Transit-style positioning)
- Tyler Reid, A. Neish, P. Enge (2016-2018)

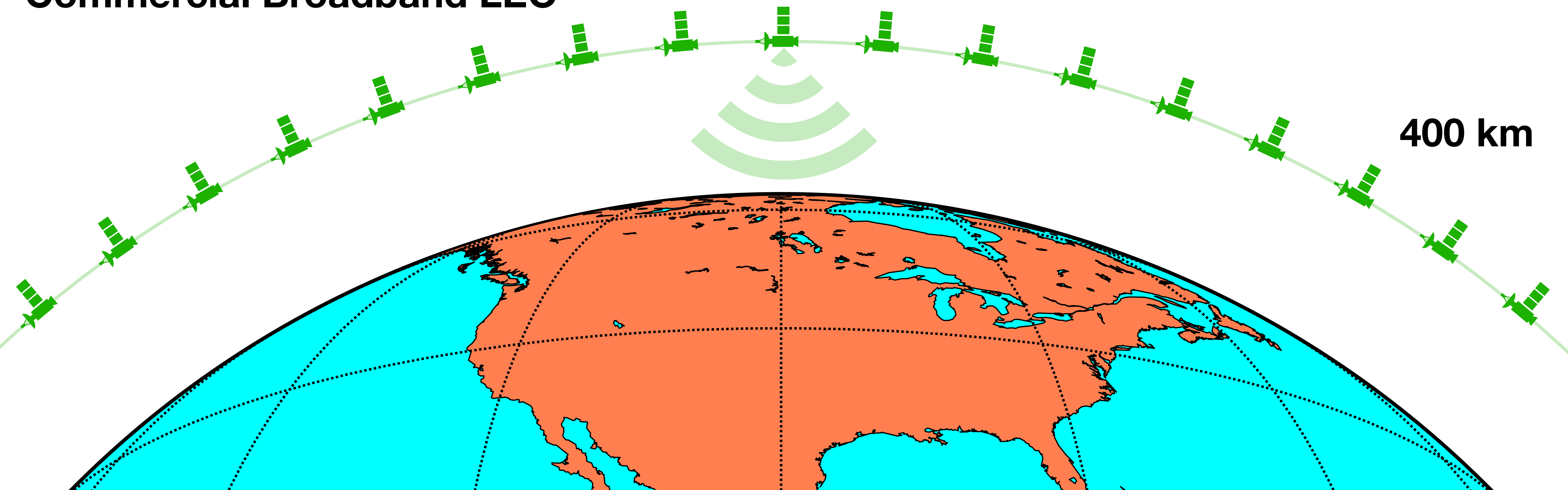
GPS

20,000 km



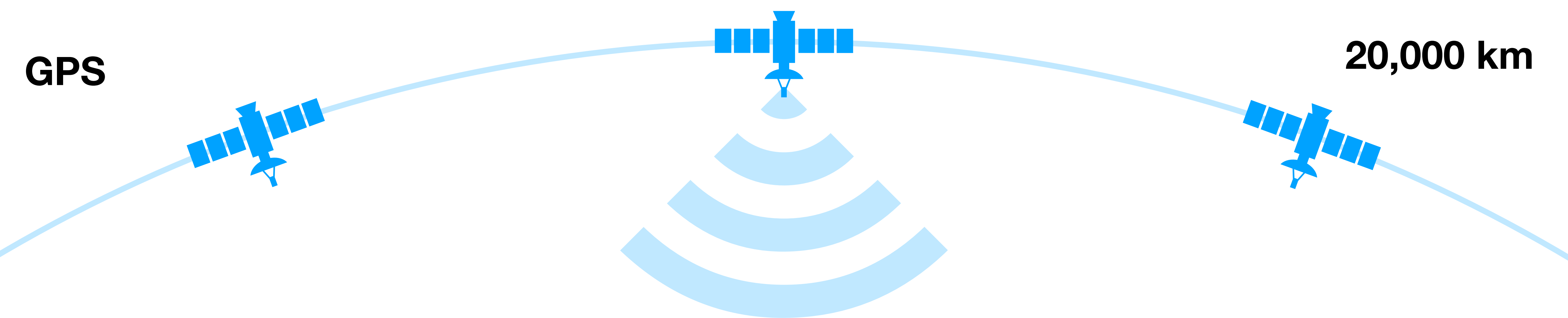
Commercial Broadband LEO

400 km



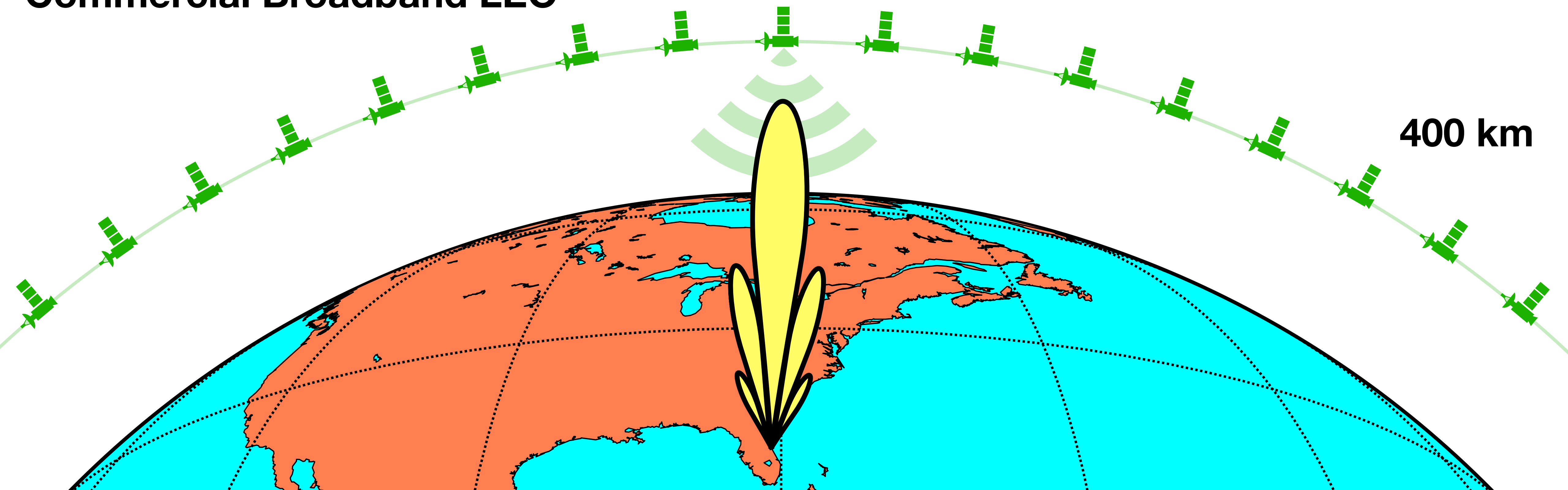
GPS

20,000 km



