A New Space Approach to Commercial LEO PNT

Alberta ION Lecture Series

December 16, 2021

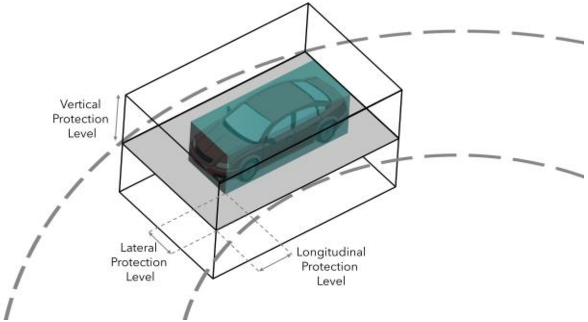
Tyler Reid, CTO

xona space systems

How would you build sat nav today?

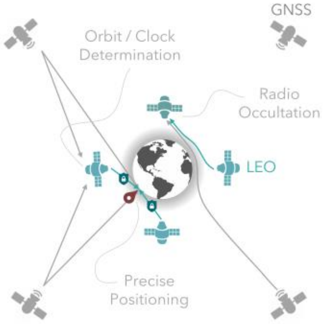
Outline

PNT Needs



Aerospace Ecosystem

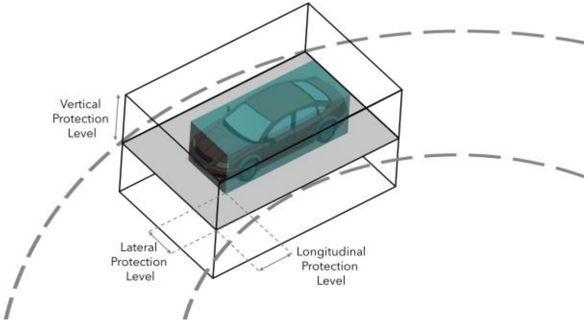
Sat Nav Architecture for Today



Xona Space Systems

Outline

PNT Needs



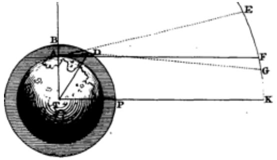
Aerospace Ecosystem

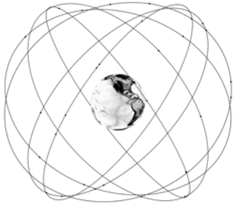
Sat Nav Architecture for Today

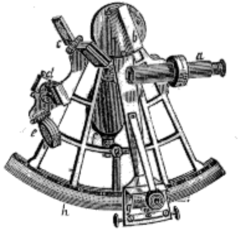
Xona Space Systems

A Brief History of Navigation

Celestial/Chrono	Loran	Transit	GPS	?
1770-1920	1940s-2010	1964-1996	1996-Present	2025+
3000 m	460 m	25 m	3 m	<0.30 m



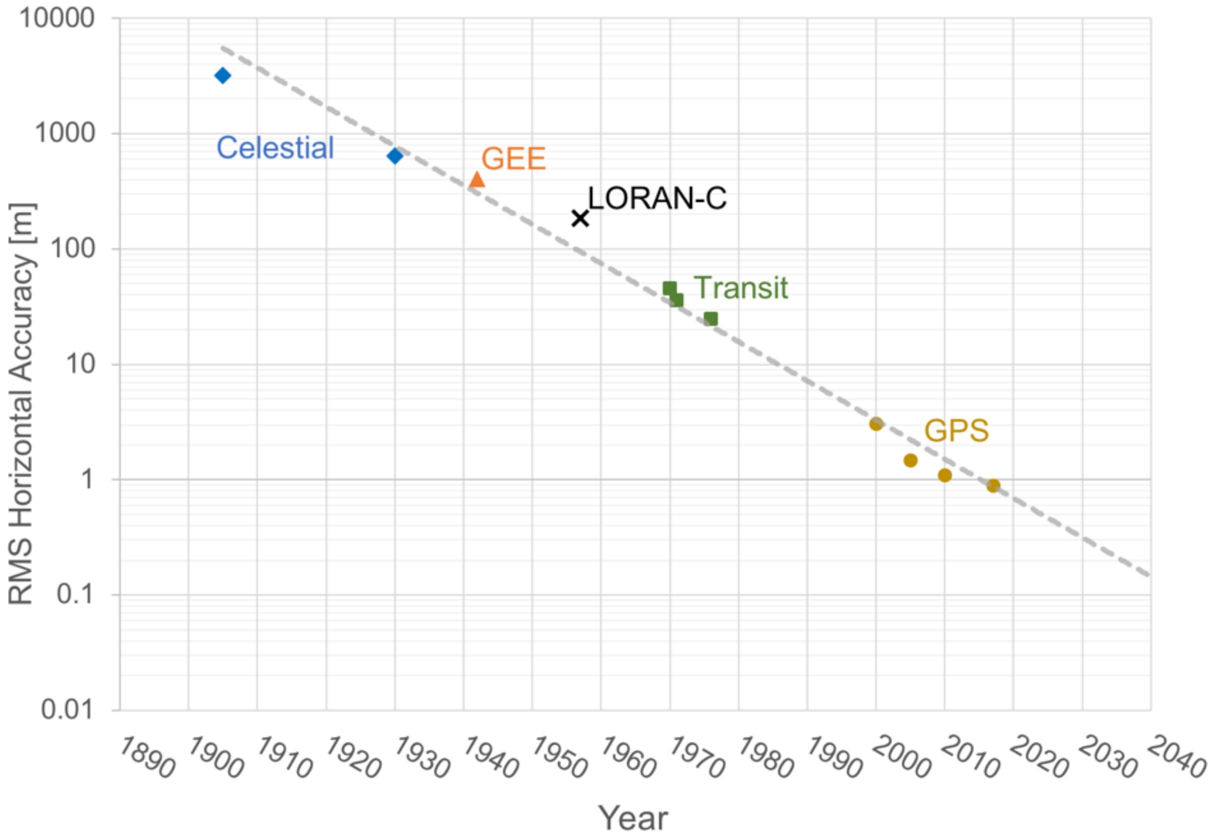




Sextant, p. 1932.

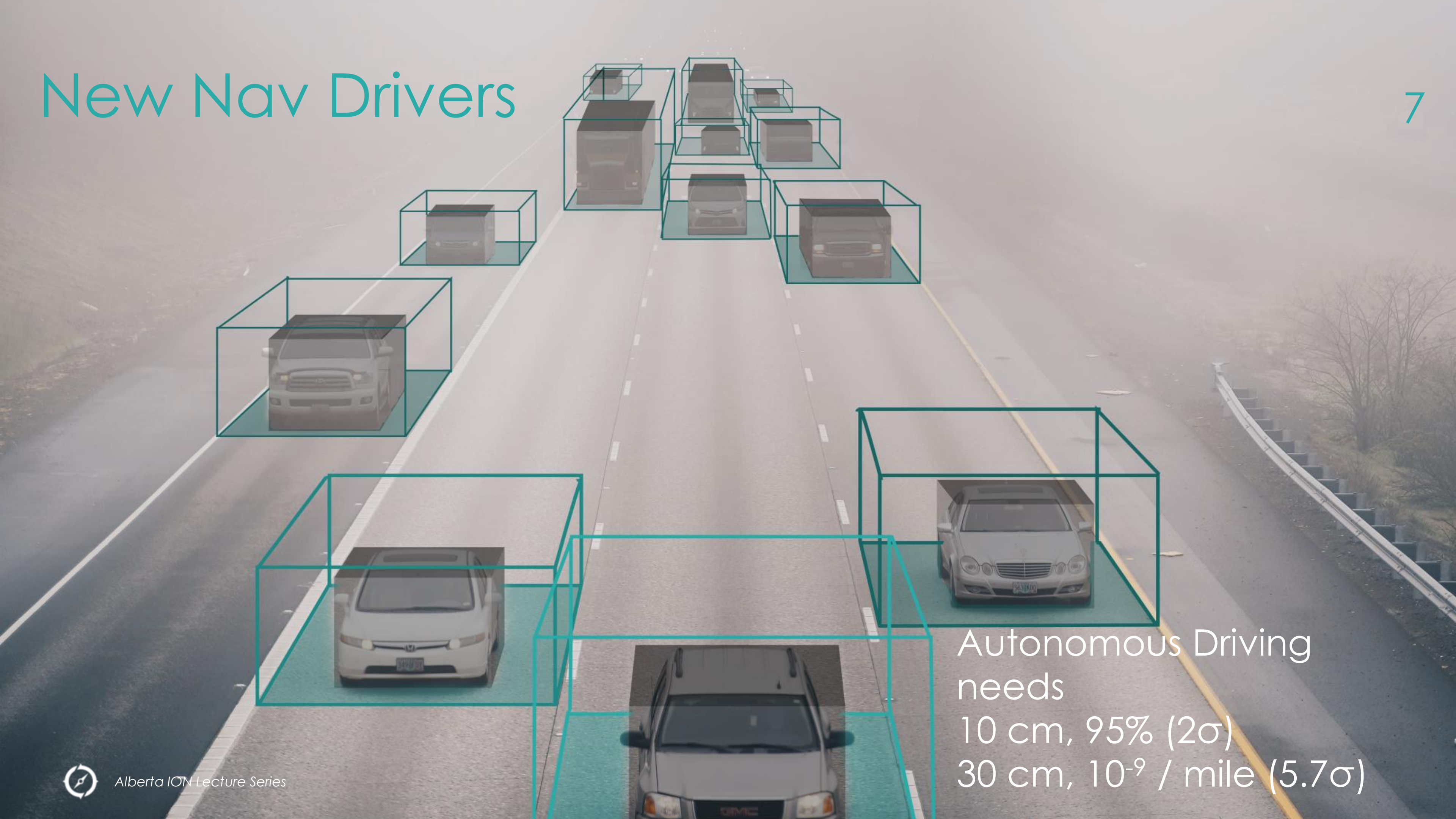
‘Moore’s’ Law of Navigation

Trend:
10x better accuracy every 30 years



2020s:
Decade of the Decimeter

New Nav Drivers



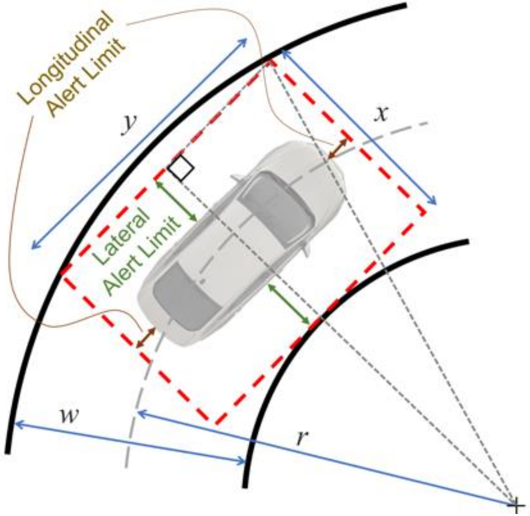
Autonomous Driving needs

10 cm, 95% (2σ)

30 cm, 10^{-9} / mile (5.7σ)

Localization Requirements

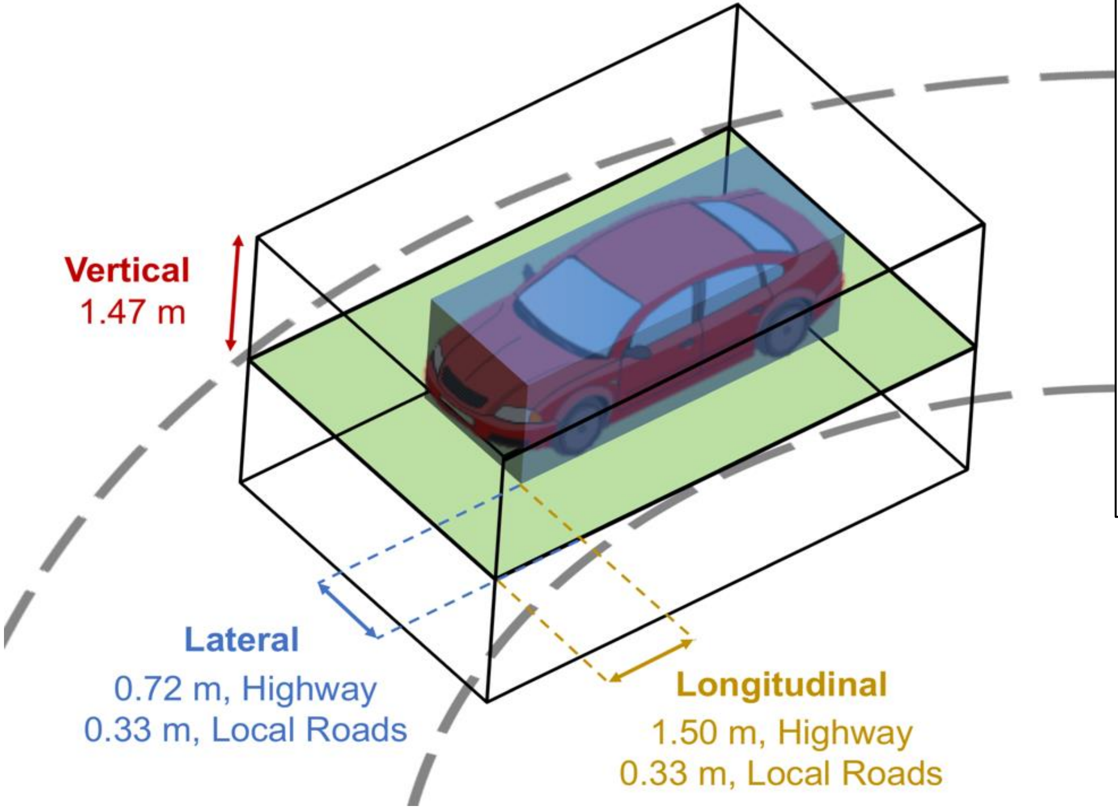
Geometry

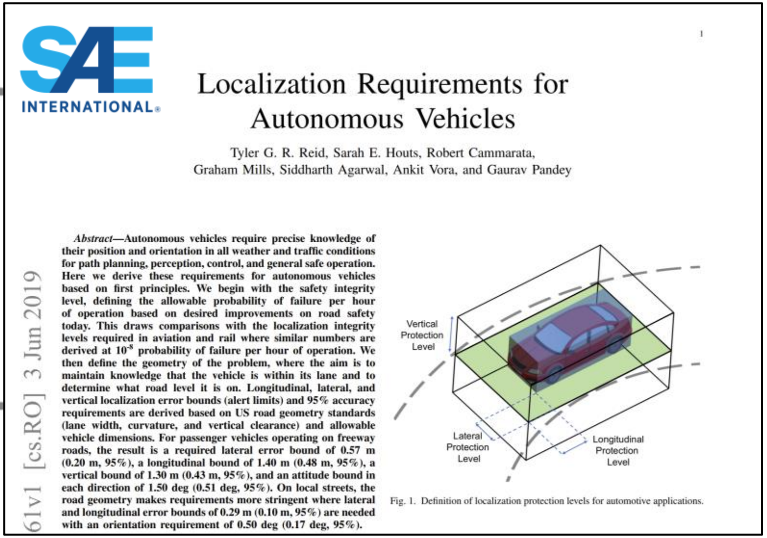


Target Level of Safety

Reid, T.G., Houts, S.E., Cammarata, R., Mills, G., Agarwal, S., Vora, A. and Pandey, G., 2019. Localization Requirements for Autonomous Vehicles. SAE International Journal of Connected and Automated Vehicles, 2(12-02-03-0012), pp.173-190.

Localization Requirements





SAE INTERNATIONAL

Localization Requirements for Autonomous Vehicles

Tyler G. R. Reid, Sarah E. Houts, Robert Cammarata, Graham Mills, Siddharth Agarwal, Ankit Vora, and Gaurav Pandey

Abstract—Autonomous vehicles require precise knowledge of their position and orientation in all weather and traffic conditions for path planning, perception, control, and general safe operation. Here we derive these requirements for autonomous vehicles based on first principles. We begin with the safety integrity level, defining the allowable probability of failure per hour of operation based on desired improvements on road safety today. This draws comparisons with the localization integrity levels required in aviation and rail where similar numbers are derived at 10^{-8} probability of failure per hour of operation. We then define the geometry of the problem, where the aim is to maintain knowledge that the vehicle is within its lane and to determine what road level it is on. Longitudinal, lateral, and vertical localization error bounds (alert limits) and 95% accuracy requirements are derived based on US road geometry standards (lane width, curvature, and vertical clearance) and allowable vehicle dimensions. For passenger vehicles operating on freeway roads, the result is a required lateral error bound of 0.57 m (0.20 m, 95%), a longitudinal bound of 1.40 m (0.48 m, 95%), a vertical bound of 1.30 m (0.43 m, 95%), and an attitude bound in each direction of 1.50 deg (0.51 deg, 95%). On local streets, the road geometry makes requirements more stringent where lateral and longitudinal error bounds of 0.29 m (0.10 m, 95%) are needed with an orientation requirement of 0.50 deg (0.17 deg, 95%).

