Assuring PNT Capability for Humanity -

an Essential Element of National Power:

Strategy and Status

Professor/Dr./Col. Brad Parkinson
Chief Designer, Advocate, and Original Development Director

Let's begin with a very short history of the Origins of GPS

The Design Decisions became essential enablers for an Explosion of PNT Applications and a path to explore techniques to ensure PNT…

"Black Thursday"

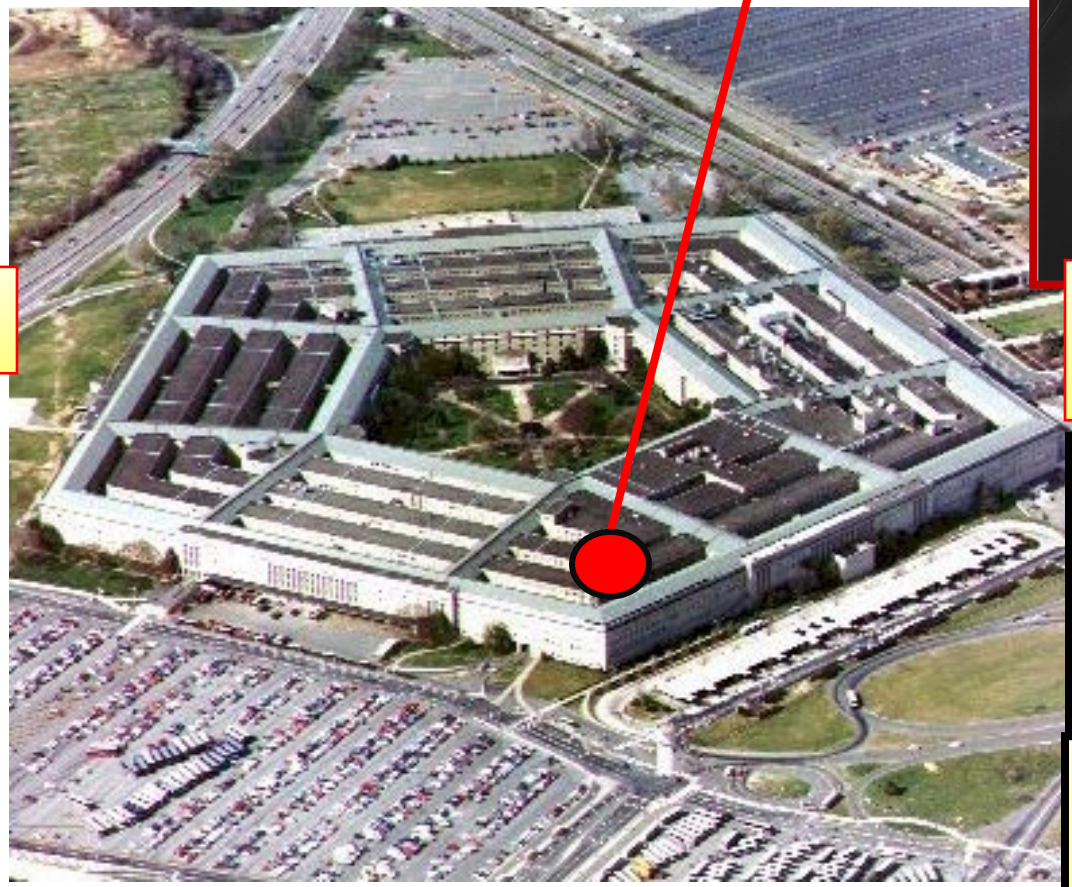
Failure

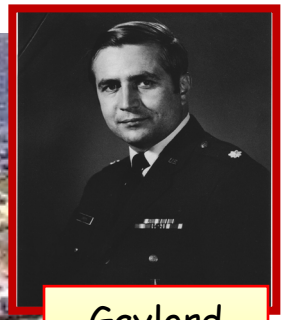
51 years ago, August 1973

Recovery from Failure -***Re-Designing the Proposal***-
~ 10 Officer/engineers at the "***Lonely Halls***" Meeting-

"Labor Day" Weekend >51 Years Ago. ***(Saturday, 1 Sept. 1973 – Monday, 3 Sept. 1973)***