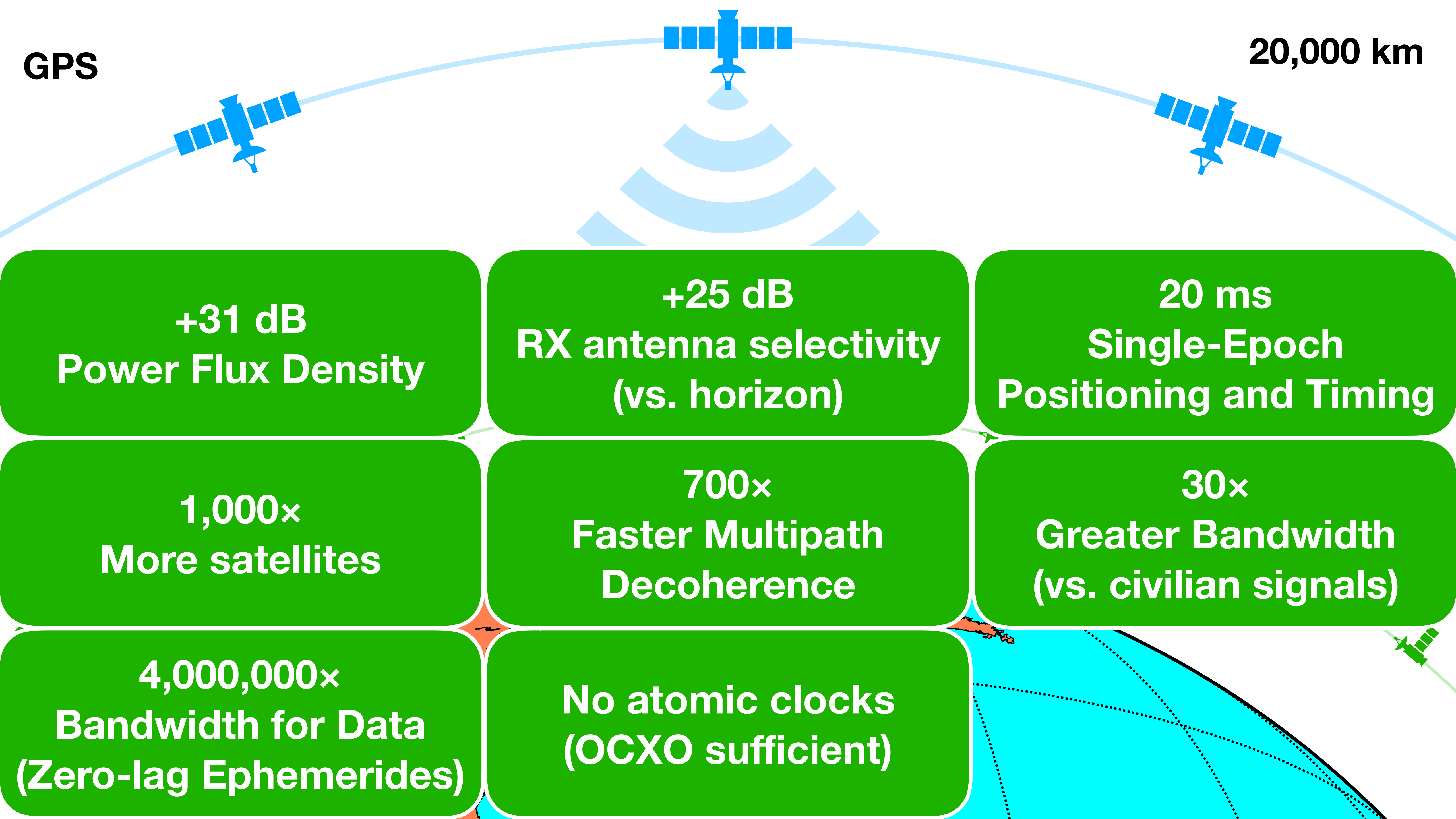
Commercial Broadband LEO

400 km



GPS

20,000 km



Bottom Line

**+56 dB
Anti-Jam**

**95% user error:
32cm (AoE 1s)
1.21m (AoE 50s)**

**Hardware costs to
US Govt:
\$0.00**

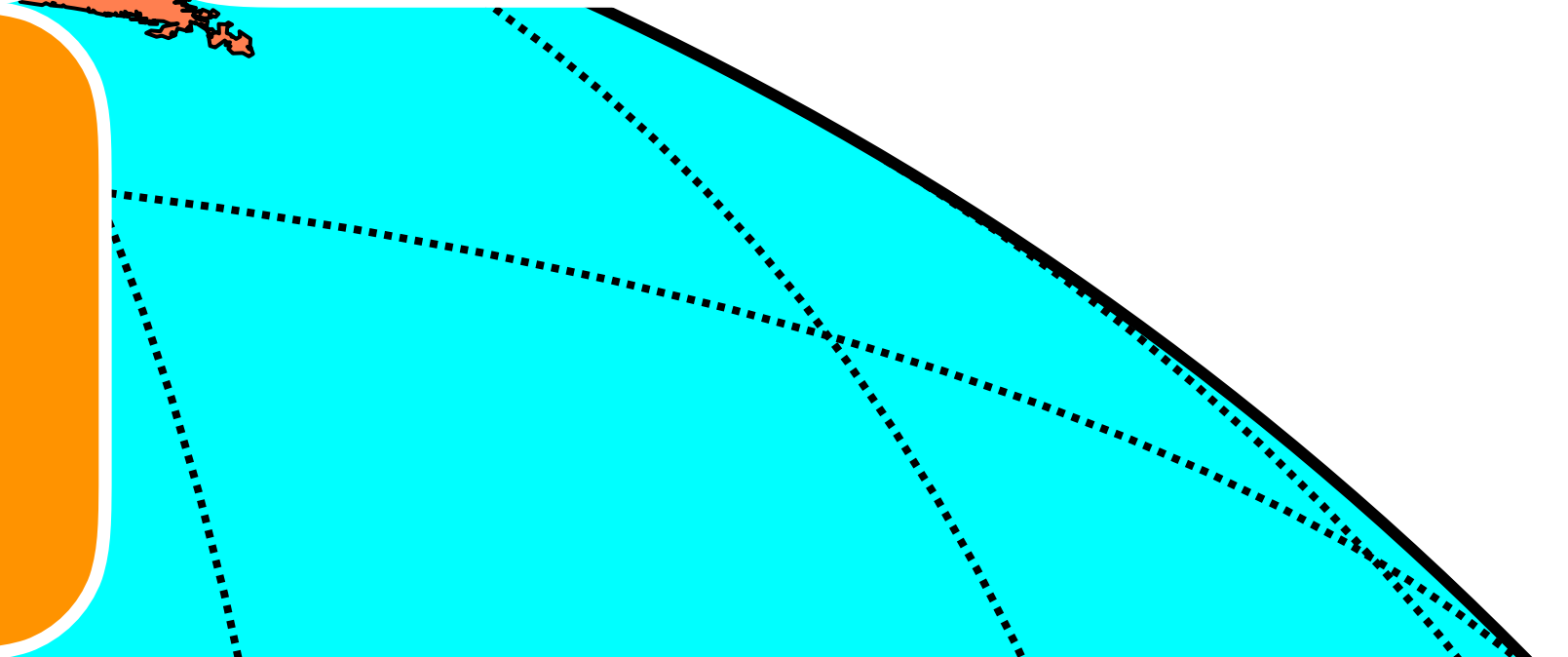
**Reliant on Commercial
Service Providers**