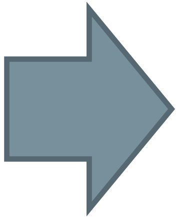
Vertical Protection Level
Lateral Protection Level
Longitudinal Protection Level

Fig. 1. Definition of localization protection levels for automotive applications.

*This assumes road standards in North America. Bounds for European roads are expected to be even tighter.

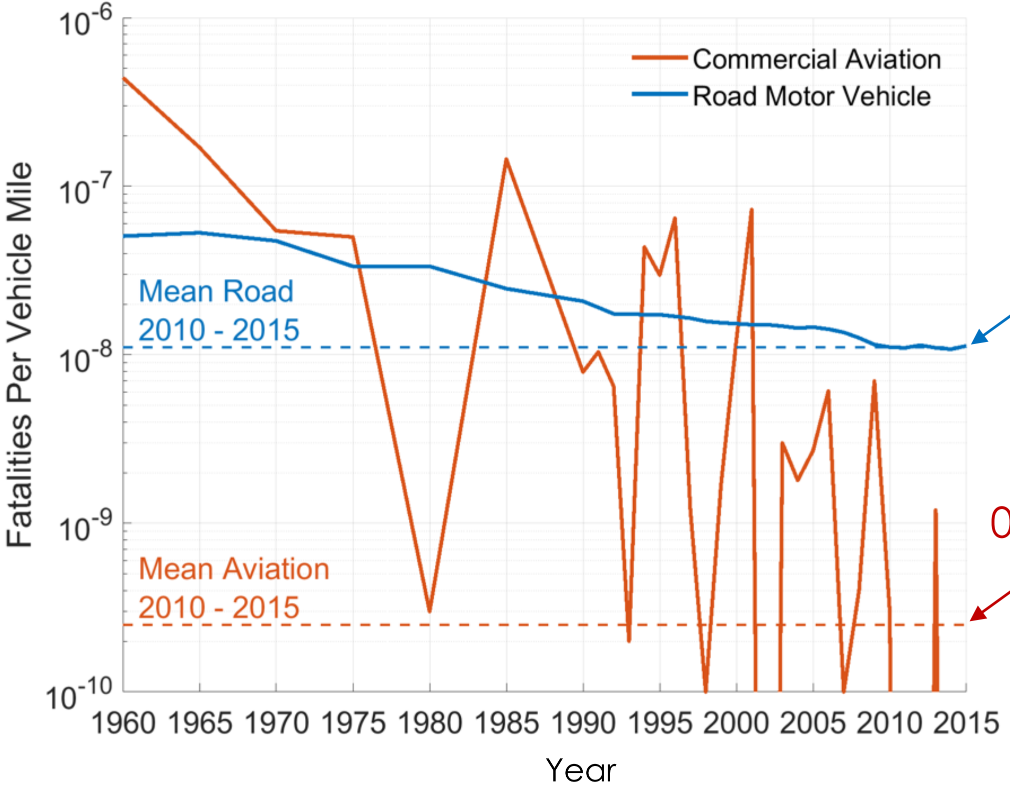
Safety in The Age of Autonomy

Expectation for self-driving: Match the safety of other modes of mass transportation



1 fatality per 10 billion miles

Target Level of Safety



1 fatality / 10^8 miles

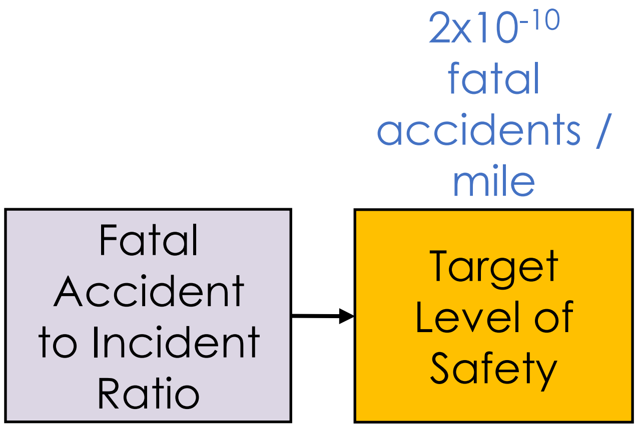
0.02 fatalities / 10^8 miles

Target Level of Safety

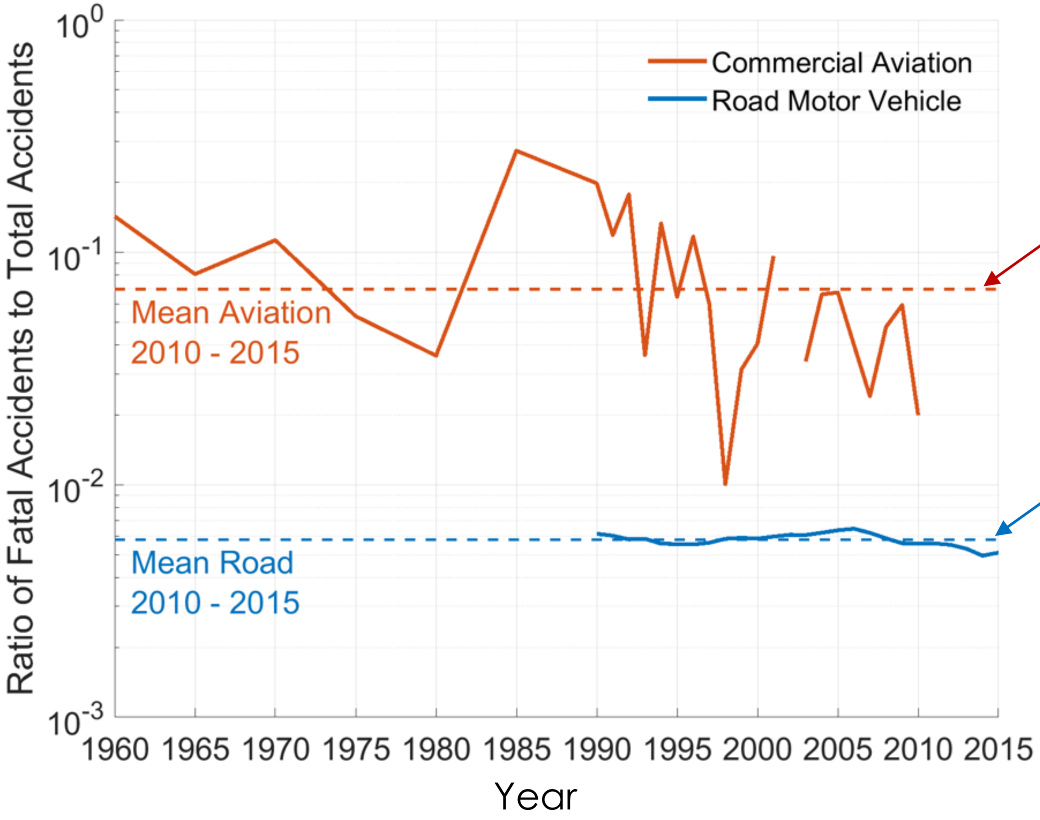
$2x10^{-10}$ fatal accidents / mile

Target Level of Safety

Target Level of Safety



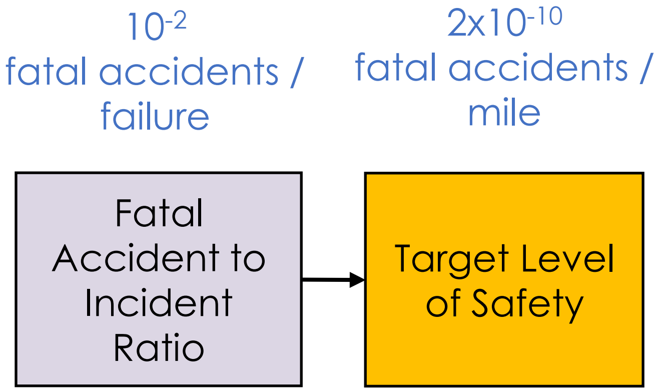
Target Level of Safety



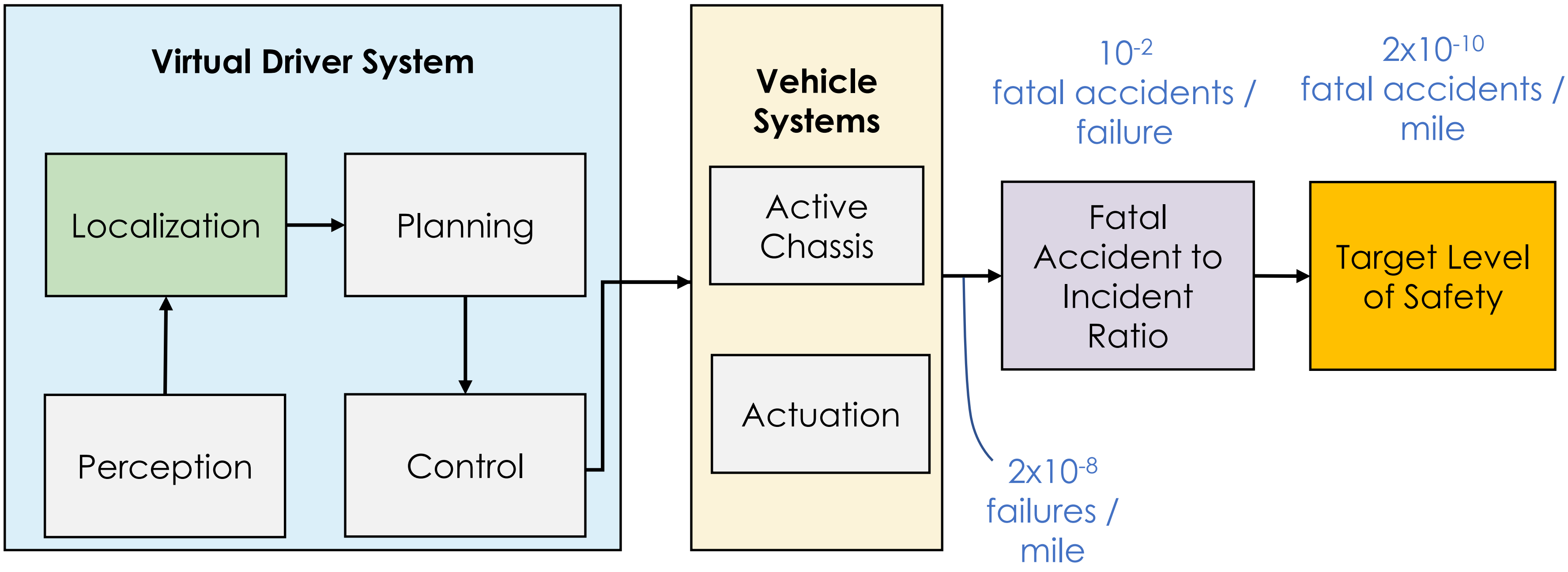
1 Fatal Accident / 14 Total Accidents

1 Fatal Accident / 172 Total Accidents

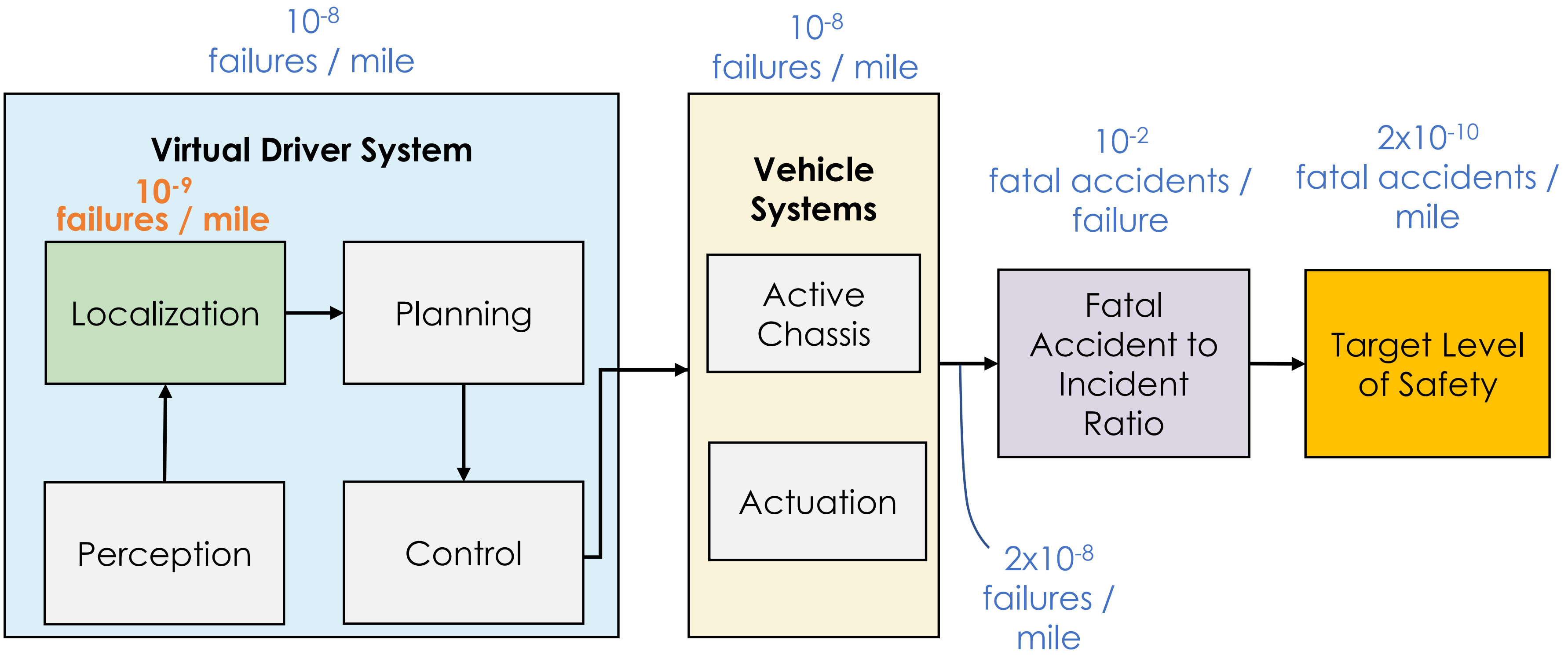
Target Level of Safety



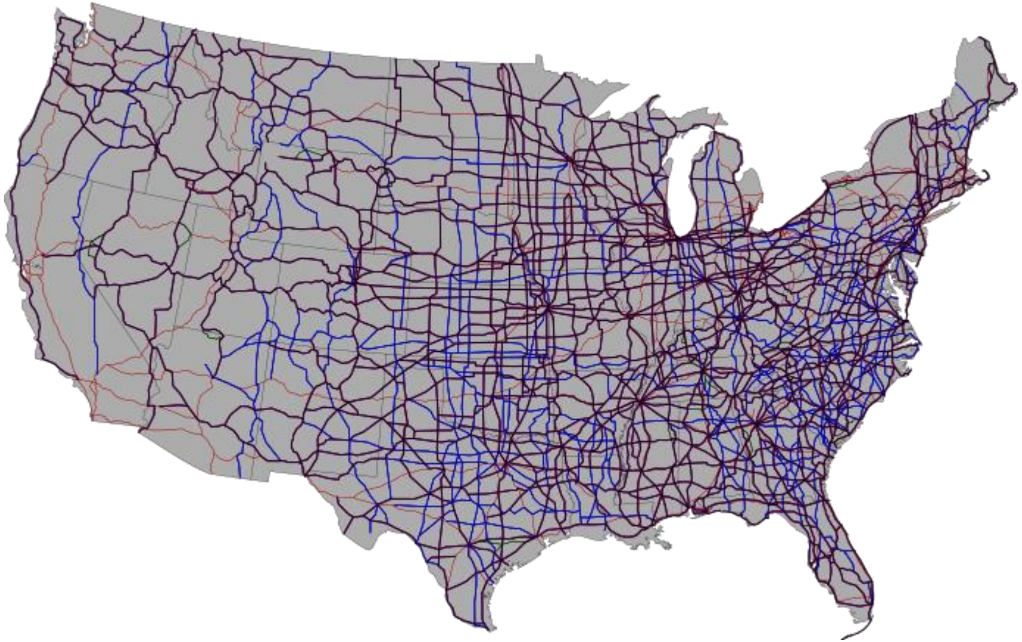
Target Level of Safety



Target Level of Safety



A Billion Miles…



250x Entire U.S. Road Network

In Other Units…

1400x Entire Canadian Road Network

Integrity

$$P_{loc} = 10^{-9}\frac{\text{failures}}{\text{mile}} \times (10 - 85)\,\frac{\text{mile}}{\text{hour}}$$
$$\approx 10^{-8}\frac{\text{failures}}{\text{hour}}$$