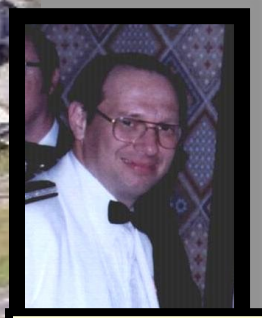
Brad Parkinson
USAF





Gaylord
Green
USAF

Steve
Gilbert
USAF



Mel
Birnbaum
USAF

The *Three Fundamenta*

Enabled *Inexpensive*, Worldwide, 3D Position plus time

1. **CONCEPT –Semi-synch (12 sidereal hour) Satellites:**
   - **Simultaneously Measure Range to Fo**
   - **Eliminated need for User's Atomi 4D Position**
   - **Global constell**ation of 24 Satelli

Enabled Unlimited Users and Accuracy to a Pencil Lead (differential) + J/S > 41 dB (12,000 to 1)

2. **PASSIVE RANGING SIGNAL DESIGN:**
   - ***Code-Division Multiple Access*** (CDMA) - - accuracy and jam resistance
   - All Satellites on the same frequency, Code and Underlying Carrier are phase locked. **RTK gives dynamic accuracies of a few centimeters**
3. **Orbiting, Hardened, Space-borne Atomic Clocks enabled accurate predictions of 4d satellite lo ion - greatly reduce ground dependency**
   - Nominal 12 Hour clock updates
   - Predictions **good for weeks** (clock drift

Enabled extended Autonomous Satellite Operation (If Ground control failure)

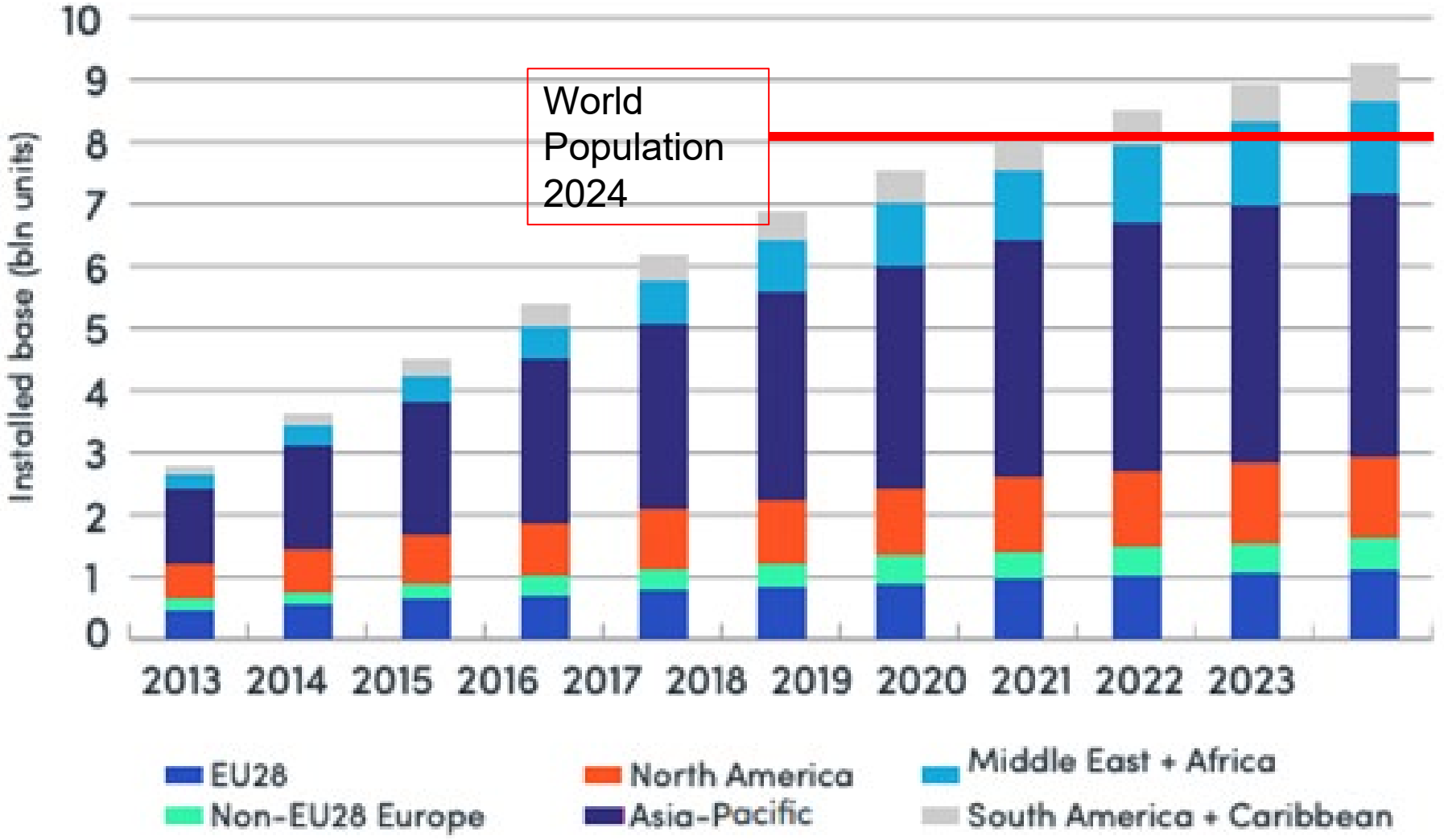
Gained Approval for Full-scale, Phase One Development - Dec. 1973