**Pay-as-you-go
(cf. Iridium)**

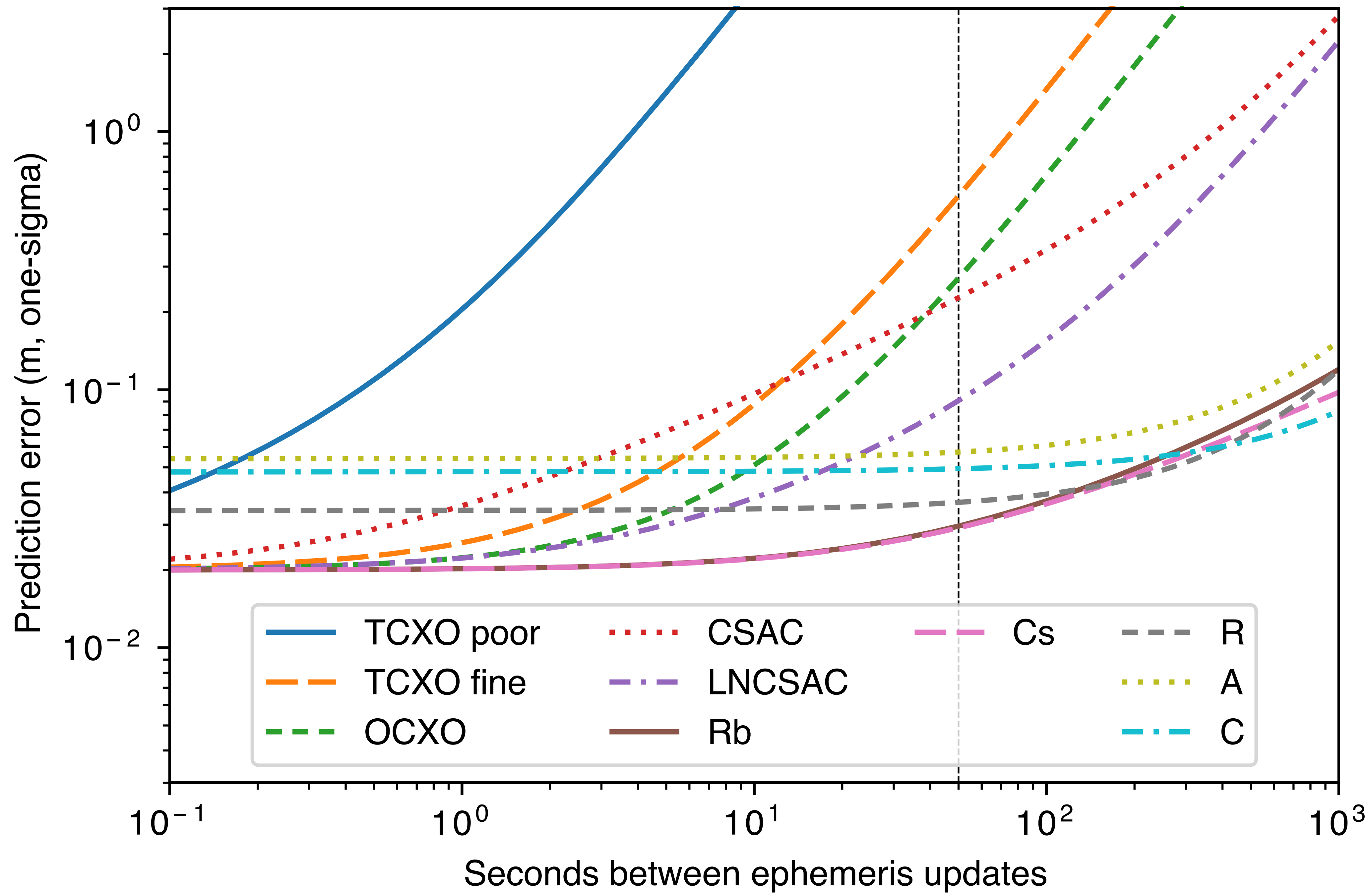
**Not resilient to
global GPS Outage
(yet)**