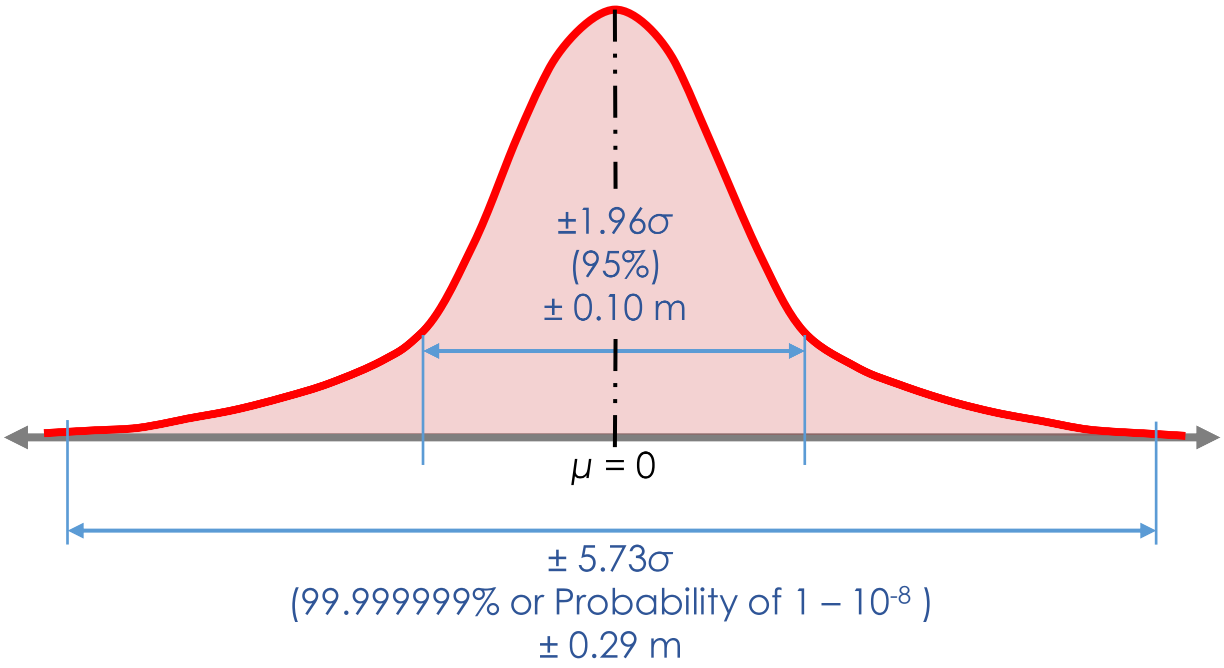
Probability of Failure per Hour	General Programmable Electronics (IEC-61508)	Automotive (ISO 26262)	Aviation (DO-178/254)	Railway (CENELEC 50126/128/129)
n/a	(SIL-0)	QM	DAL-E	(SIL-0)
$10^{-6} – 10^{-5}$	SIL-1	ASIL-A	DAL-D	SIL-1
$10^{-7} – 10^{-6}$	SIL-2	ASIL-B/C	DAL-C	SIL-2
$10^{-8} – 10^{-7}$	SIL-3	ASIL-D	DAL-B	SIL-3
$10^{-9} – 10^{-8}$	SIL-4	-	DAL-A	SIL-4

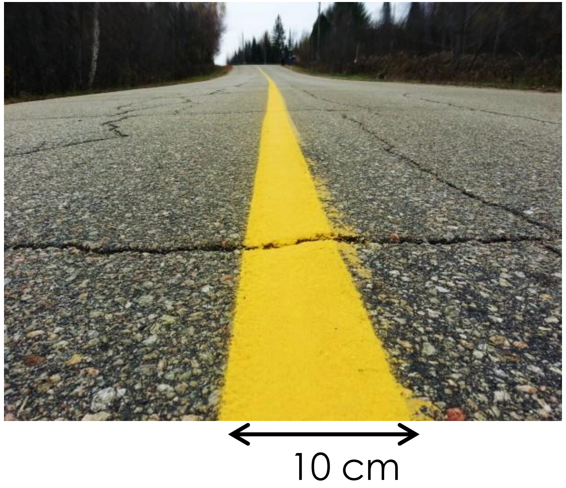
Requirements for City Roads

Vehicle Type	Accuracy (95%)				Alert Limits				Prob. of Failure (Integrity)
	Lat. [m]	Long. [m]	Vert. [m]	Att* [deg]	Lat. [m]	Long. [m]	Vert. [m]	Att* [deg]	
Mid-Size	0.15	0.15	0.48	0.17	0.44	0.44	1.40	0.5	10^{-9} /mile (10^{-8} /h)
Full-Size	0.13	0.13	0.48	0.17	0.38	0.38	1.40	0.5	10^{-9} /mile (10^{-8} /h)
Standard Pickup	0.12	0.12	0.48	0.17	0.34	0.34	1.40	0.5	10^{-9} /mile (10^{-8} /h)
Passenger Vehicle Limits	**0.10**	**0.10**	**0.48**	**0.17**	**0.29**	**0.29**	**1.40**	**0.5**	**10^{-9} /mile (10^{-8} /h)**

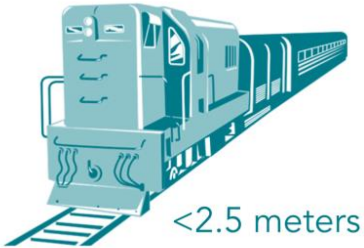
**Error in each direction (roll, pitch, and heading).*

Example of Desired Lateral Error Distribution





Why is This Hard?



Other modes of transportation require the same level of safety, but tolerate much larger position errors

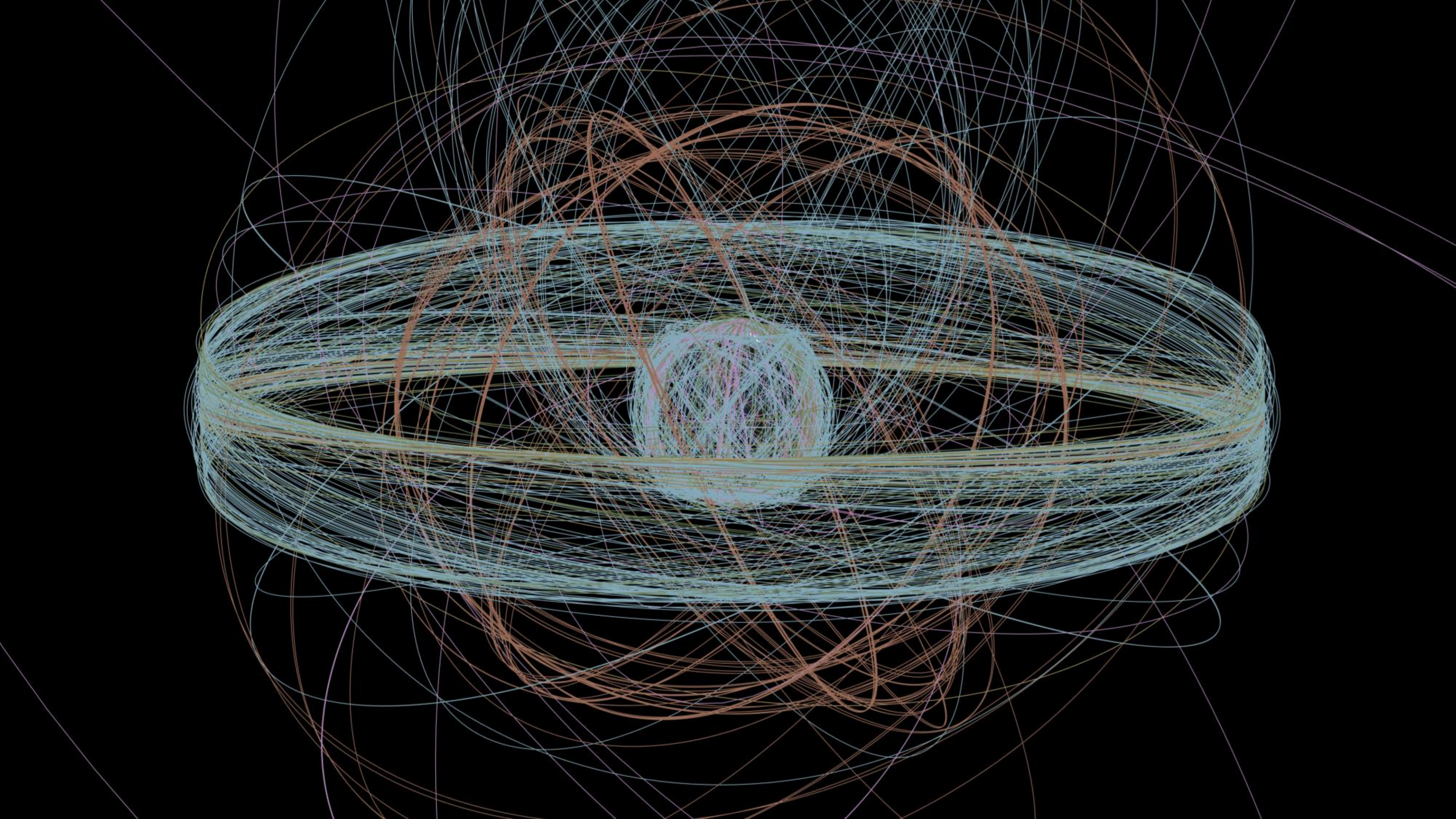
Outline

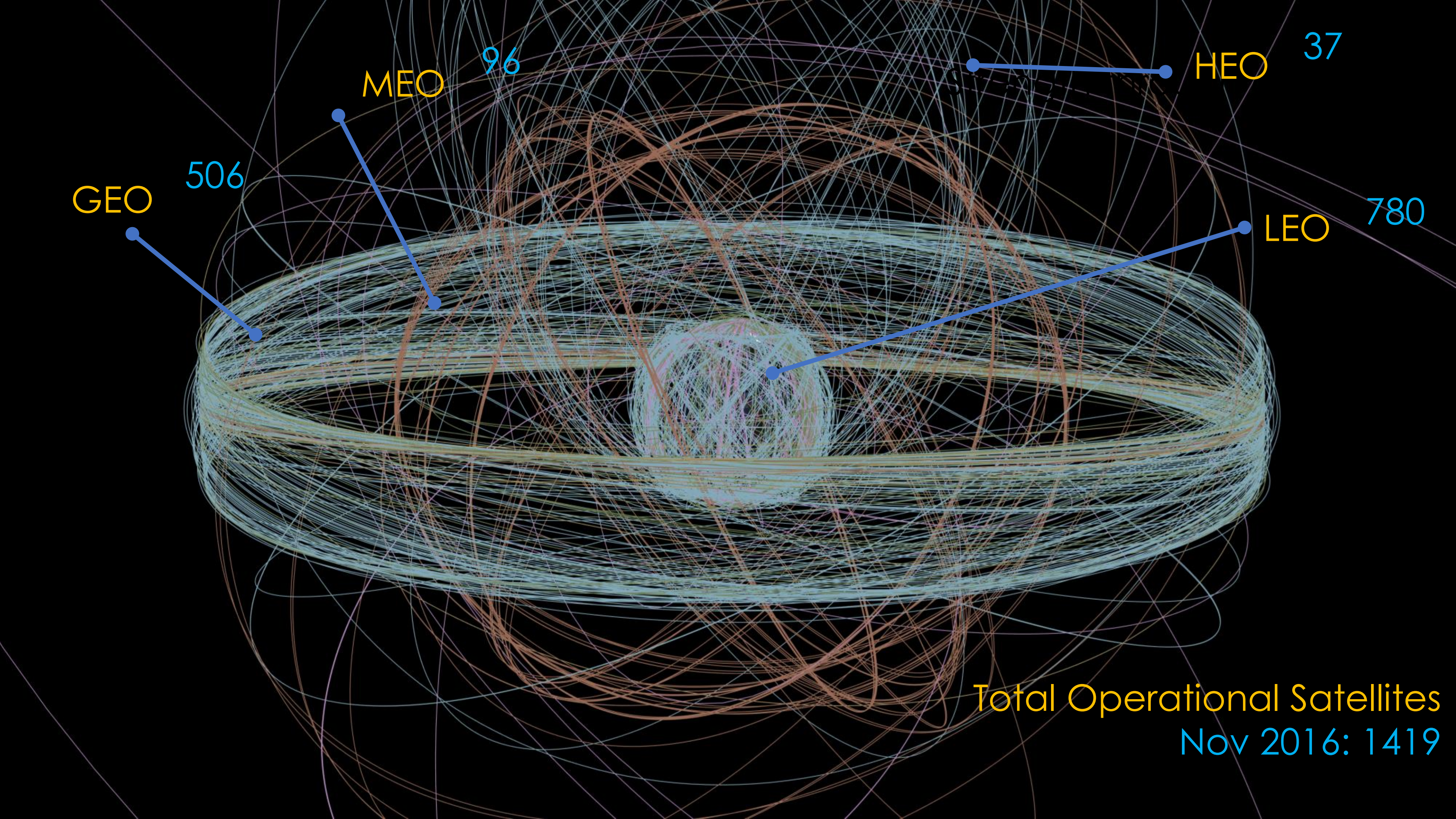
PNT Needs

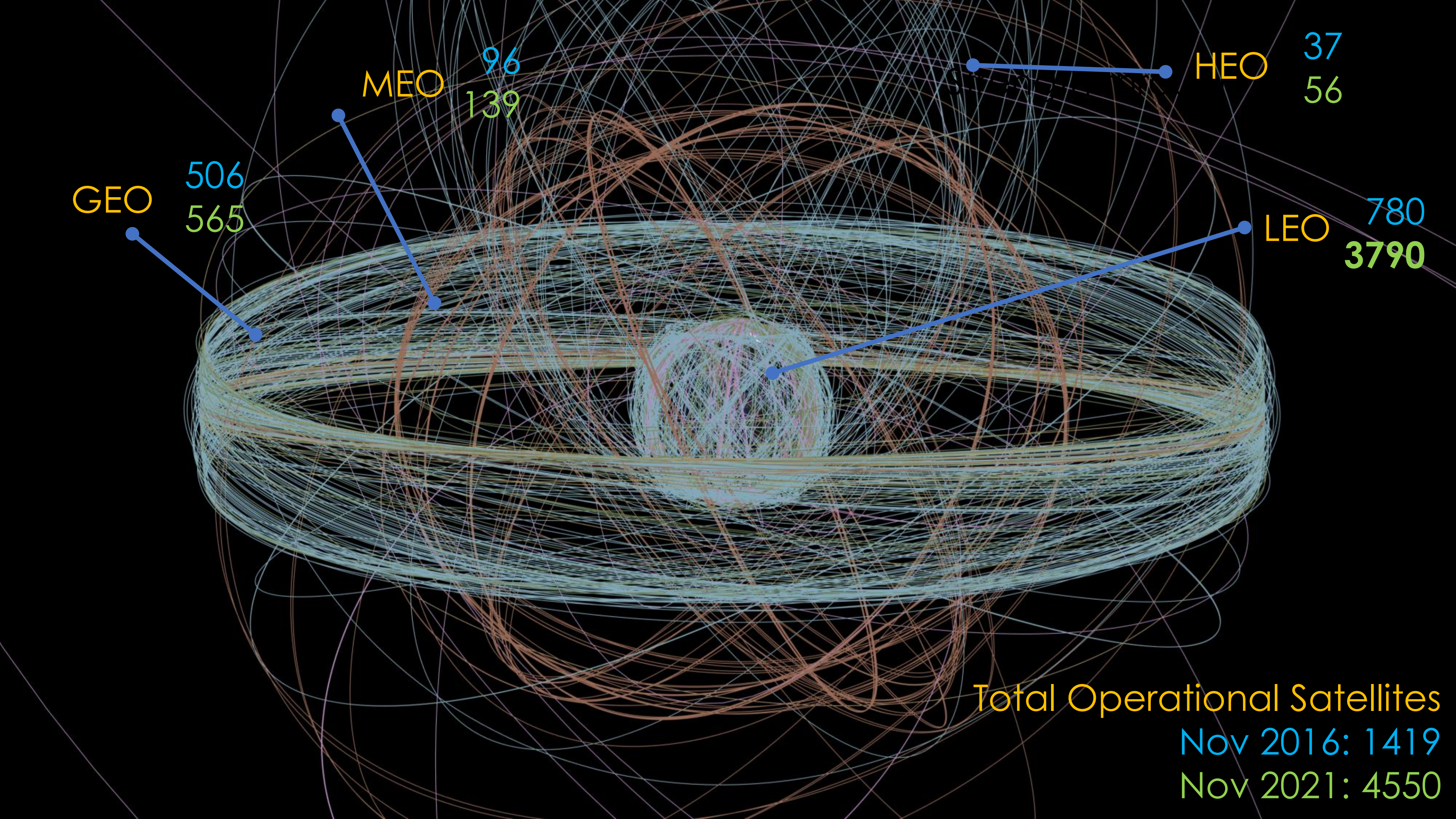
Aerospace Ecosystem

Sat Nav Architecture for Today

Xona Space Systems



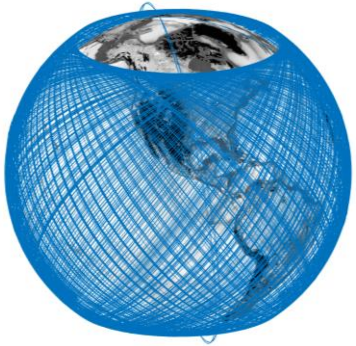

MEO
96
HEO
37
GEO
506
LEO
780
Total Operational Satellites
Nov 2016: 1419



MEO 96 139
HEO 37 56
GEO 506 565
LEO 780 3790
Total Operational Satellites
Nov 2016: 1419
Nov 2021: 4550