- First launch of GPS February 1978 – ***44 months after contract award.***
- By 1979, Extensive testing confirmed all capability promises made in 1973…
- Full Operational Capability (FOC) on April 27, 1995 **(21 years after Phase 1 Approval)**

Three Critical Events Accelerated GPS Acceptance and Applications

1. **Pres. Reagan** Guarantees GPS to the World (1983) Due to shootdown of KAL007.
2. **Pres. Clinton** orders ***Deliberate Civil errors (S/A) turned off*** on May 1, 2000.
3. **Integrated Chips** drove GPS receiver cost to less than $5 and # of Channels >100.

Installed and Projected Base of GNSS Devices by Region



Source: GSA GNSS Market Report 2015 Issue 4_0, March 2015.

Reminder: Prerequisites for GPS/GNSS contribution to **Assured world-wide PNT** – If 3D and time are required:

Clear and truthful Passive Ranging to ≥ 4 Satellites

- Must have Line of Sight to "enough" GPS/GNSS
  - **For sky-impaired (large shading angles), need densification**
    (GPS+ Galileo+ GLONASS +Bediou)
- Must be able to accurately measure range
  - **Overcome local interference**
- Must ensure ***Integrity*** of received signals
  - **Self- integrity (RAIM/ARAIM)**
  - **External rapid-checking**
    (e.g. WAAS, Egnos, MSAS)
  - **+ (potentially) NASA's GDGPS**

A Tribute to the Space Force Operators (2 SOPS)

FAA Continuously Monitors GPS in the US.

In 2024, Median Horizontal accuracy of "Raw" GPS : 3.52m *(95th Percentile)*

Civil Report Card On GPS Performance
Feb 2025

Operational Performance Parameter	CY 2024	Jan 2025	Feb 2025	Long term	Short term
Availability Parameters					
Average Number of satellites usable	30.71	30.28	30.97	↑	↑
Average number of satellites usable in primary slots	23.78 (99.08%)	24.00 (100.00)	24.00 (100.00)	↑	→
Average availability of 6 satellites in view	100%	100%	100%	→	→
99.99% Horizontal DOP					
Area Median	1.29	1.31	1.28	↑	↑
Worst Site	4.54	2.36	3.74	↑	↓
99.99% Vertical DOP					
Area Median	2.26	2.38	2.32	↓	↑
Worst Site	9.85	5.03	9.87	↓	↓
99.99% Position DOP (PDOP)					
Area Median	2.57	2.67	2.59	↓	↓
Worst Site	10.50	5.45	10.56	↓	↓
100% RAIM Availability (HAL=185m)					
NPA Service Area (NSA)	76.12%	86.21%	96.95%	↑	↑
World	78.14%	79.35%	83.91%	↑	↑
Accuracy Parameters					
RMS Single Frequency User Range Error					
Constellation Median (m)	2.41	2.50	2.44	↓	↑
Worst Satellite (m)	48.54	29.01	29.31	↑	↓
95% Horizontal Error					
Area Median (m)	3.52	3.38	3.45	↑	↓
Worst Site (m)	15.12	11.79	12.27	↑	↓
Availability (% <4.5m (historical 3-sigma))	95.96%	95.62%	95.96%	→	↑
95% Vertical Error					
Area Median (m)	5.30	7.18	5.89	↓	↑
Worst Site (m)	12.78	10.57	11.30	↑	↓
Availability (% < 9m (historical 3-sigma))	98.68%	97.78%	99.02%	↑	↑