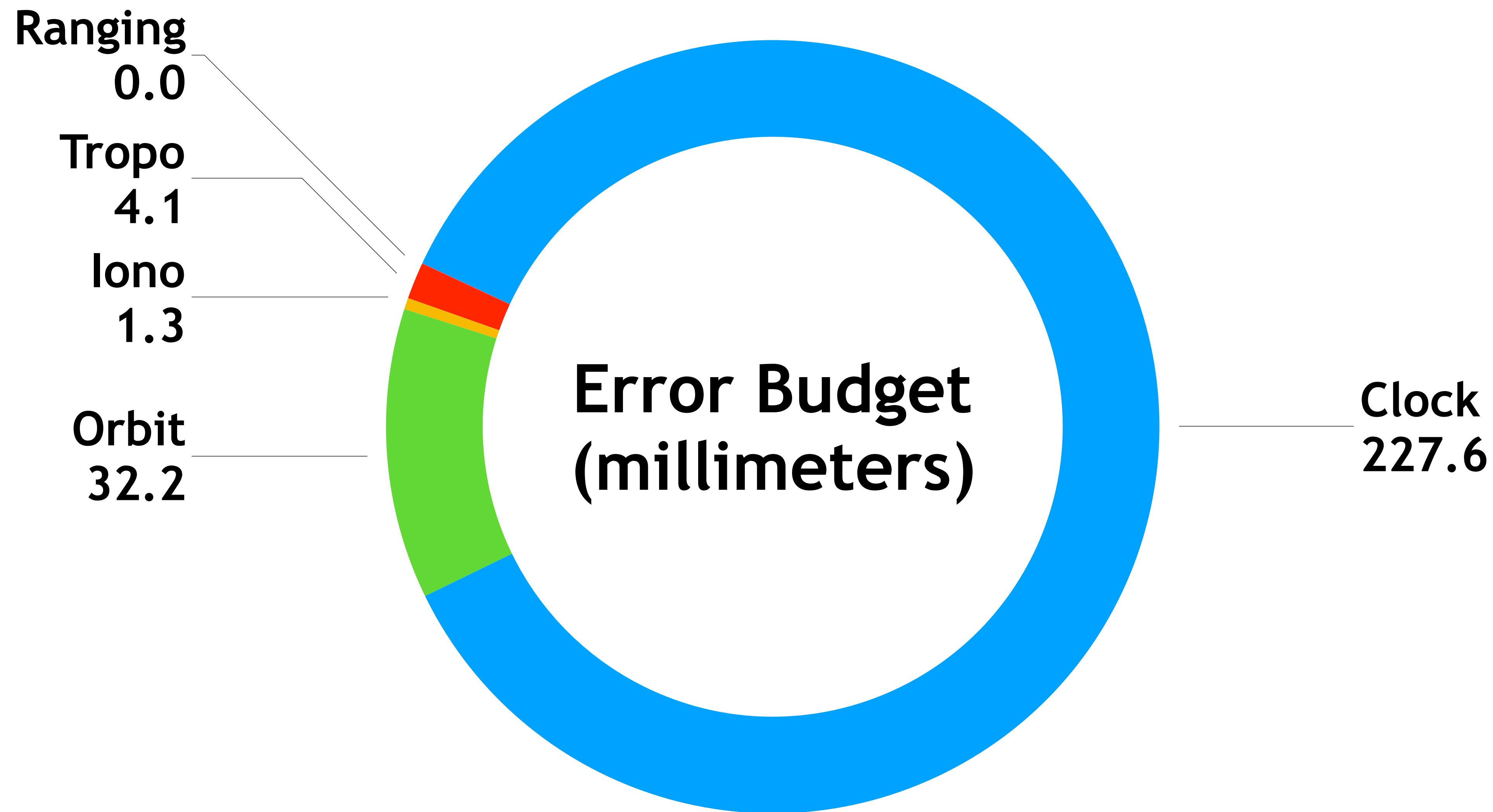
Intermittent Ranging

**Bulky RX Antenna
("pizza-box sized")**

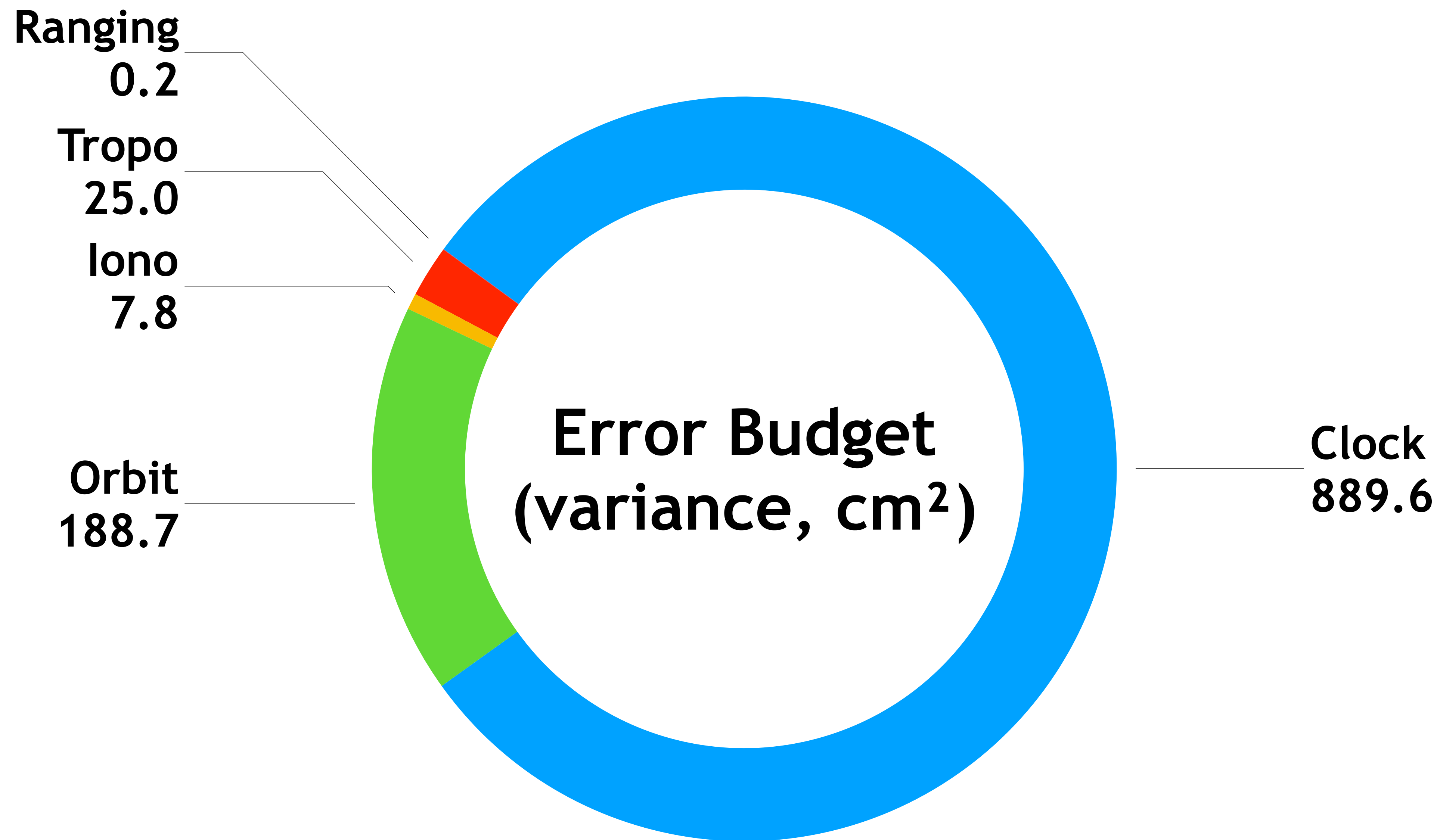


Back-up Slides

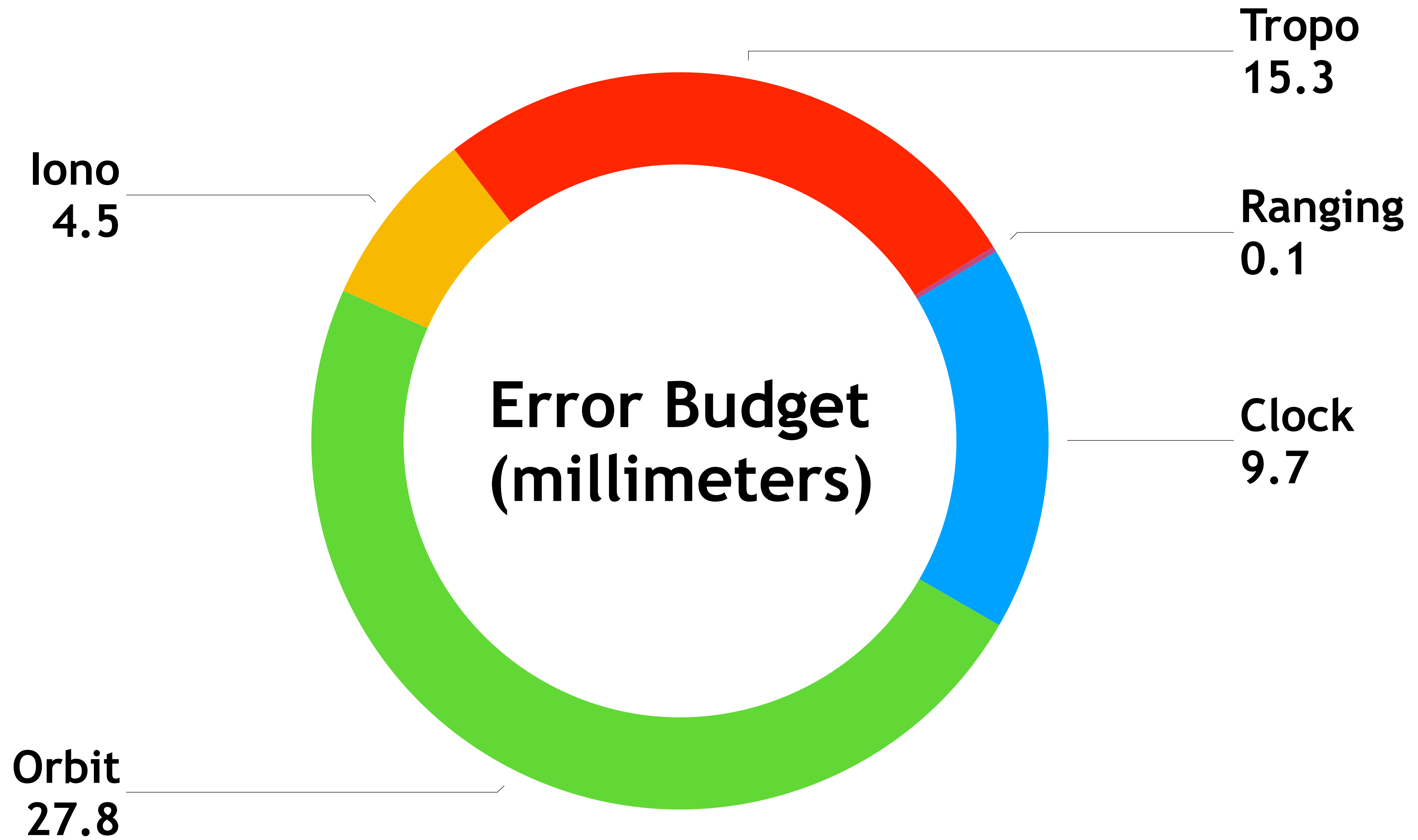




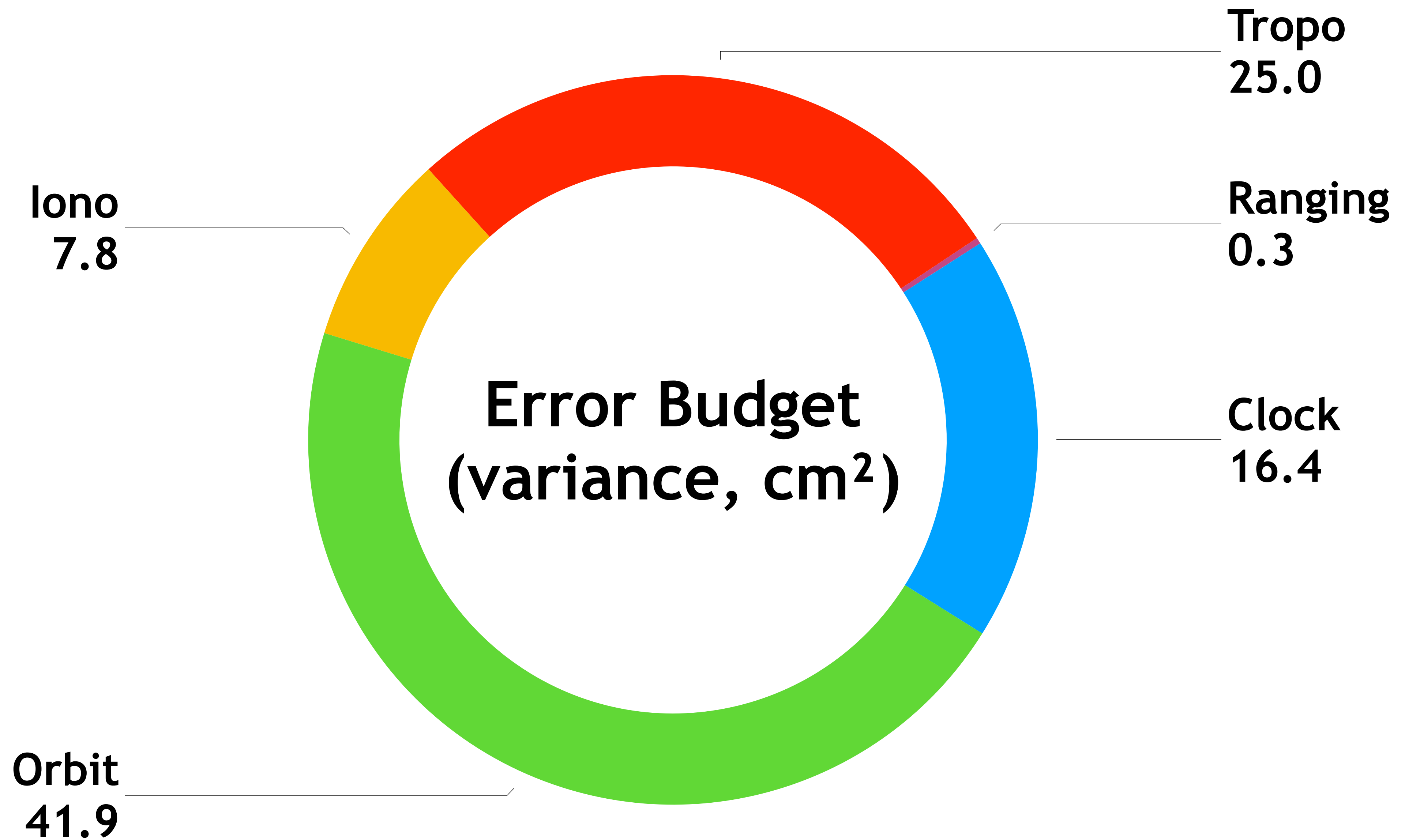
Age-of-Ephemeris = 50s



Age-of-Ephemeris = 50s

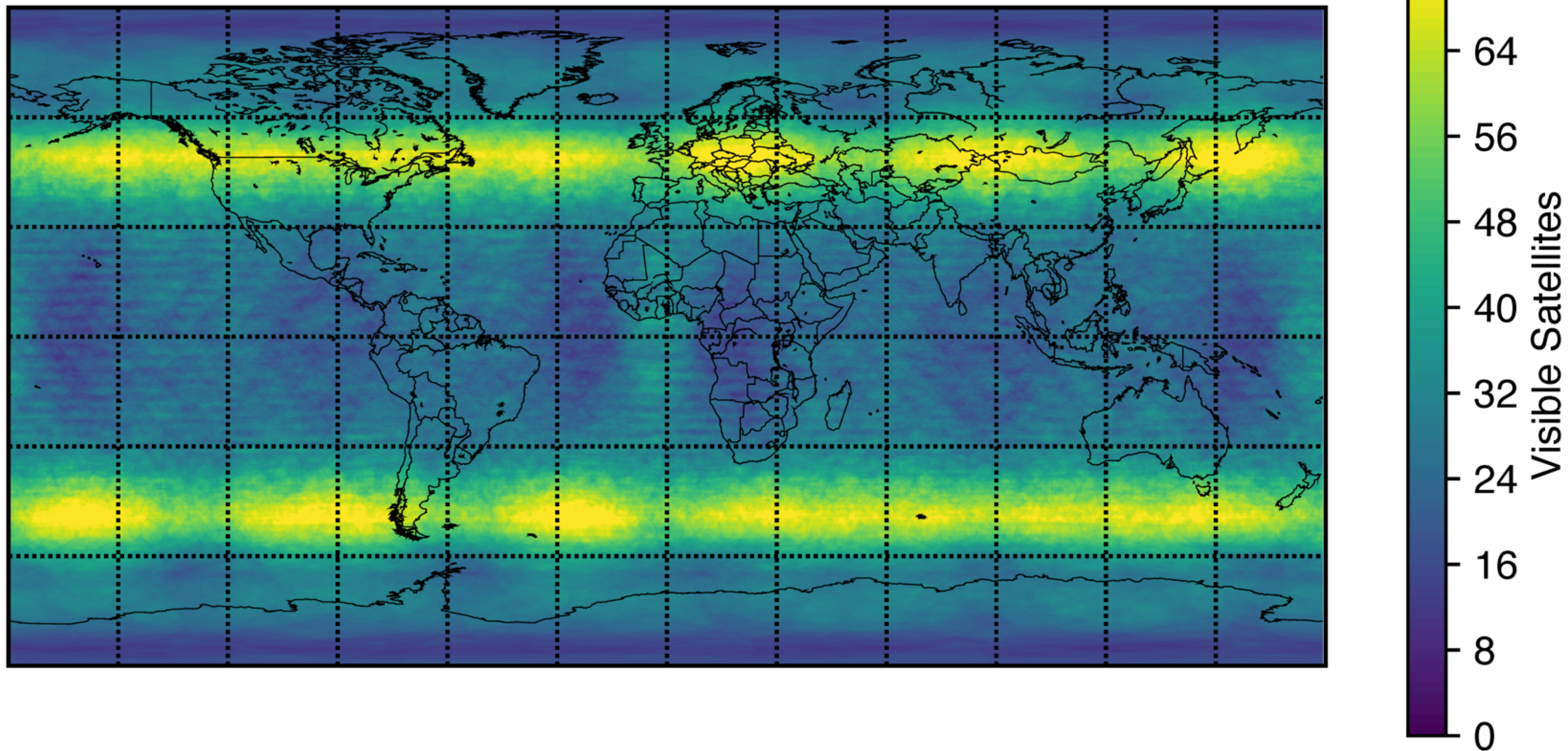


Age-of-Ephemeris = 1s

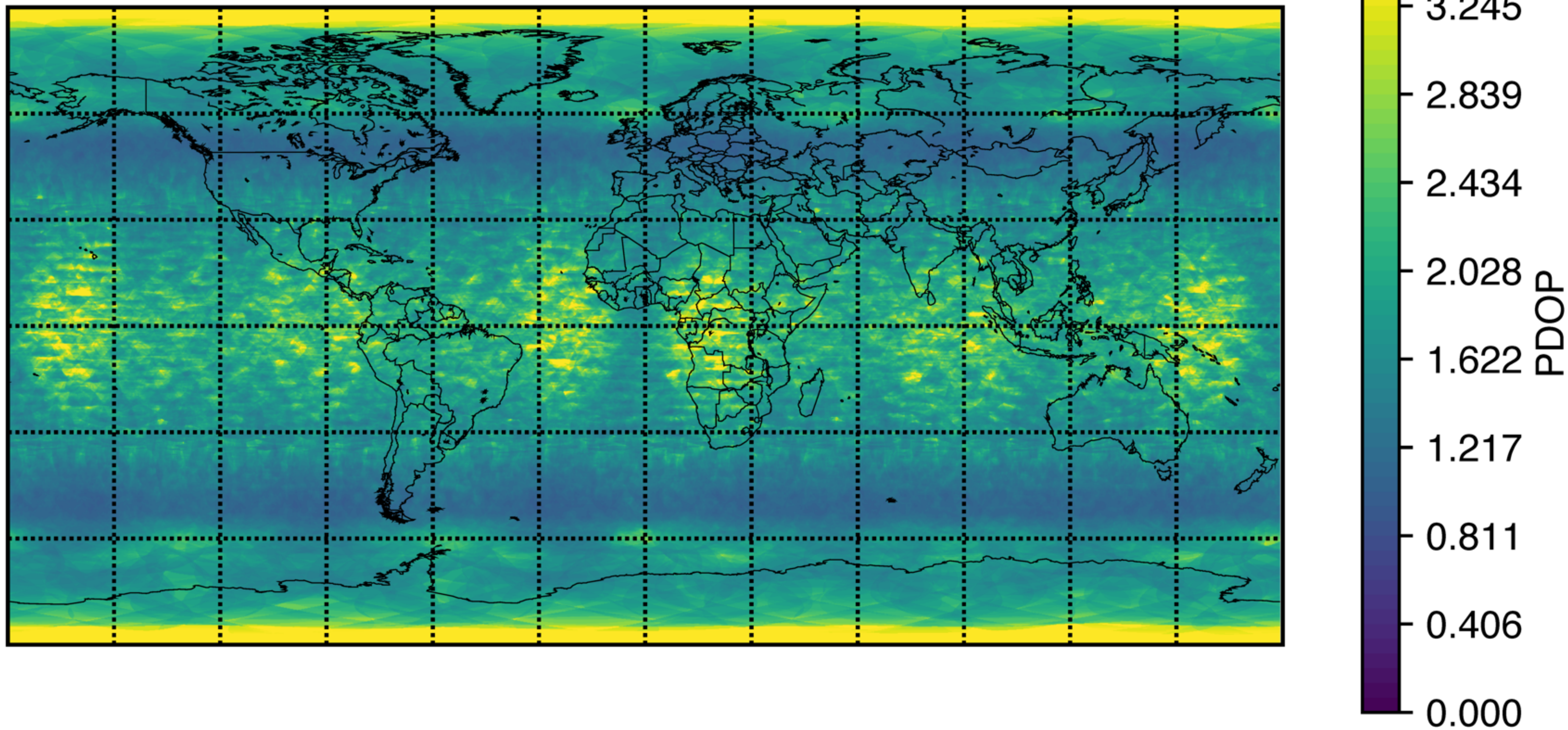


Age-of-Ephemeris = 1s

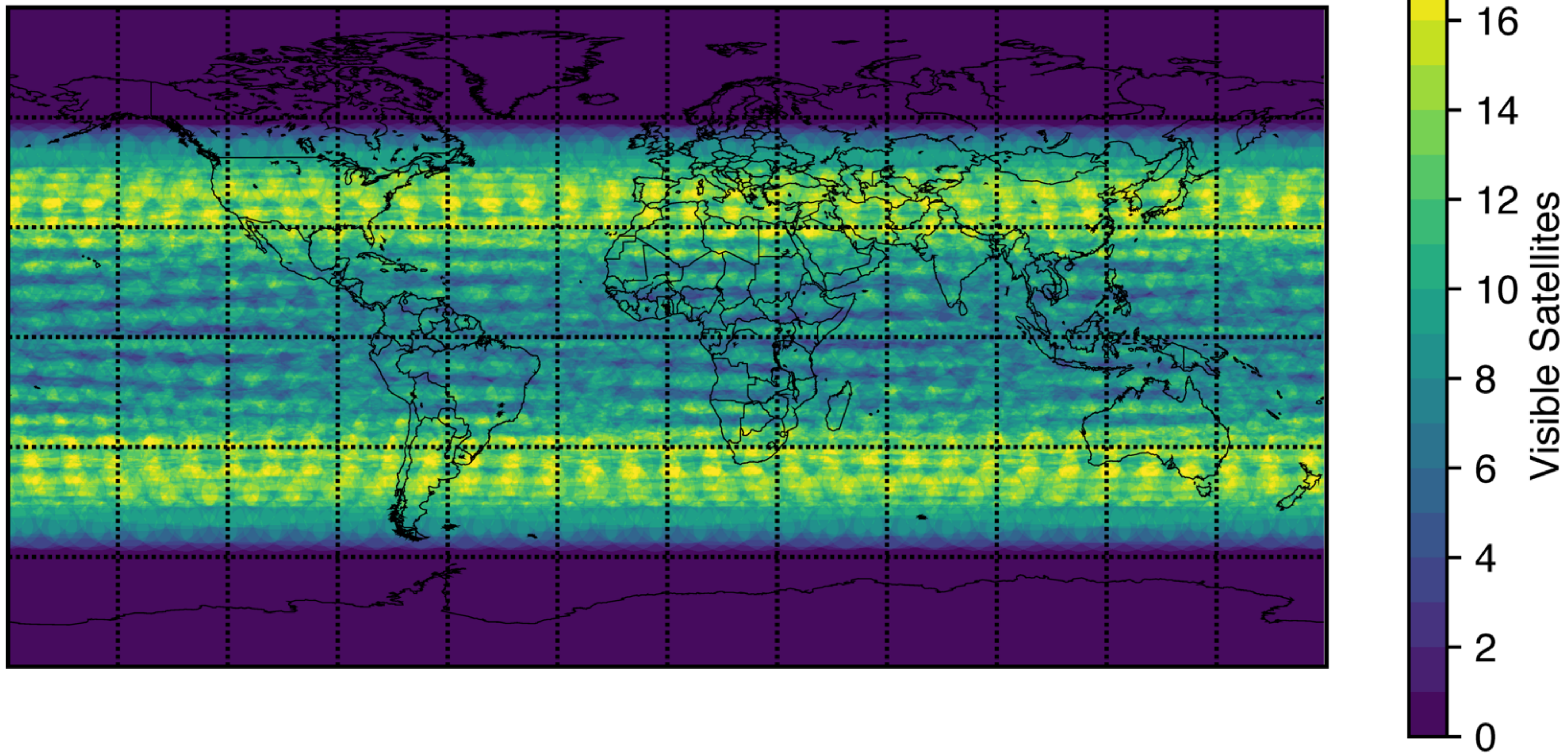
Starlink Visible Satellites



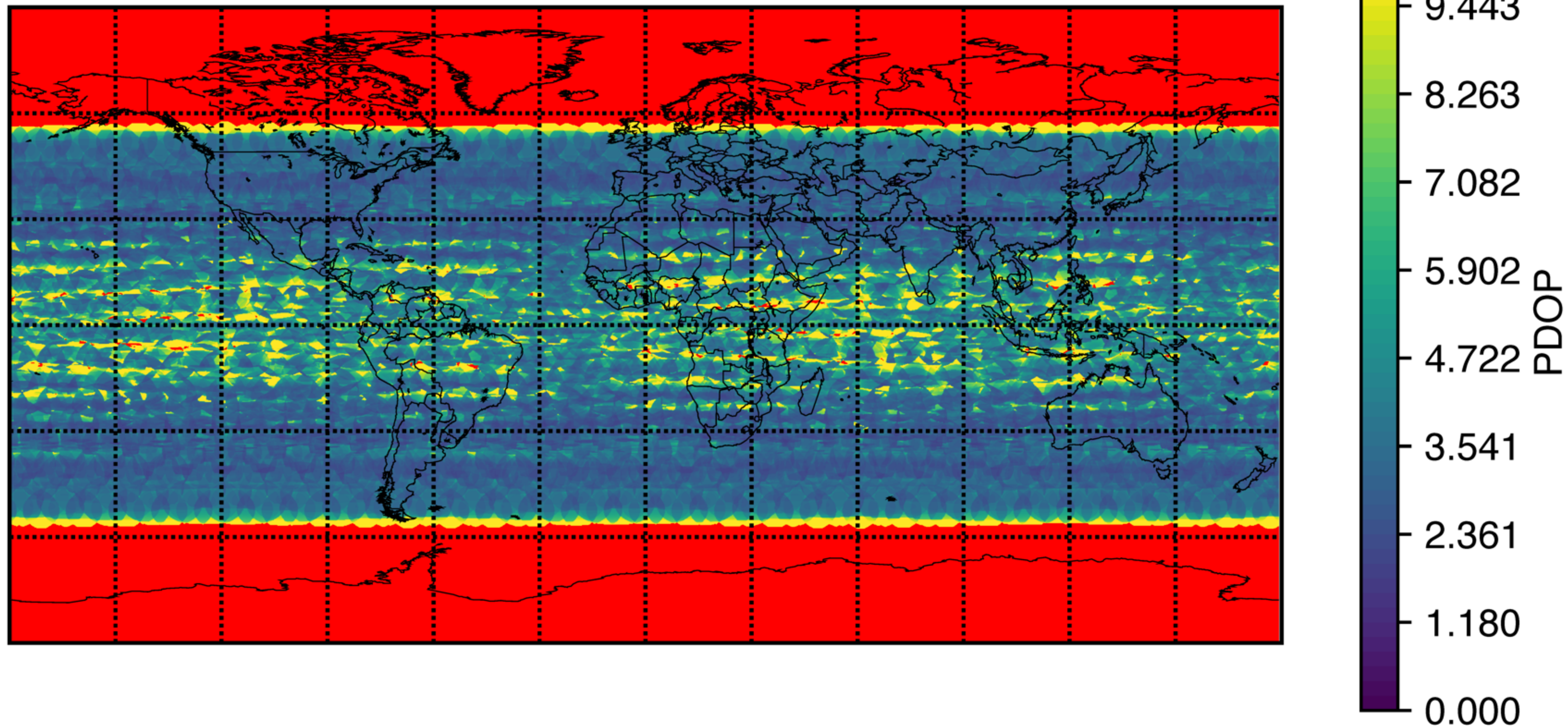
Starlink PDOP

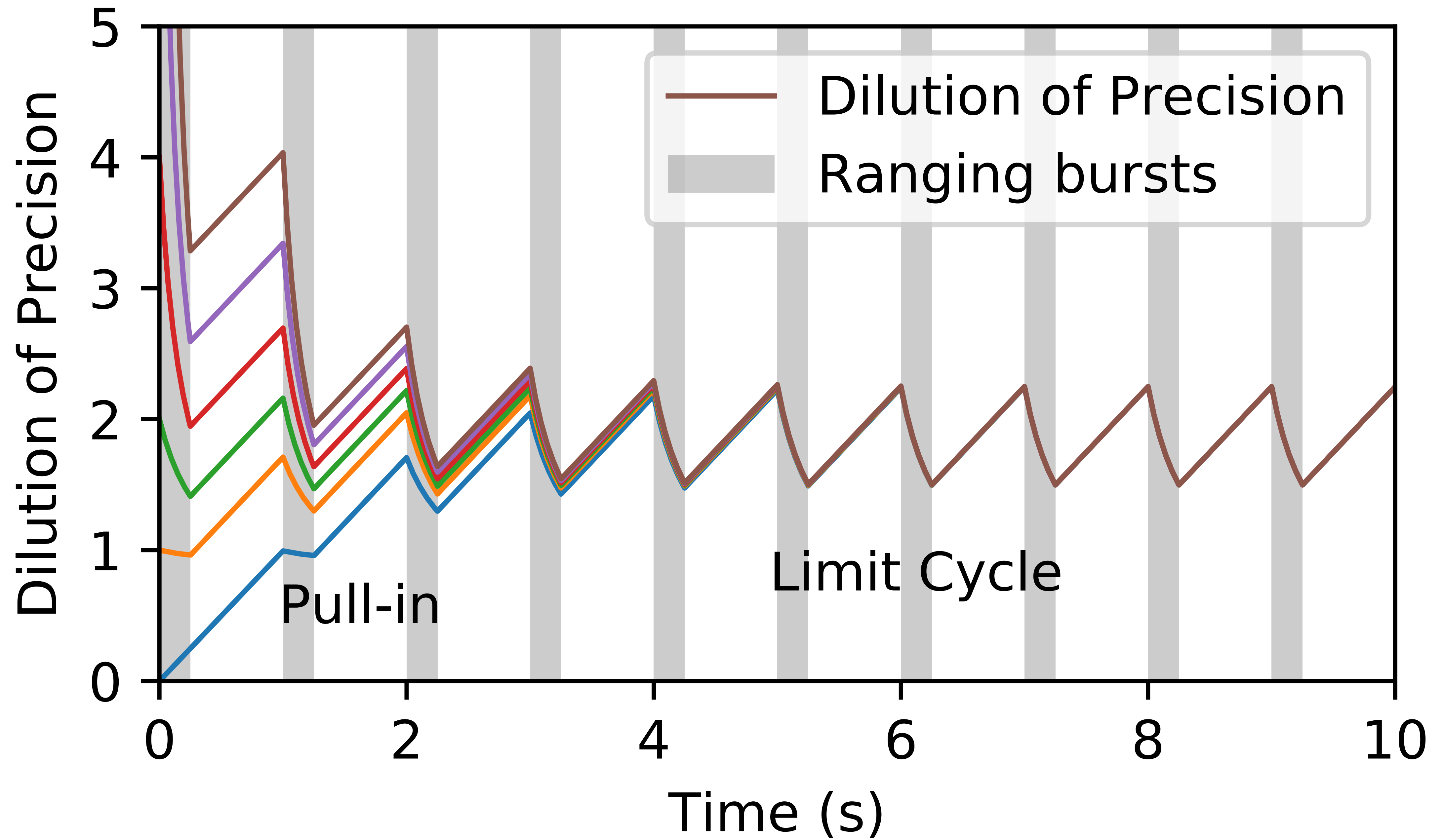


Kuiper Visible Satellites

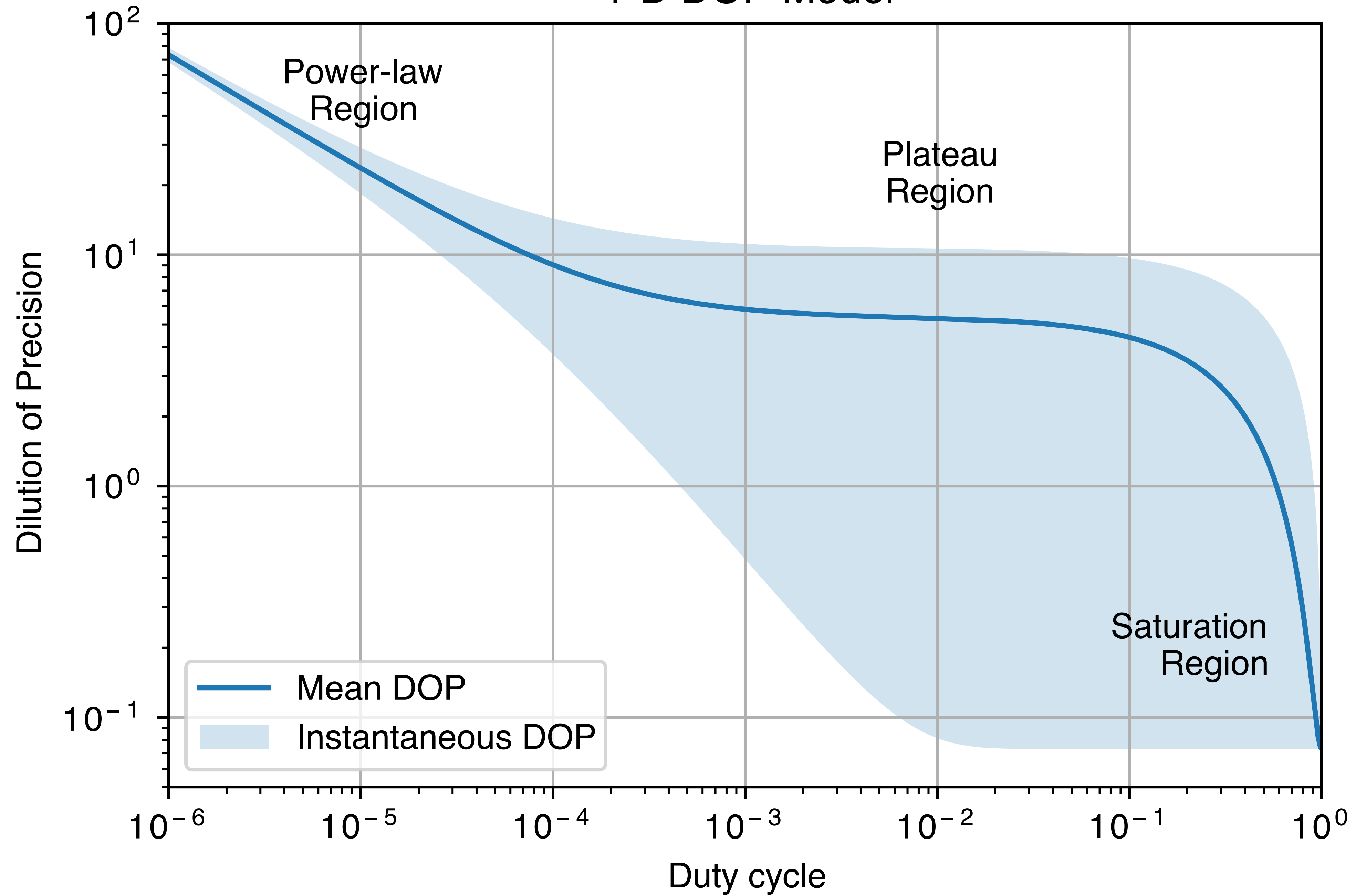


Kuiper PDOP





1-D DOP Model



Quantity	Description	Estimate
τ	Ephemeris Update Interval	50 s
T	Clock RMS error, worst case	0.271 m
R	Orbit RMS error radial, worst case	0.037 m
A	Orbit RMS error along-track, worst case	0.057 m
C	Orbit RMS error cross-track, worst case	0.049 m
w_R	Geometric weight factor, radial	0.774
w_A	Geometric weight factor, along-track	0.448