LEO Mega-Constellations

Broadband

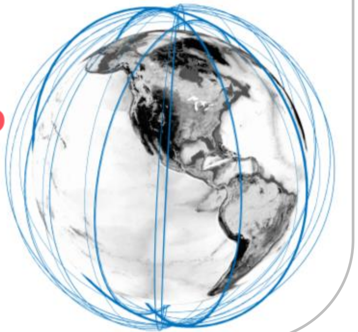


STARLINK

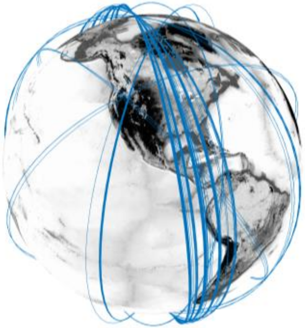
#Sats = 1674

OneWeb

#Sats = 358



Remote Sensing



planet.

#Sats = 189

spire

#Sats = 120

Navigation

xona

#Sats = 276

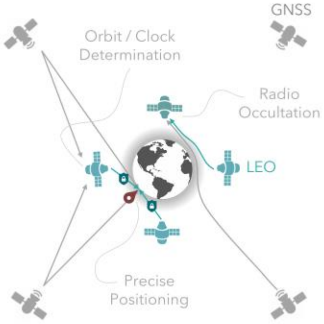
Coming Soon

Outline

PNT Needs

Aerospace Ecosystem

Sat Nav Architecture for Today

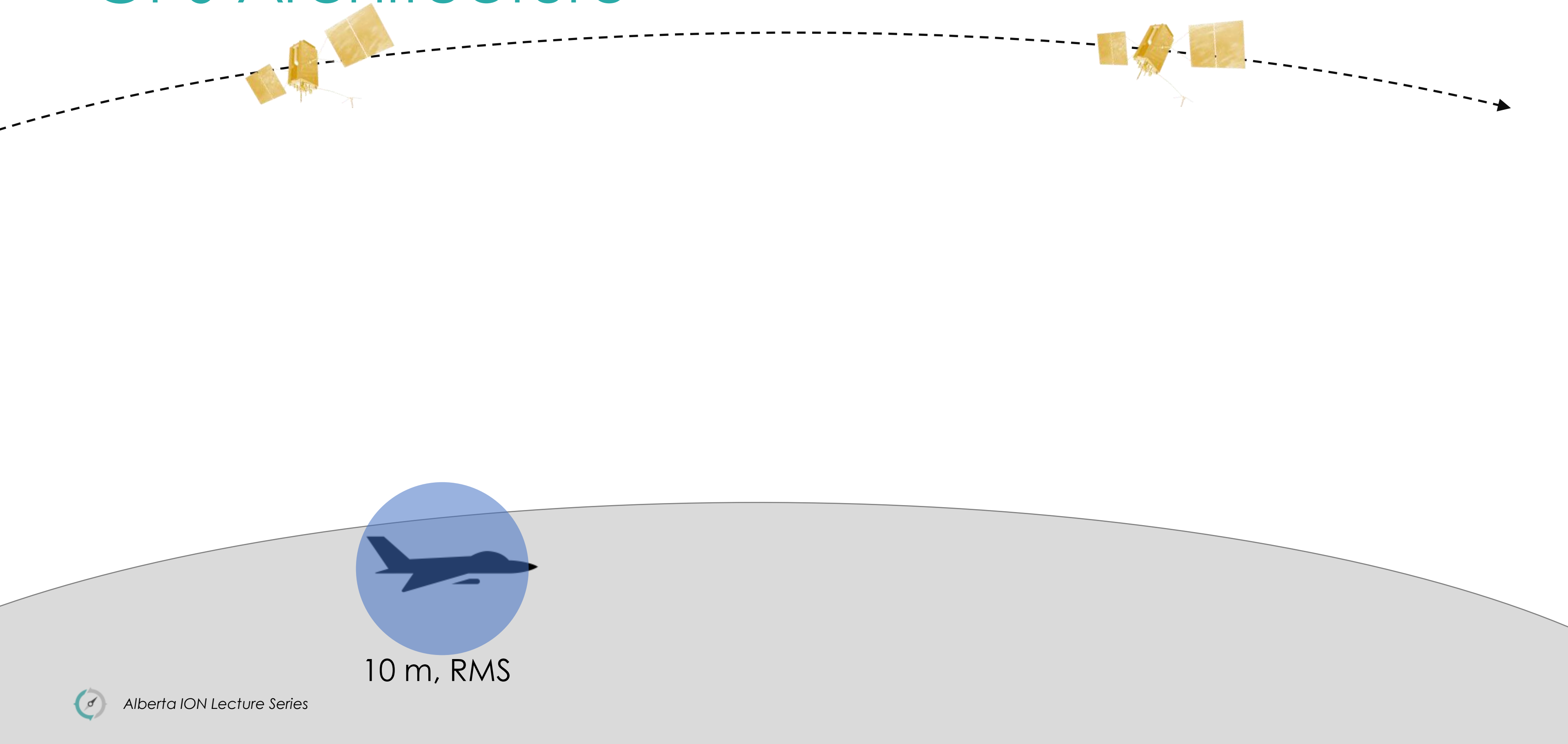


Xona Space Systems

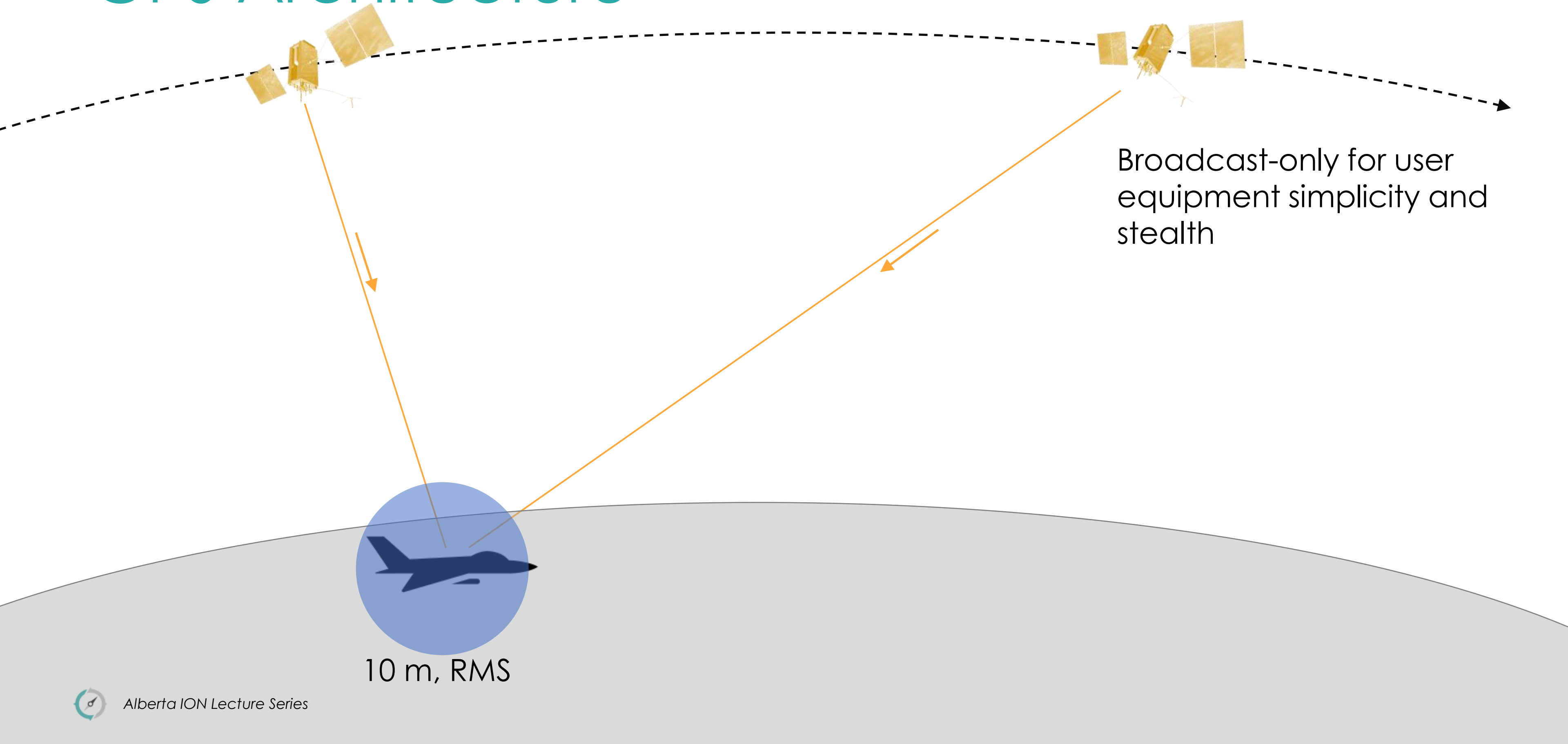
A Comparison of Requirements

	GPS	Sat Nav for Today
Focus User Group	Government	Commercial
Accuracy	5 bombs in the same hole	Keep self-driving cars in their lane
Availability	Global	Global, enhanced in population centres
Resistance to Interference	State-level actor	Unintentional & PPD’s
Cost-Effective Space / Ground Segment	Government	Commercially viable
Affordable User Equipment	Portable	Mass market