Key: ↑ improving ↓ worsening → no significant change
Long Term is current month vs. prior 12 months; Short Term is current month vs. prior month

Compiled from WAAS network as requested by the Defense Science Board

The 4th Dimension: ***Time Synchronization***

T

- Many "hidden" applications for precise time-
  Power Grid, Stock Mkt, Banking, Cell Phone towers…
  - Requirements millisec. (10^{-3}s) to nanosec. (10^{-9}s).
  - Some need synchronization to
    Universal Coordinated Time (UTC) -
    - GPS distributes UTC time ~10 to 25 nanosecs.
    - GPS Synchronizes to 2-15 nanosecs. ("Commonview")
- Most references are implemented with GPS and a flywheel clock – frequently Rubidium Atomic.
- Major efforts to find timing augmentation to GPS, creating "uninterruptable" sources

Categories – "Assured PNT" – How should "assured" be interpreted?

User Requirements for GPS PNT:
Accuracies/Dimensions/Integrity/Jamming Resistance
Vary Greatly by Application –
So "Assurances" can be quite different, depending on application.

Let us **Define 5 Broad**
PNT Capability/Requirement *Categories*
To help assess "Assurance" solutions …

Five PNT Capability Categories

	C	B	A	S	T
User Category	General 3D Dynamic	Precision 3D Dynamic	Ultra-Precise 3D Dynamic	Survey Class Static	Time Sync & Transfer
Horizontal Accuracy	25 Meters 95th Percentile, Dynamic.	2.5 Meters 95th Percentile Dynamic	10 cm. 95th Percentile Dynamic	1 cm– 0.1mm Static	Time: microsec to nanosec
GPS Technique	"Raw" ***GPS***	***Differential*** GPS (Local, or Continental [WAAS] GPS "Reference" Receivers)			
		WAAS Corrected	RTK	Base Station	Master Reference
Examples	Cell Phones, Watches, Autos	Aircraft Landing	Real-Time Kinematic (GIS, Auto Farming, Machine control)	Survey Class, Plate Techtonics	Banking, Power Grid

Summarizing: "Assured" PNT solutions depend on User Needs:
Categories of User PNT Capabilities/Requirements

- **Cat A (RTK, 10 cm or better, 3D)** (carrier-tracking differential) – Dynamic User, –up to 10^{-5} Integrity can use RAIM and ARAIM
- **Cat B (WAAS integrity and Accuracy corrections, ~2.5 meters, 3D,)** Dynamic User, up to 10^{-7} Integrity.
- **Cat C (unaided GPS ~25 meters 95th percentile worst location, 3D/2D?)**. Dynamic User, Ionospheric model.
- **Cat S (Survey/Scientific)** –Static User, Averaging over time. Accuracies: sub centimeter to sub millimeter
- **Cat T (Time)** Static users. **Nanoseconds to Microseconds** Many with local flywheel atomic clock

> 60 Example Applications: **Categories A,B and S – *(RTK & High PNT Precision) in Red--***

Group	Example applications
Aviation	Area navigation, approach, landing up to Cat III, NextGen
Cell Phones	Used for many other apps – Automotive, Tracking et al.
Agriculture	AutoFarming: crop spraying, precision planting, yield assessment
Automotive	Turn-by-turn guidance, OnStar, driverless cars
Emergency and Rescue Services	911, ambulance, fire, police, rescue helicopters, emergency beacons, airplane and ship locaters, OnStar
Intelligent Transportation	Train control and management, UAVs, Intelligent Highways
Military	Rescue, precision weapon delivery, unit and individual location
Recreation	GeoCaching, control of models, hiking, outdoor activities
Robotics & Machine Control	Bull dozers, Earth graders, mining trucks, oil drilling, Container ship loading, Urban UAV control, Snowplow control
Scientific	Earth movement and shape, atmosphere, weather forecasting, climate modeling, ionosphere, space weather, tsunami warning, soil moisture, ocean roughness, wind velocity, snow, ice, and foliage coverage, ...
Survey and GIS	Mapping, geographic tags, environmental monit., disease outbreaks
Timing	Cell phone towers, banking, power grid
Tracking	Fleets, assets, Space Satellites, equipment, shipments, children, Alzheimer's patients, wildlife, animals, law enforcement, criminals,