w_C	Geometric weight factor, cross-track	0.448
σ_{SISURE}	Satellite timing and positioning errors	0.301 m
σ_{IONO}	Ionospheric delay error	0.028 m
σ_{TROPO}	Tropospheric delay error	0.050 m
σ_{RNM}	Receiver noise and multipath errors	0.005 m
σ_{URE}	User ranging error per satellite	0.307 m
$\Delta x_{95,H}$	95% horizontal error	0.558 m
$\Delta x_{95,V}$	95% vertical error	0.717 m
Δx_{95}	95% total error	1.205 m

Age-of-Ephemeris = 50s

95% horiz. error = $\sigma_H \cdot \sqrt{F_{\chi_2^2}^{-1}(0.95)}$, where $\sigma_H^2 = \text{HDOP} \cdot \sigma_{\text{URE}}^2$

95% vert. error = $\sigma_V \cdot \sqrt{F_{\chi_1^2}^{-1}(0.95)}$, where $\sigma_V^2 = \text{VDOP} \cdot \sigma_{\text{URE}}^2$

$\sigma_{\text{URE}}^2 = \sigma_{\text{SISURE}}^2 + \sigma_{\text{IONO}}^2 + \sigma_{\text{TROPO}}^2 + \sigma_{\text{RNM}}^2$

σ_{SISURE} = Signal-in-Space User Range Error

σ_{IONO} = Ionospheric delay uncertainty

σ_{TROPO} = Tropospheric delay uncertainty

σ_{RNM} = Receiver noise and multi-path