GPS Architecture



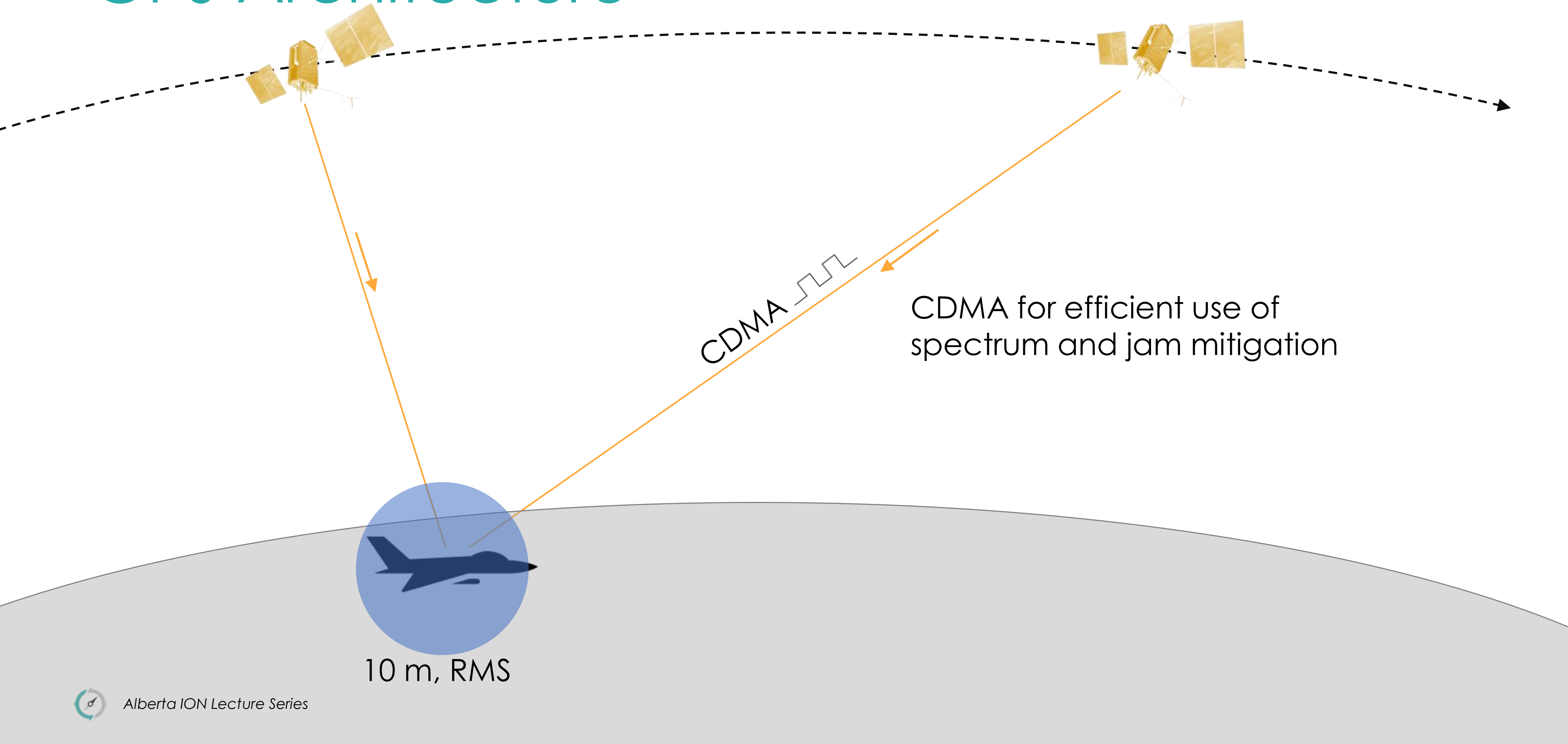
GPS Architecture



Broadcast-only for user equipment simplicity and stealth

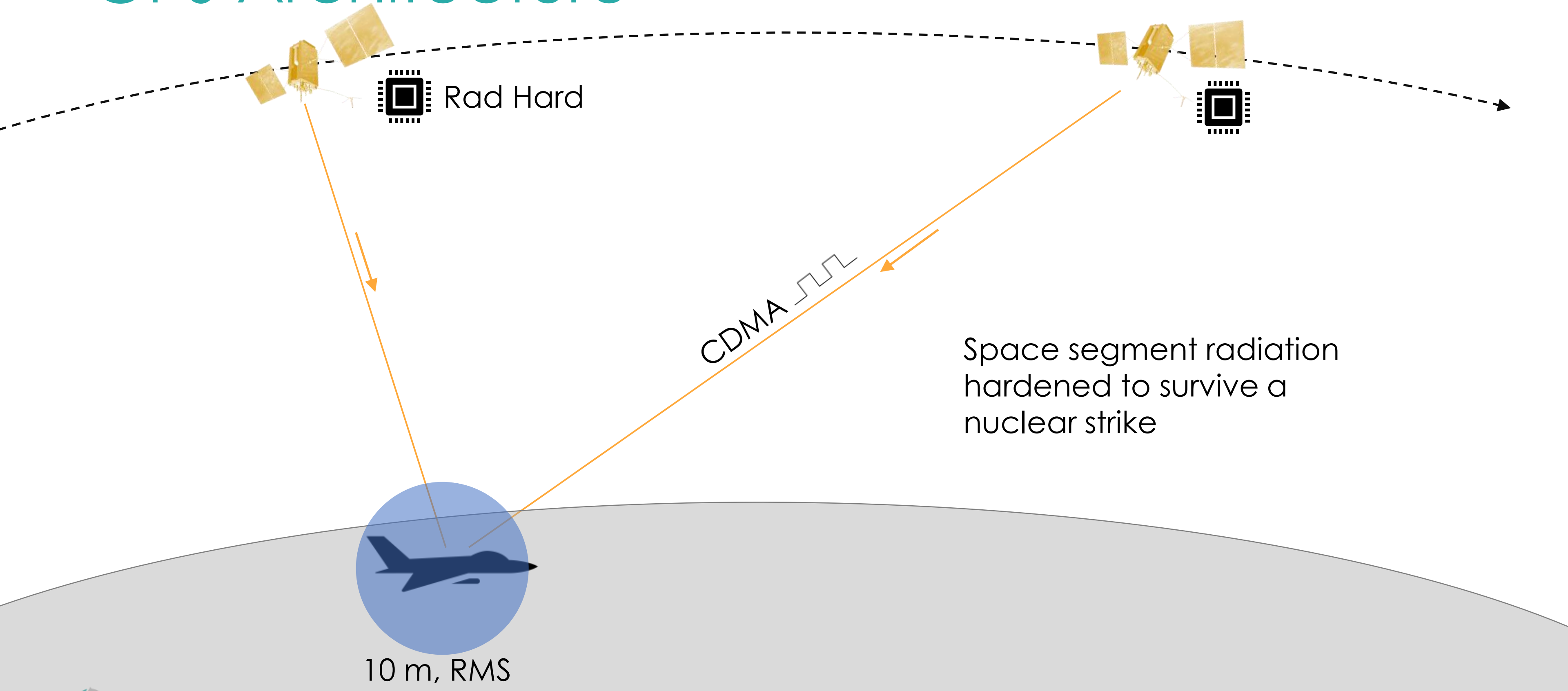
10 m, RMS

GPS Architecture



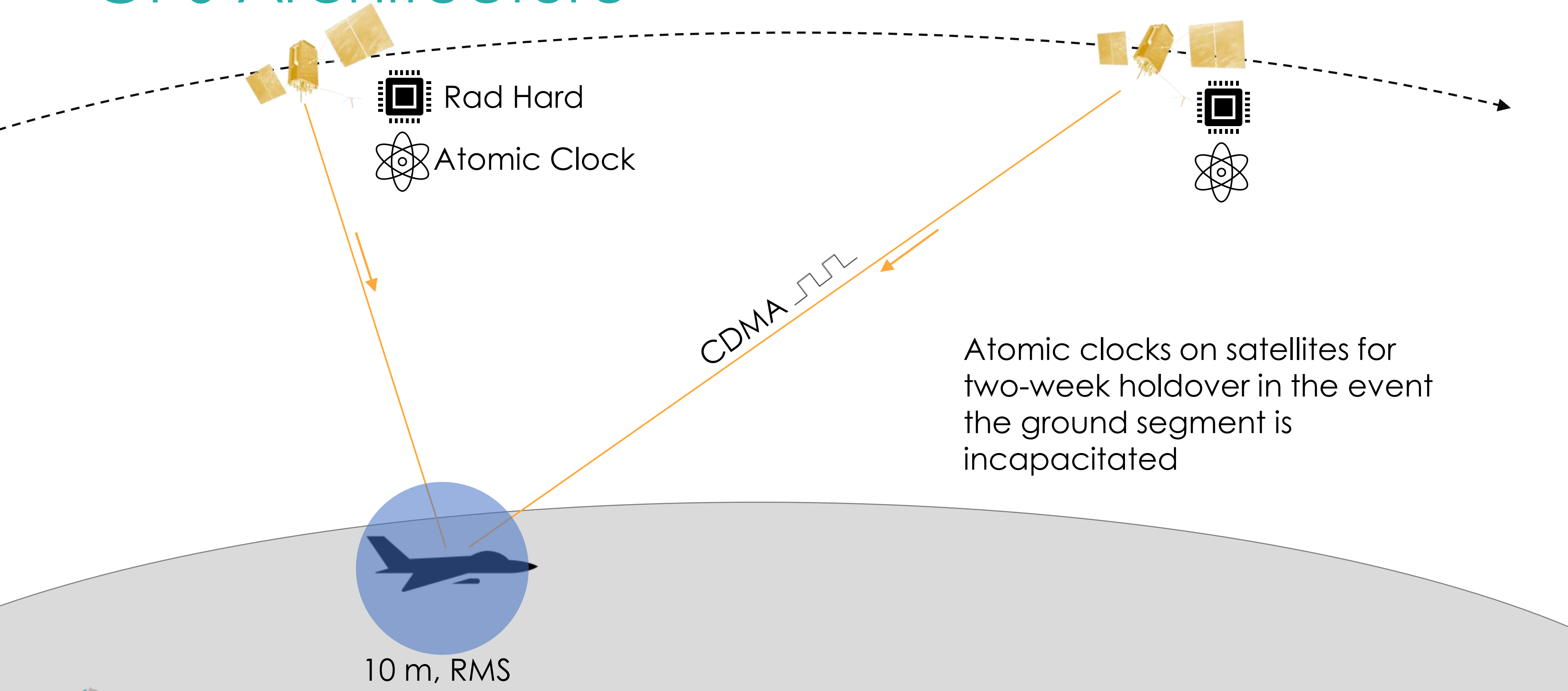
CDMA for efficient use of spectrum and jam mitigation

GPS Architecture



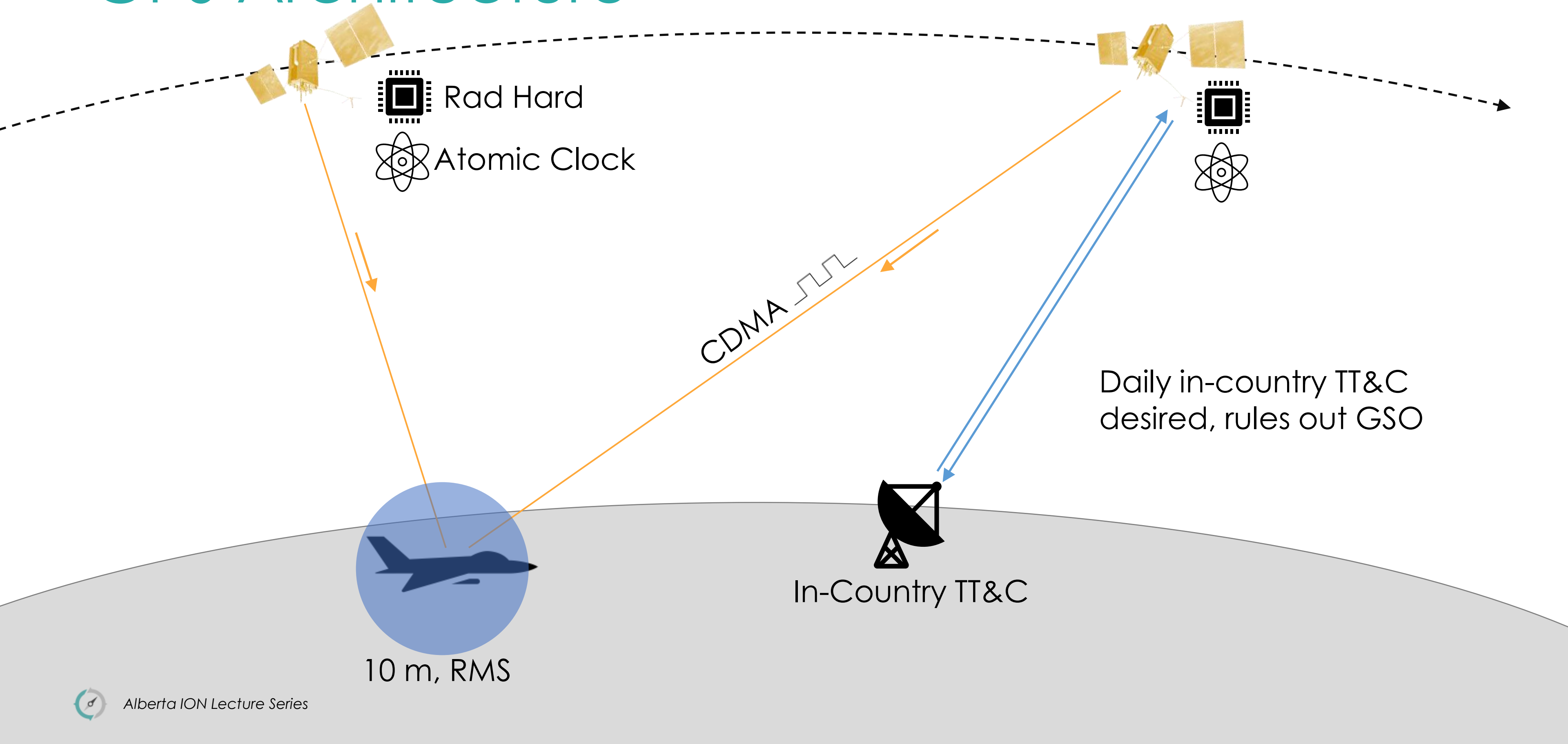
Space segment radiation hardened to survive a nuclear strike

GPS Architecture

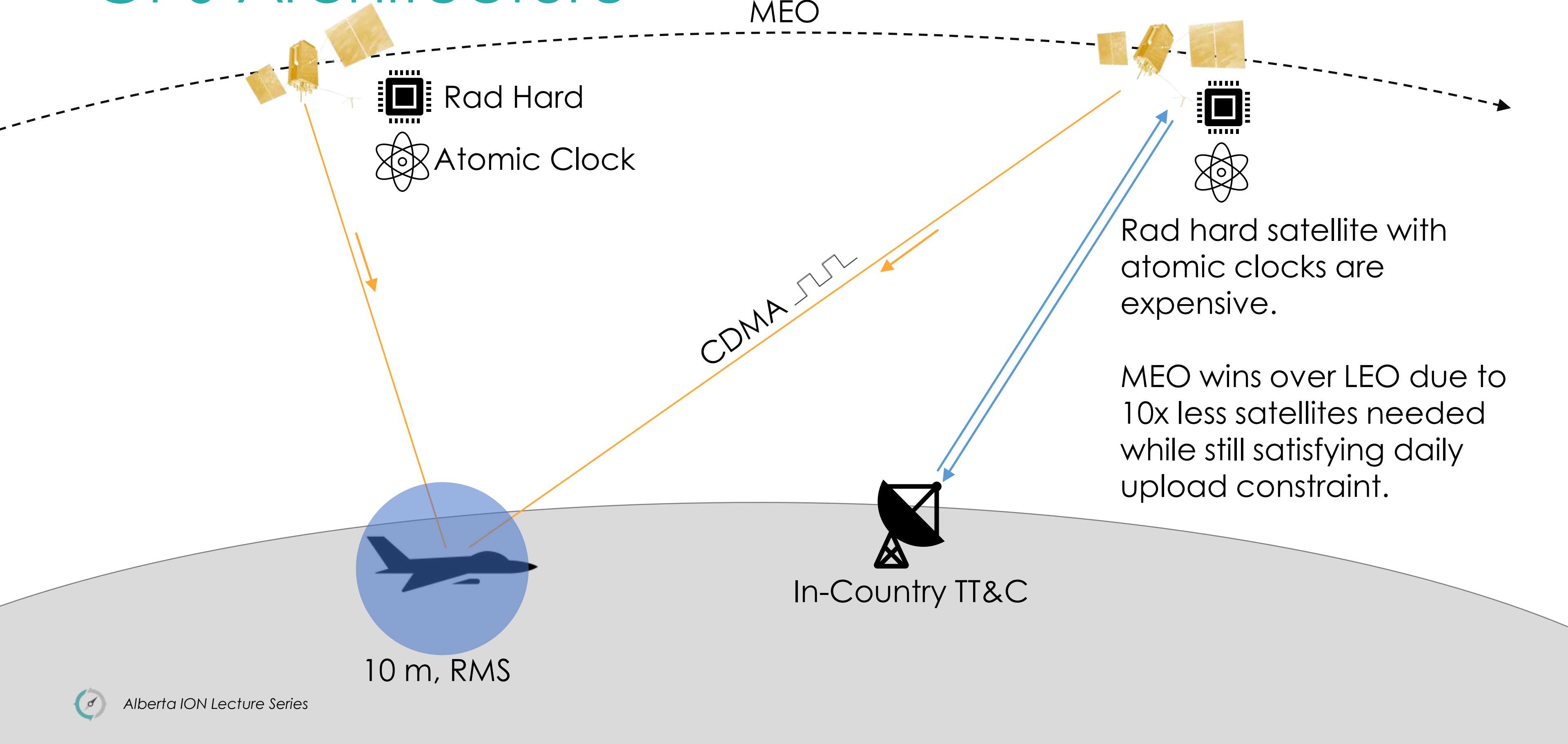


Atomic clocks on satellites for two-week holdover in the event the ground segment is incapacitated