Examples of PNT Categories A, and B (dynamic users):

Applications mostly need 3 dimensions–***Accuracy*** down to 0.04 cm. and

Integrity – better than one HMI error in 100,000 –

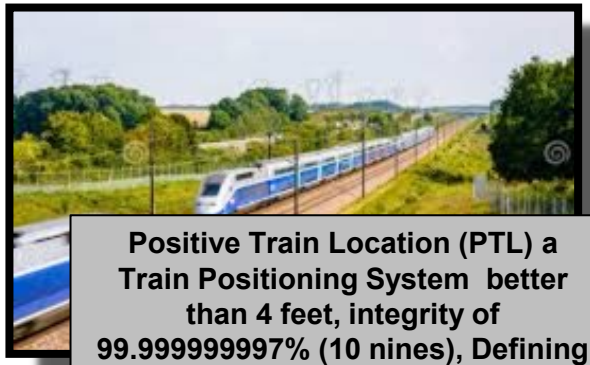
(one HMI fault in 10,000,000 for precision aircraft landing)

Machine Control to 2 inches

Locating underground utilities to 6 inches

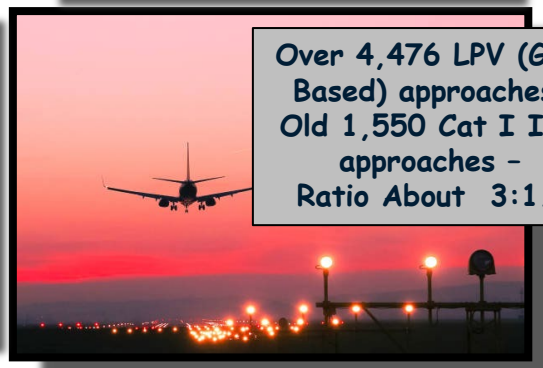
Land and Maneuver BVLOS 3D and a few feet

Autofarming – 2 inches



Positive Train Location (PTL) a Train Positioning System better than 4 feet, integrity of 99.999999997% (10 nines), Defining train length and track discrimination.

Automatic unloading of Container ships - inches



Over 4,476 LPV (GPS Based) approaches, Old 1,550 Cat I ILS approaches – Ratio About 3:1.

Economic Value and National Power

National Power Elements Typically Include:

- Population,
- Geography,
- Natural Resources,
- Political Stability,
- Leadership,
- Diplomacy,
- Cultural Influence.

GPS

- Military Capability,
- Technology,
- Economic Strength,
  - Direct Benefits
  - Impacts when not available

Economic Value and Loss Impact –

at least 3 major studies on GPS economic value

- RTI International (Sponsored by NIST, 2017) ***valued GPS*** at $1.4 Trillion since its inception.
  - **Extrapolating to 2025, the current cumulative value of GPS to the US is over $2 Trillion.**
- In 2017, RTI estimated impact of ***GPS loss*** **at about $1 Billion per day.**

  (UK study reached nearly same impact for UK)
  - Agriculture was so dependent on very precise GPS (Category **A**), loss would balloon to **$1.3 Billion per day** during the ***critical planting season***.
- **Both Value and Loss Estimates heavily driven by Categories A and B GPS users.**
- **Clearly, Assuring PNT is a high priority goal for the economy, for infrastructure and for safety**

Others have Recognized Power: There are now 4 Global Navigation Satellite Systems (GNSS) –
All use the GPS design: the ***Digital Signal***, ***4 satellite Solutions*** and ***Spaceborne Atomic Clocks***

GLONASS -
(Russia)

GPS
(USA)

- First Operational Civil Signal
- Moving to 10 signals

Galileo
(European)

Compass
(Beidou China)