$$\sigma_{\text{IONO}}^2 = \left(\frac{40.3 \times 10^{16} \text{ m/s}^2 / \text{TECU} \cdot \sigma_{\text{STEC}}}{f^2} \right)^2 \approx (0.028 \text{ m})^2$$

$$\sigma_{\text{TROPO}}^2 = \sigma_{\text{TROPO (GPS)}} \approx (0.050 \text{ m})^2$$

$$f = \text{center frequency} \approx 12 \text{ GHz}$$

$$\sigma_{\text{STEC}} = \text{Uncertainty in Slant Total Electron Content} \approx 10 \text{ TECU}$$

$$\sigma_{\text{RNM}}^2 \geq \frac{3c^2 k_B T_{\text{RX}}}{2\pi^2 W^2 P t_{\text{integrate}}}$$

k_B = Boltzmann's constant

T_{RX} = noise temperature

$$= 273 \text{ K} \cdot 10^{0.1 \cdot \text{noise figure}}$$

W = bandwidth = 60 MHz

P = received power

$t_{\text{integrate}}$ = ranging burst duration = 500 μs

noise figure = 6 dB

$$T = c \cdot \sqrt{\frac{2\pi^2}{3} h_{-2} \tau^3 + \frac{1}{2} h_0 \tau + \begin{bmatrix} t & 1 \end{bmatrix} \Sigma_0 \begin{bmatrix} t \\ 1 \end{bmatrix}}$$

$$h_{-2} \approx 6 \times 10^{-25} \text{ s}^{-1}$$

$$h_0 \approx 2 \times 10^{-25} \text{ s}$$