GPS Architecture



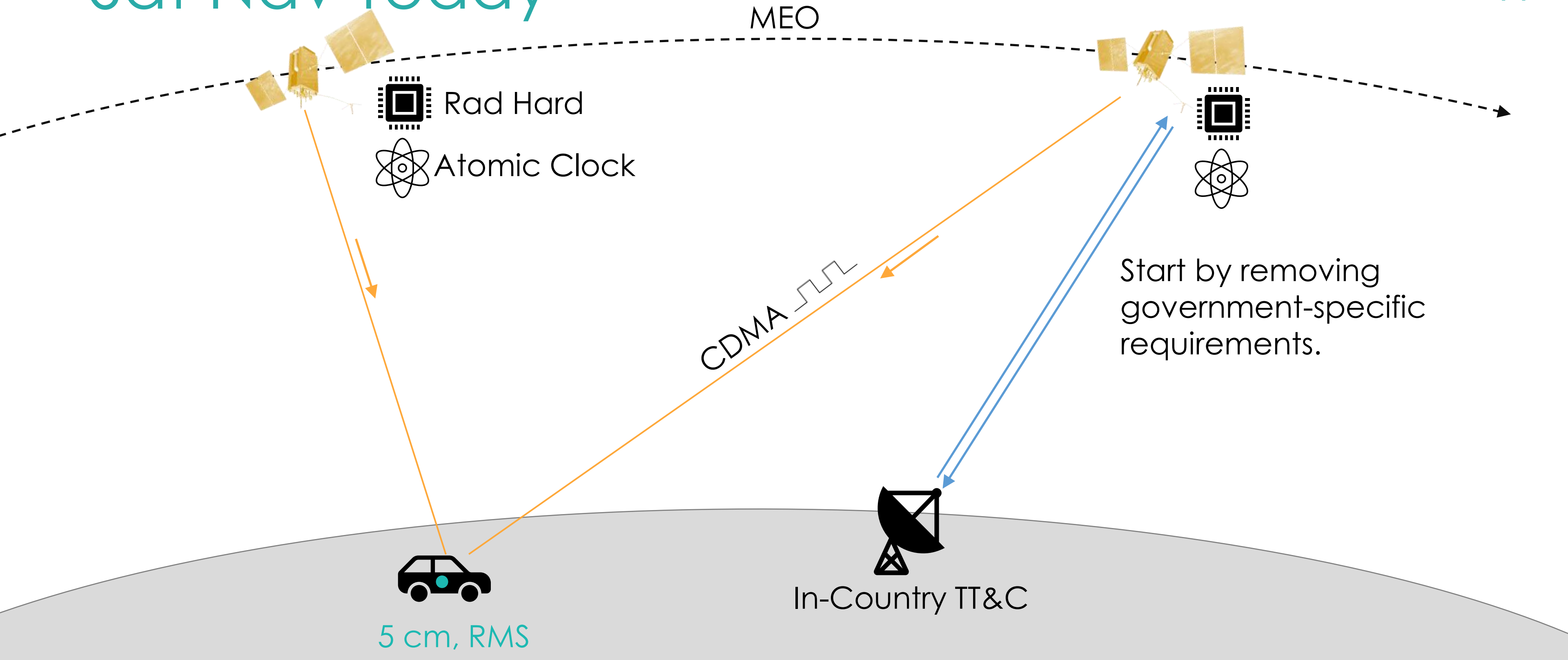
GPS Architecture



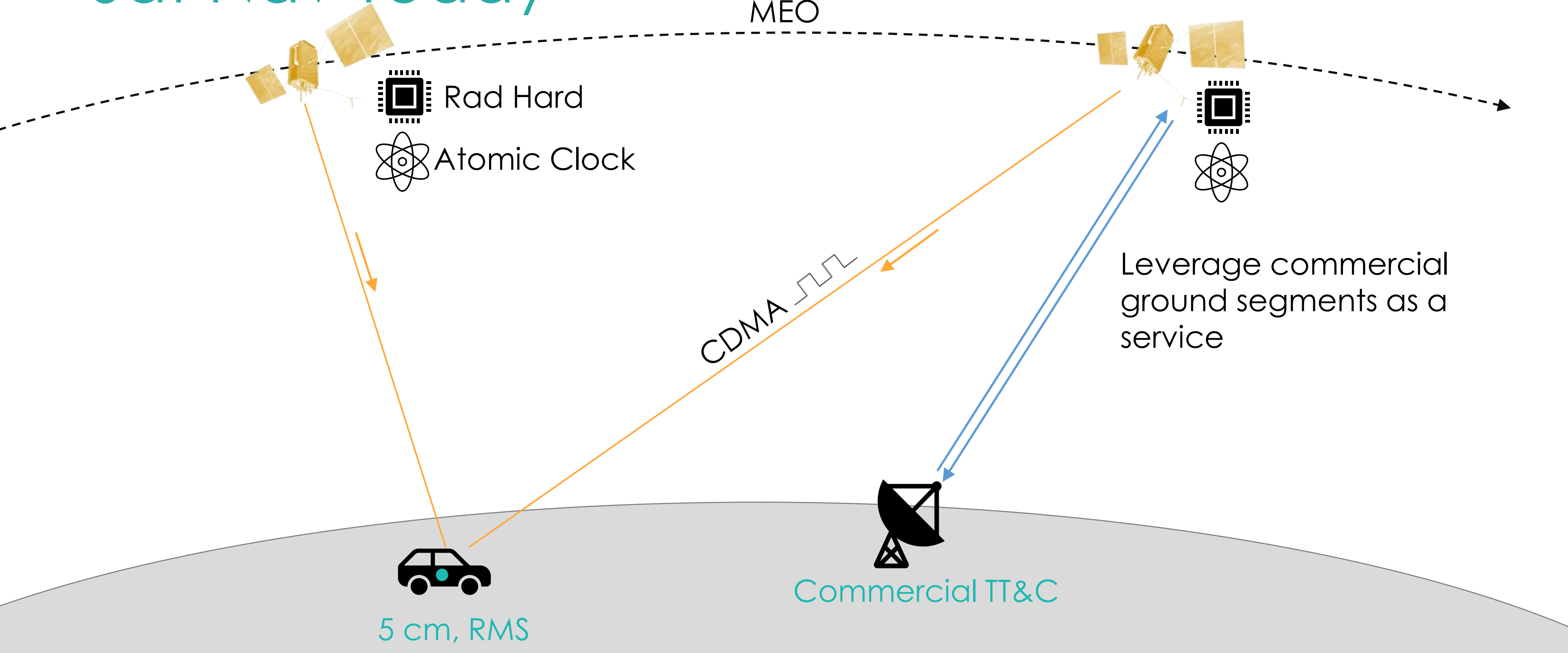
Rad hard satellite with atomic clocks are expensive.

MEO wins over LEO due to 10x less satellites needed while still satisfying daily upload constraint.