$$d \begin{bmatrix} f_t \\ \phi_t \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} f_t \\ \phi_t \end{bmatrix} dt + \begin{bmatrix} \pi \sqrt{h_{-2}} & 0 \\ 0 & \sqrt{h_0}/2 \end{bmatrix} \begin{bmatrix} dB_{1,t} \\ dB_{2,t} \end{bmatrix}$$

$$\begin{bmatrix} f_0 \\ \phi_0 \end{bmatrix} \sim \mathcal{N}(0, \Sigma_0)$$

$$\sigma_{\text{SISURE}}^2 \leq (w_R R + T)^2 + w_A^2 A^2 + w_C^2 C^2$$

T = RMS clock ephemeris error

R = RMS orbit ephemeris error, radial

A = RMS orbit ephemeris error, along-track

C = RMS orbit ephemeris error, cross-track

w_A^2 = Geometric weight factor for along-track errors to contribute to average ranging error

$$= \frac{a^2 + a(u+1) + 1}{8a^2} + \frac{(a^2 - 1)^2 \log((a-1)^2/(1-2au+a^2))}{16a^3(1-u)}$$

w_C^2 = Geometric weight factor for cross-track errors to contribute to average ranging error

$$= w_A^2$$

w_R^2 = Geometric weight factor for radial errors to contribute to average ranging error

$$= 1 - 2w_A^2$$

$$u = \frac{\cos^2 E + \sqrt{a^2 - \cos^2 E} \sin E}{a}$$