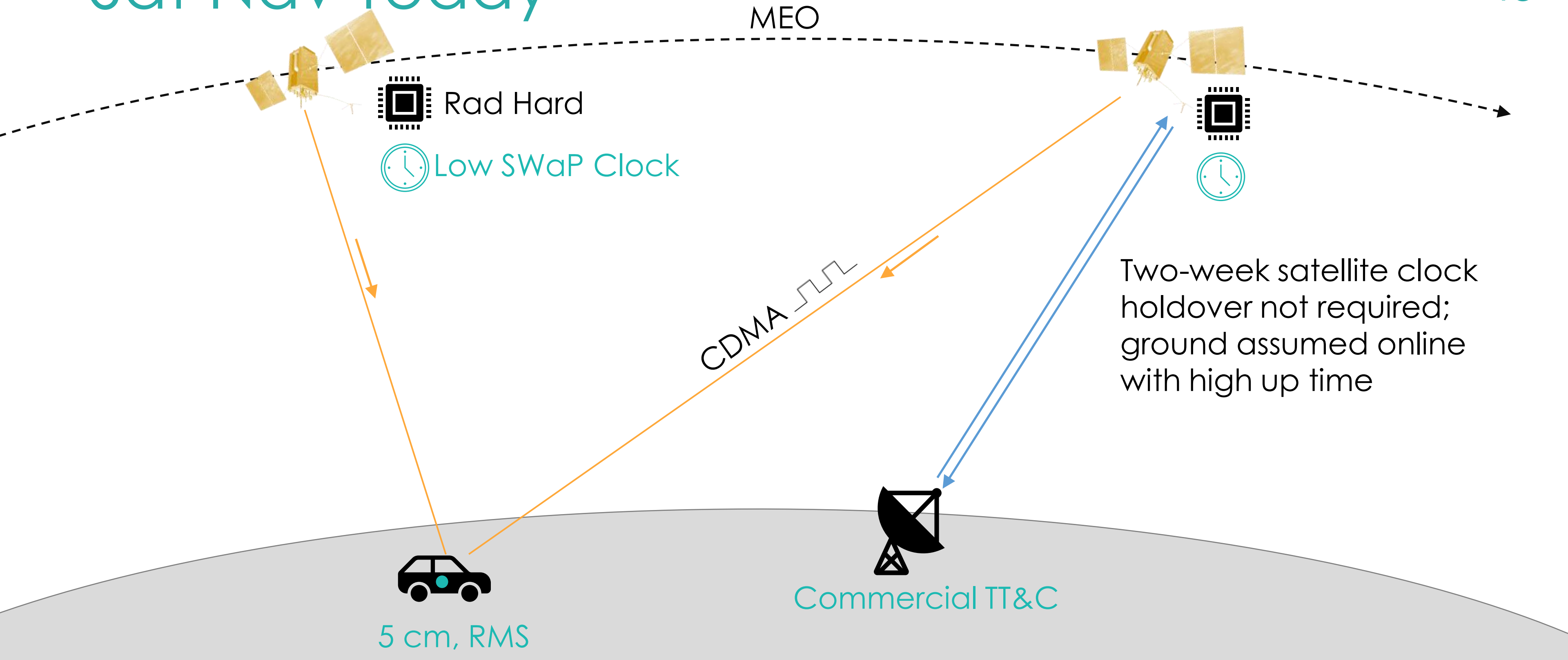
Sat Nav Today



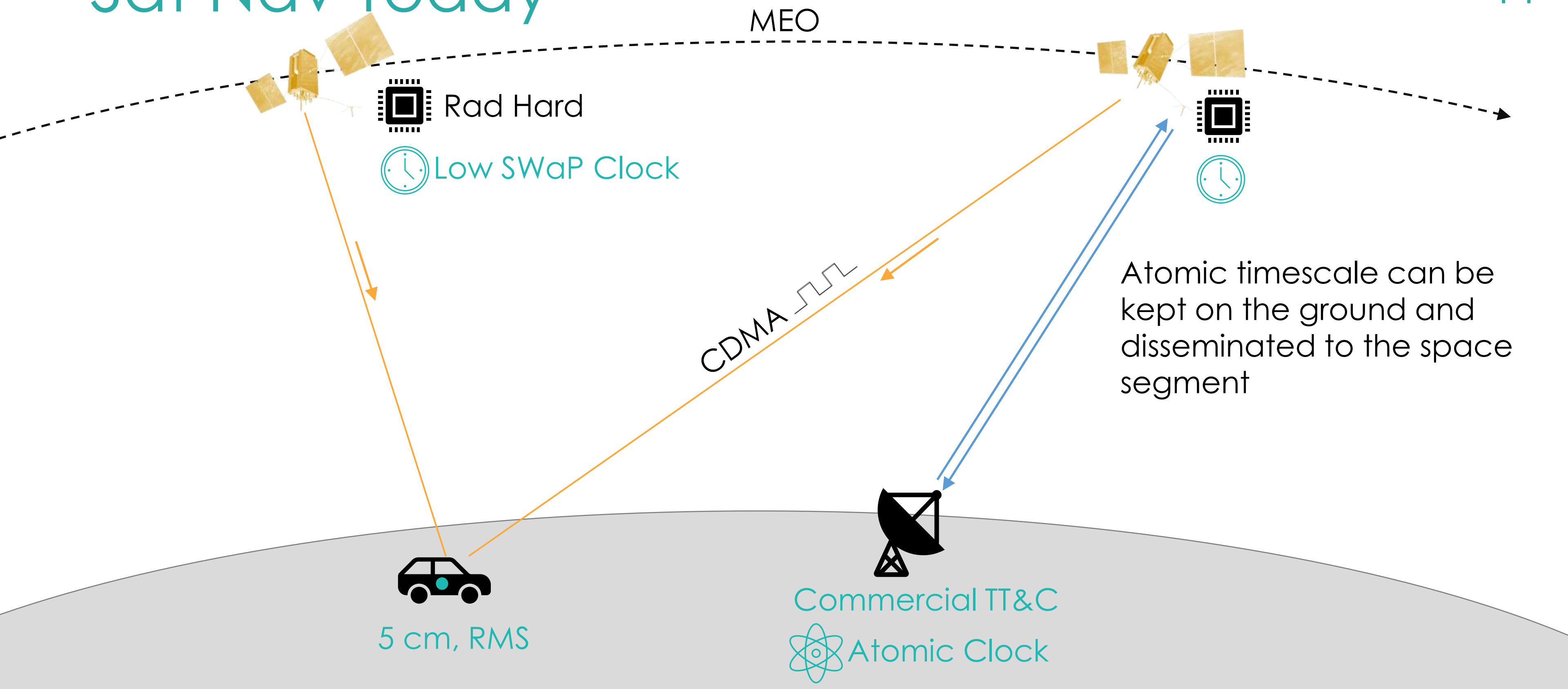
Sat Nav Today



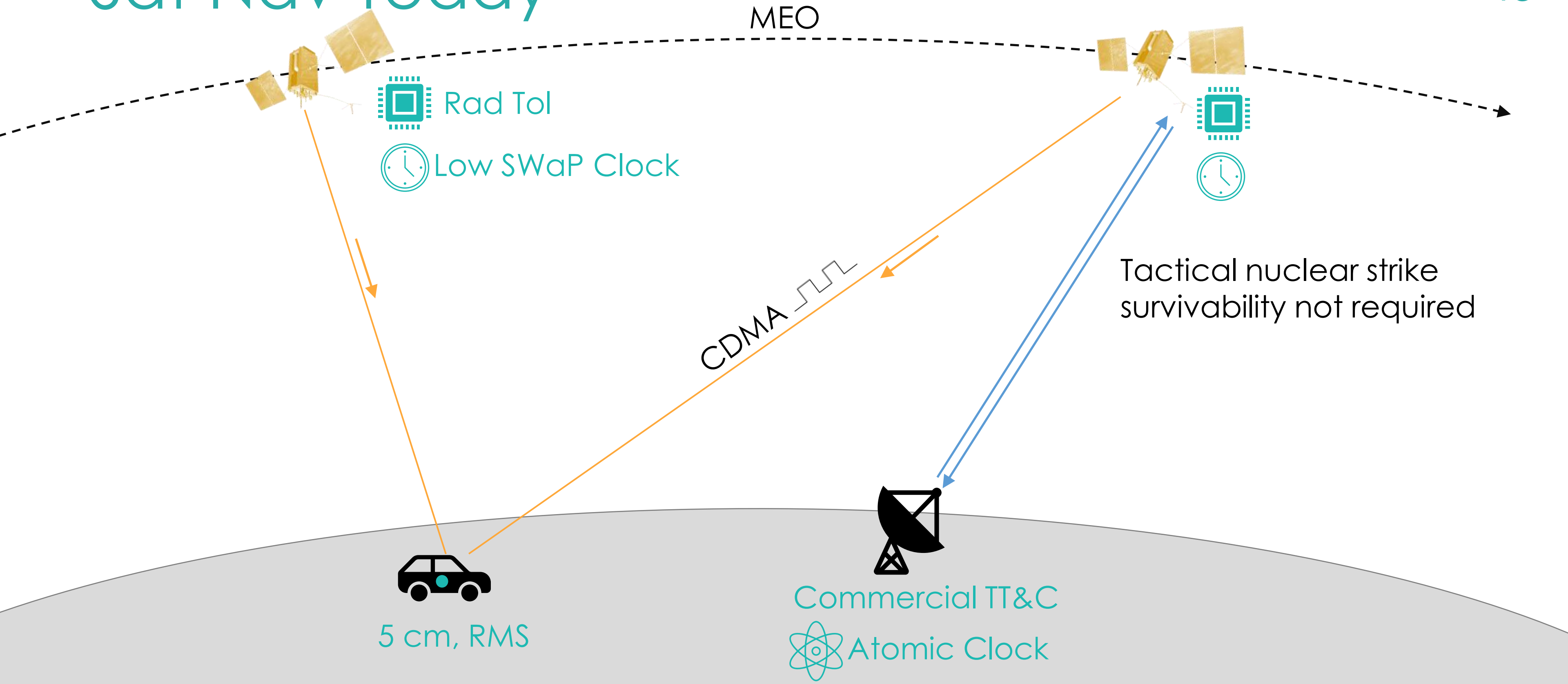
Sat Nav Today



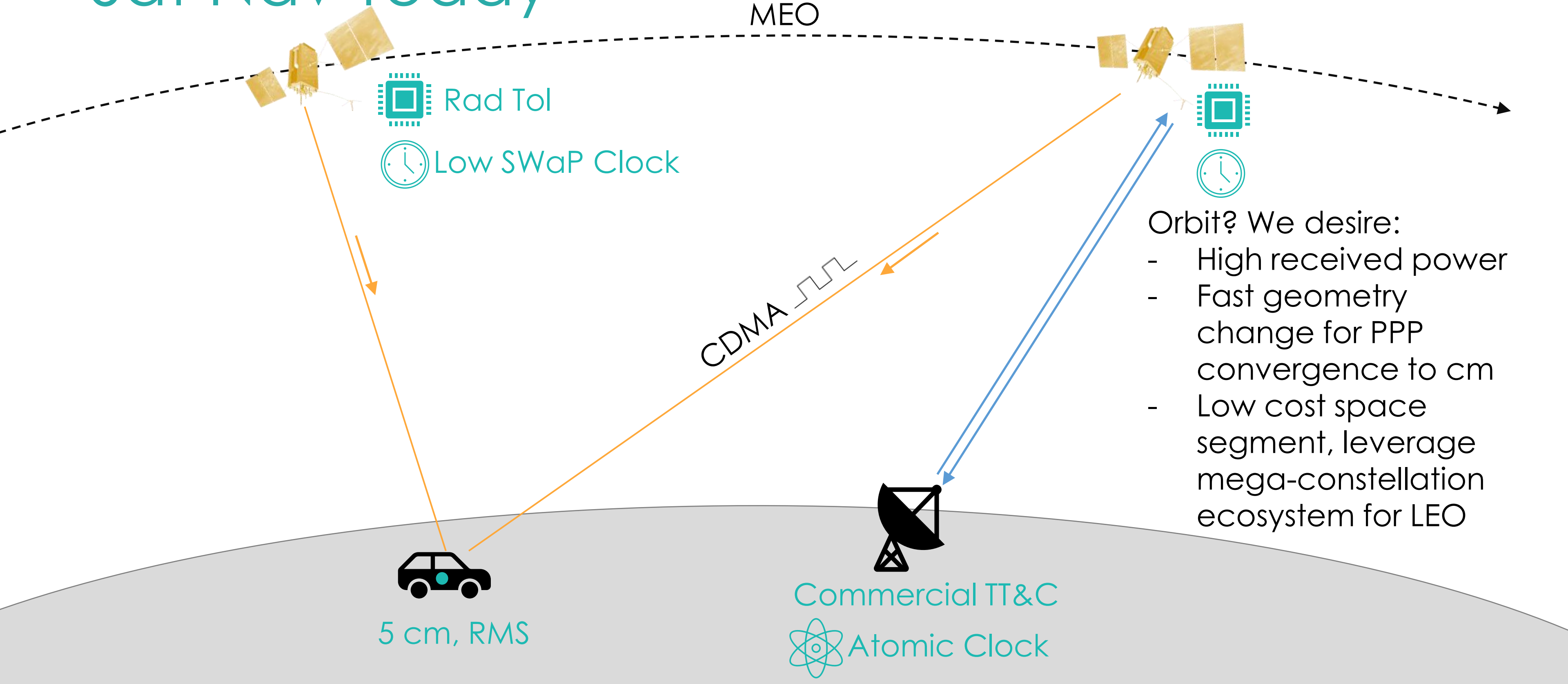
Sat Nav Today



Sat Nav Today

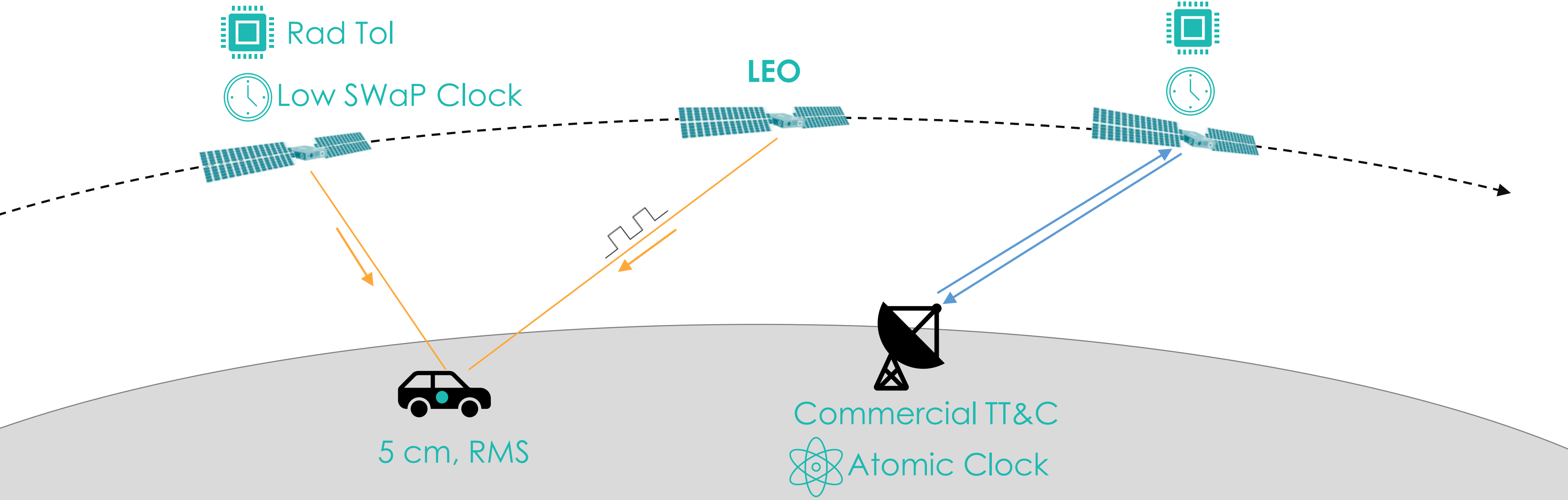


Sat Nav Today



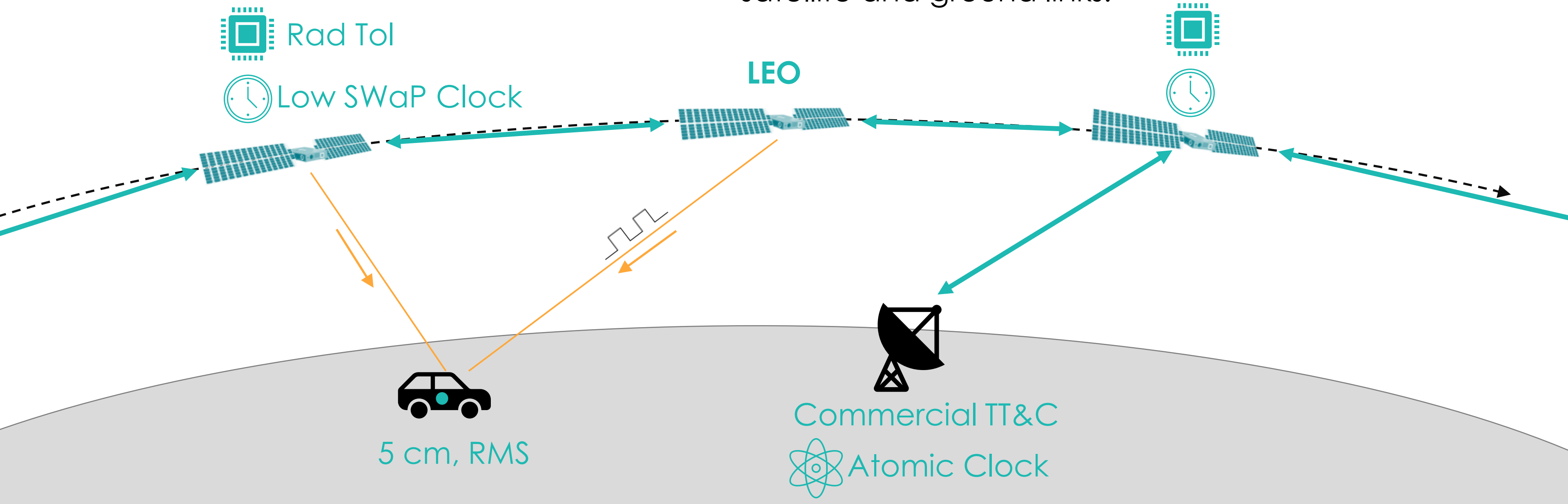
Sat Nav Today

Move to LEO



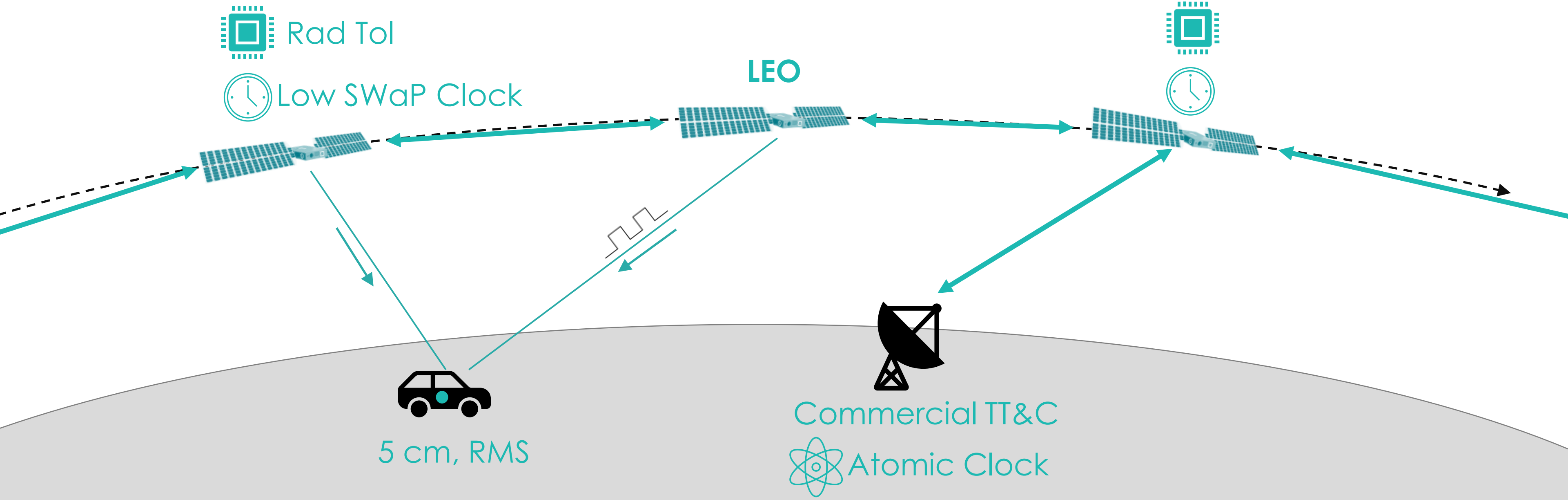
Sat Nav Today

Constellation orbit determination and time synchronization can be achieved independently of existing GNSS via inter-satellite and ground links.



Sat Nav Today

Novel signals can be introduced, unbounded by legacy GNSS

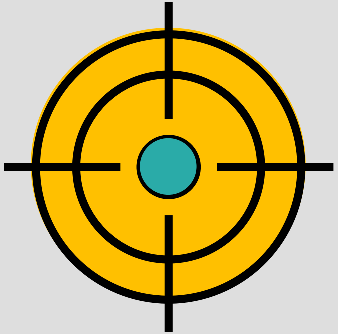


Dedicated LEO GNSS vs Comms Piggyback

Geometry
Narrow Beam Means Limited Visibility

User Equipment
Large & Complex Phased Array vs. Small & Passive Antenna

Accuracy & Independence
Comms systems rely on GNSS and is not designed for high accuracy PNT



Outline

PNT Needs

Aerospace Ecosystem

Sat Nav Architecture for Today

Xona Space Systems

Where We Are

Xona's Canadian operations are run out of our office in **Vancouver**.

The **UK** is the centre for Xona European operations.

San Mateo is home to the US R&D center and prototype lab.

XONA

SATELLITE NAVIGATION FOR THE AGE OF AUTONOMY

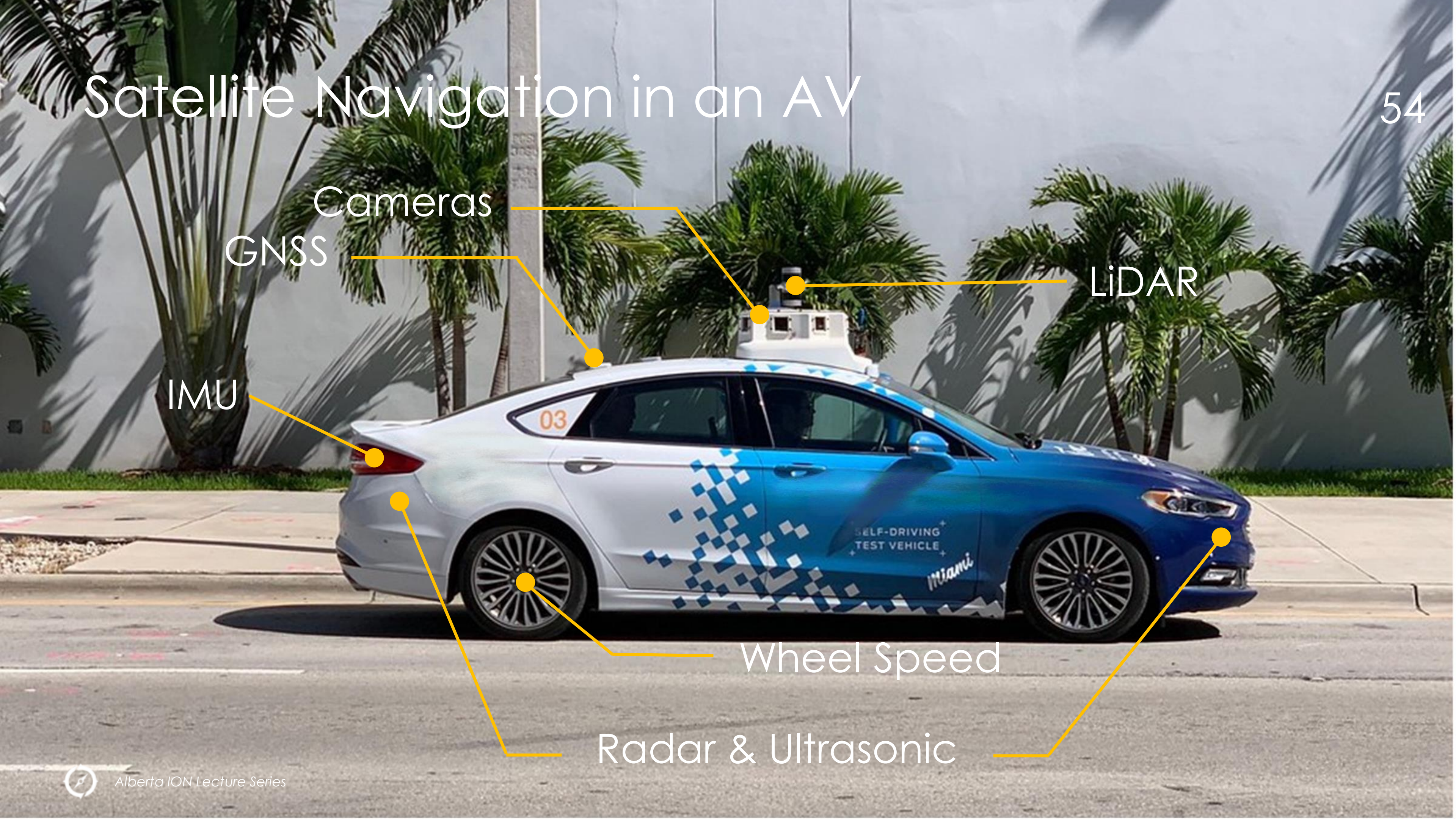
OUR MISSION

Enable modern technologies to operate safely in any environment, anywhere on Earth.

OUR METHOD

Provide the world's most resilient and accurate position, navigation, and timing services.

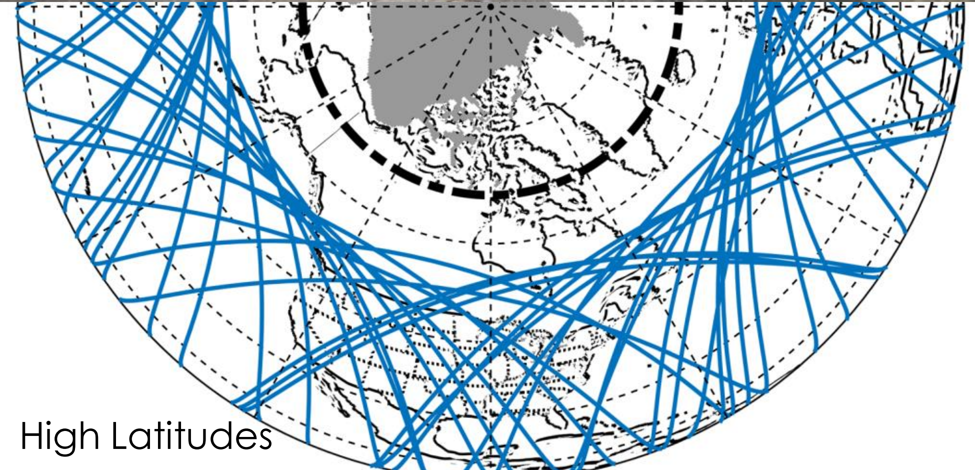
Satellite Navigation in an AV



Canadian Challenges


Adverse Weather


Vast & Sparse


High Latitudes

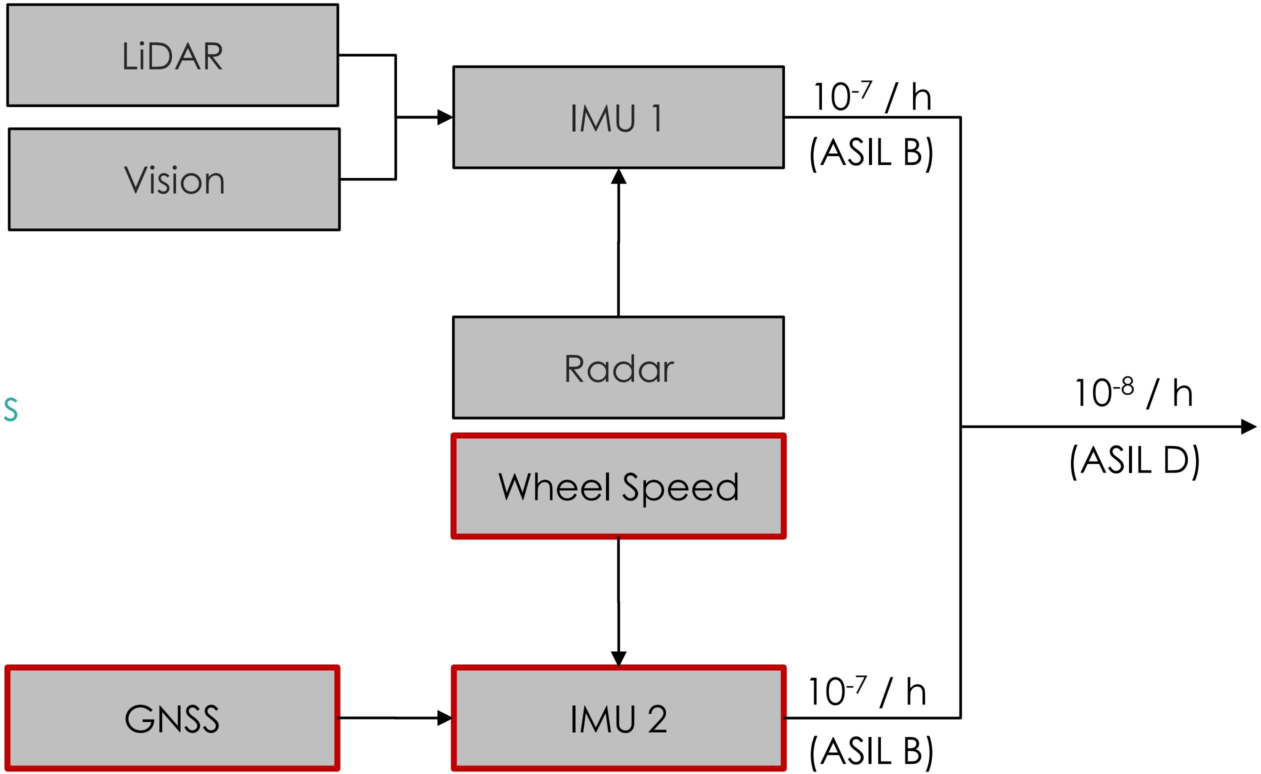

Space Weather

Satellite Navigation in an AV

Relative Localization

2x "independent" systems

Absolute Localization

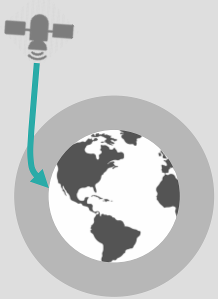


How to Get GNSS to 10^{-7}

GNSS Integrity =

Combine Faults From…

Atmospheric Effects



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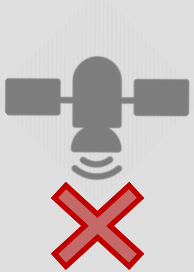
Satellite Faults