$$a = 1 + \text{altitude}/r_{\text{Earth}}$$

E = elevation mask = 35°

c = speed of light

$$R, A, C = \sqrt{\frac{1}{3} \sigma_a^2 \tau_a (2(t - \tau_a)^3 - 12e^{-t/\tau_a} t \tau_a^2 + 5\tau_a^3 - 3e^{-2t/\tau_a} \tau_a^3)} + v^T \Sigma_0 v, \text{ with}$$

$$v = \begin{bmatrix} 1 \\ t \\ \tau_a(t + \tau_a(e^{-t/\tau_a} - 1)) \end{bmatrix}$$

$$\sigma_{a,R}^2 = (100 \times 10^{-9} \text{ m/s}^2)^2$$

$$\tau_{a,R} = 2400 \text{ s}$$

$$\sigma_{a,A}^2 = (100 \times 10^{-9} \text{ m/s}^2)^2$$

$$\tau_{a,A} = 2400 \text{ s}$$

$$\sigma_{a,C}^2 = (20 \times 10^{-9} \text{ m/s}^2)^2$$

$$\tau_{a,C} = 2400 \text{ s}$$

$$R_0 = 0.034 \text{ m} \quad A_0 = 0.054 \text{ m} \quad C_0 = 0.048 \text{ m}$$

$$d \begin{bmatrix} p_t \\ v_t \\ a_t \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & -1/\tau_a \end{bmatrix} \begin{bmatrix} p_t \\ v_t \\ a_t \end{bmatrix} dt + \begin{bmatrix} 0 \\ 0 \\ \sigma_a/\sqrt{\tau_a} \end{bmatrix} dB_t$$

$$\begin{bmatrix} p_0 \\ v_0 \\ a_0 \end{bmatrix} \sim \mathcal{N}(0, \Sigma_0)$$