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Availability

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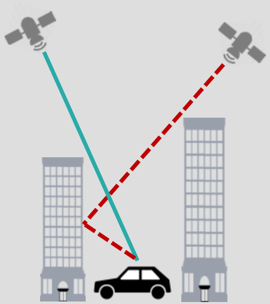
Multipath



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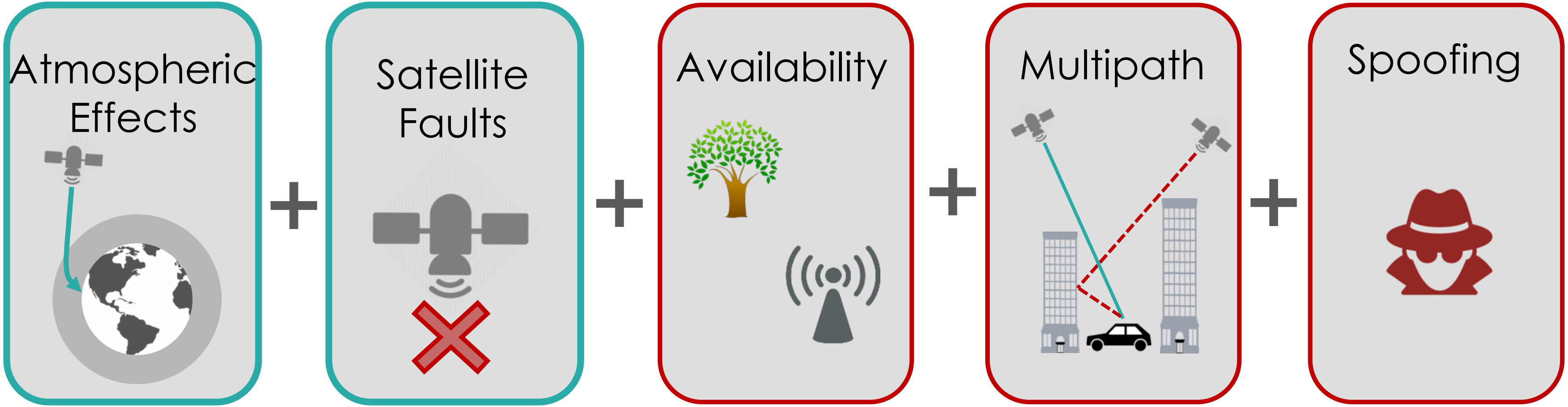
Spoofing

How to Get GNSS to 10^{-7}

GNSS Integrity =

Combine Faults From…



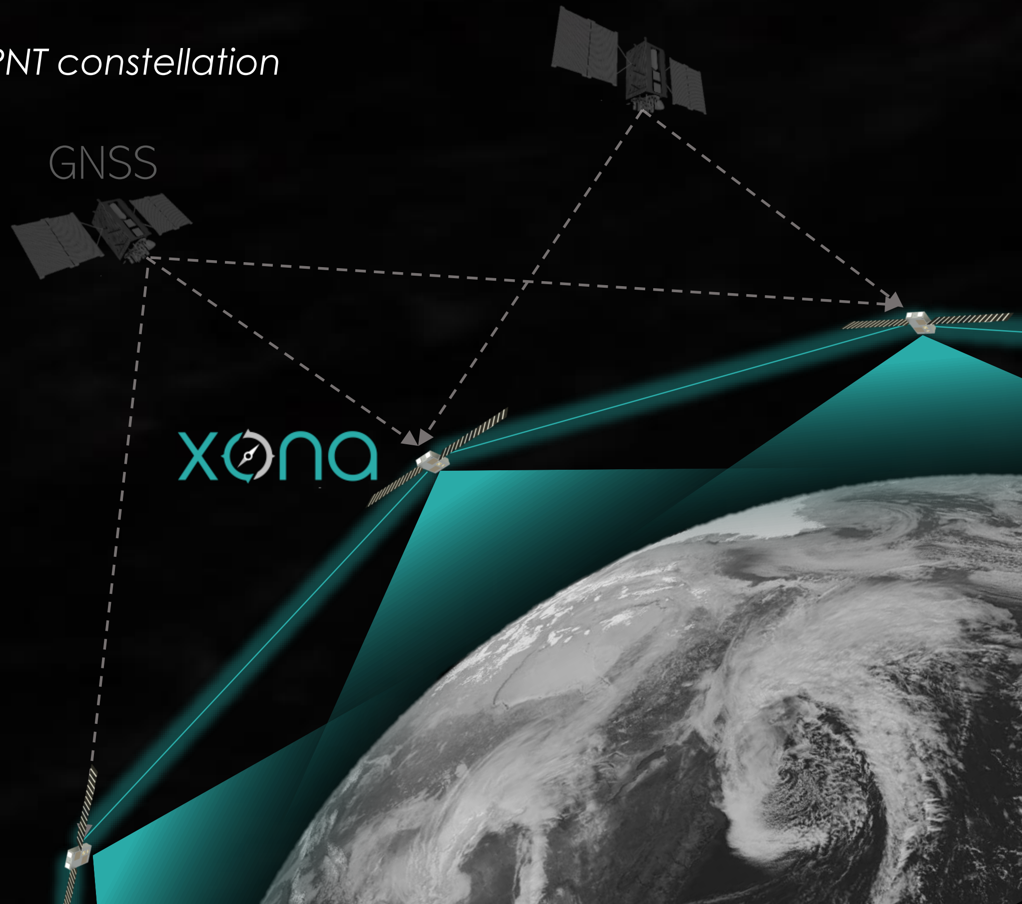
Advanced Receivers and Augmentation Services

New Space Unlocks New Solutions

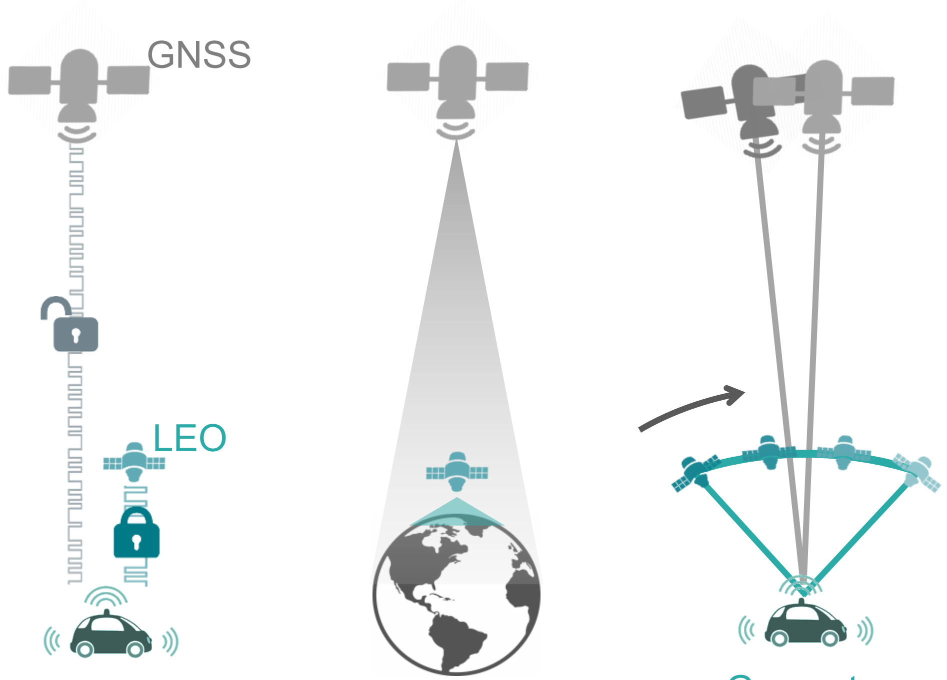
PULSAR: The first dedicated, commercial LEO PNT constellation

Xona's PULSAR will be the first ever service designed bring aviation-level reliability to mass market applications.

- 10x more accurate and up to 1,000x more powerful than GPS
- Sub-10cm positioning
- High-security encrypted and authenticated signal
- Capable of fully GNSS-independent operation



Commercial LEO PNT



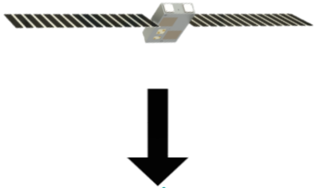
Encryption & Authentication

Stronger Signals

Geometry Change For Precision

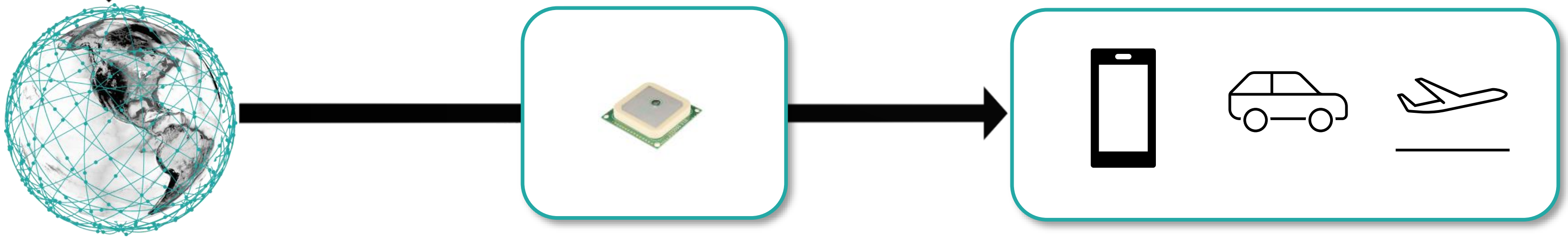
Navigation & Timing as a Service

Xona is developing the infrastructure…



…working to partner with Tier 1's and receiver manufacturers to integrate Xona functionality…

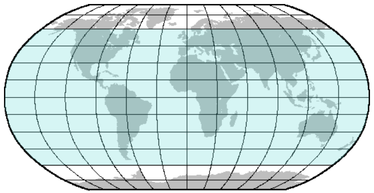
…to provide service on a subscription model.



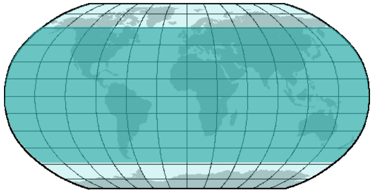
Phased Roll Out

70% of World Population Serviced with 36 Satellites

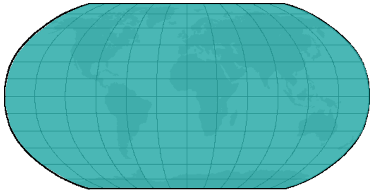
Phase 1
36 Satellites



Phase 2
66 Satellites



Phase 3
276 Satellites



• **Pulsar™ for Stationary Users** • **Corrections for Mobile Users**	>99% Availability Mid-Latitudes	>99% Global 100% Mid Lat	100% Global Coverage
• **Pulsar™ for Mobile Users**	-	>50% Global Coverage	100% Global Coverage

Demo Mission Launching in 2022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Spirent Federal to Simulate Signals for LEO PNT Firm Xona Space Systems

September 1, 2021 — By Inside GNSS

Powerful, Protected, Precise PNT from LEO

With support from…

SERAPHIM CAPITAL

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Stellar SOLUTIONS

TRUCKS

How to Get GNSS to 10^{-7}

xona

Only Xona's satellite infrastructure can address challenges with availability, jamming, multipath, and spoofing.

Thank You!

For more information, please see our work in:

ION INSTITUTE OF NAVIGATION

Satellite Navigation For The Age of Autonomy

Tyler G.R. Reid, Bryan Chan, Ashish Goel, Kazuma Gunning, Brian Manning, Jerami Martin, Andrew Neish, Adrien Perkins, Paul Tarantino
Xona Space Systems
San Mateo, CA & Vancouver, BC
{tyler, bryan, ashish, kaz, brian, jerami, andrew, adrien, paul}@xonaspace.com

ubiquitous backbone for navigation services that are robust, reliable, and secure.

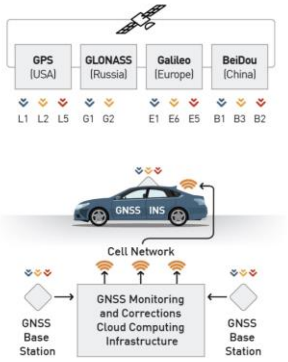
To understand, where navigation is headed, we first turn to the past and begin with an assessment of the historical trend. This includes contemporary drivers of new needs in accuracy, coverage, and capability as well as the technologies developed in the evolution from the sextant to the now more than one hundred navigation satellites in service today. This shows a clear trend: In the last century, there has been an order of magnitude improvement in location accuracy every thirty years. Each step has required investment in new infrastructure to reach new capabilities. With meter-level positioning first widely available in the mid-1990s with GPS, this implies that the mid 2020s will demand decimeter, or better, performance.

Autonomous systems are one of many coming applications that drive this need, where it is estimated that 10 cm, 95% accuracy in position will be required for self-driving cars [2]. Several technologies are emerging to meet this challenge. LiDAR, computer vision, radar, and GNSS are all striving towards this requirement. Though some have shown progress in meeting these needs in certain circumstances or conditions, they all struggle to fully solve the problem to the level of reliability, safety, and security that is needed. LiDAR and vision struggle in inclement weather due to absorption or scattering and is

IEEE

Developments in Modern GNSS and Its Impact on Autonomous Vehicle Architectures

Niels Joubert, Tyler G. R. Reid, and Fergus Noble



SAE INTERNATIONAL

Localization Requirements for Autonomous Vehicles

Tyler G. R. Reid, Sarah E. Houts, Robert Cammarata, Graham Mills, Siddharth Agarwal, Ankit Vora, and Gaurav Pandey

Abstract—Autonomous vehicles require precise knowledge of their position and orientation in all weather and traffic conditions for path planning, perception, control, and general safe operation. Here we derive these requirements for autonomous vehicles based on first principles. We begin with the safety integrity level, defining the allowable probability of failure per hour of operation based on desired improvements on road safety today. This draws comparisons with the localization integrity levels required in aviation and rail where similar numbers are derived at 10^{-8} probability of failure per hour of operation. We then define the geometry of the problem, where the aim is to maintain knowledge that the vehicle is within its lane and to determine what road level it is on. Longitudinal, lateral, and vertical localization error bounds (alert limits) and 95% accuracy requirements are derived based on US road geometry standards (lane width, curvature, and vertical clearance) and allowable vehicle dimensions. For passenger vehicles operating on freeway roads, the result is a required lateral error bound of 0.57 m (0.20 m, 95%), a longitudinal bound of 1.40 m (0.48 m, 95%), a vertical bound of 1.30 m (0.43 m, 95%), and an attitude bound in each direction of 1.50 deg (0.51 deg, 95%). On local streets, the road geometry makes requirements more stringent where lateral and longitudinal error bounds of 0.29 m (0.10 m, 95%) are needed with an orientation requirement of 0.50 deg (0.17 deg, 95%).

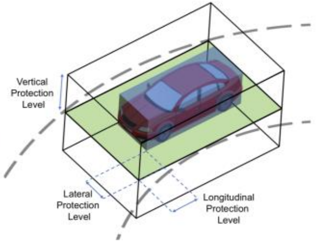


Fig. 1. Definition of localization protection levels for automotive applications.

61v1 [cs.RO] 3 Jun 2019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