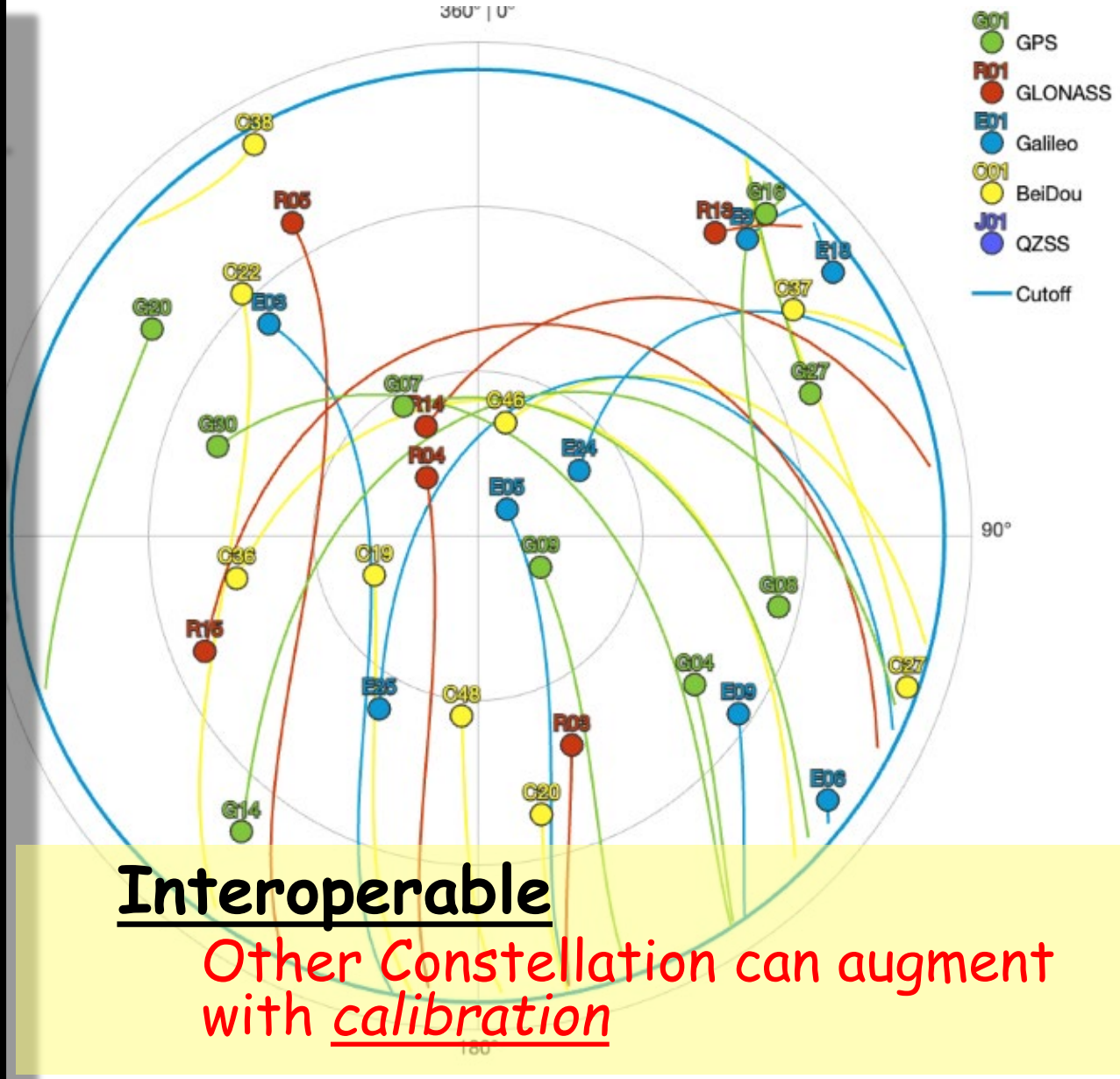
Typically about 30 GNSS ***satellites*** above the horizon-
and about 10 ***different types*** of signals available from each – Over 200 signals potentially in view

Example of available signals.

Typical Skymap at San Luis Obispo, CA (31 sats in view)

Each satellite is broadcasting multiple signals

Most cell phones now use all – PNT Category C

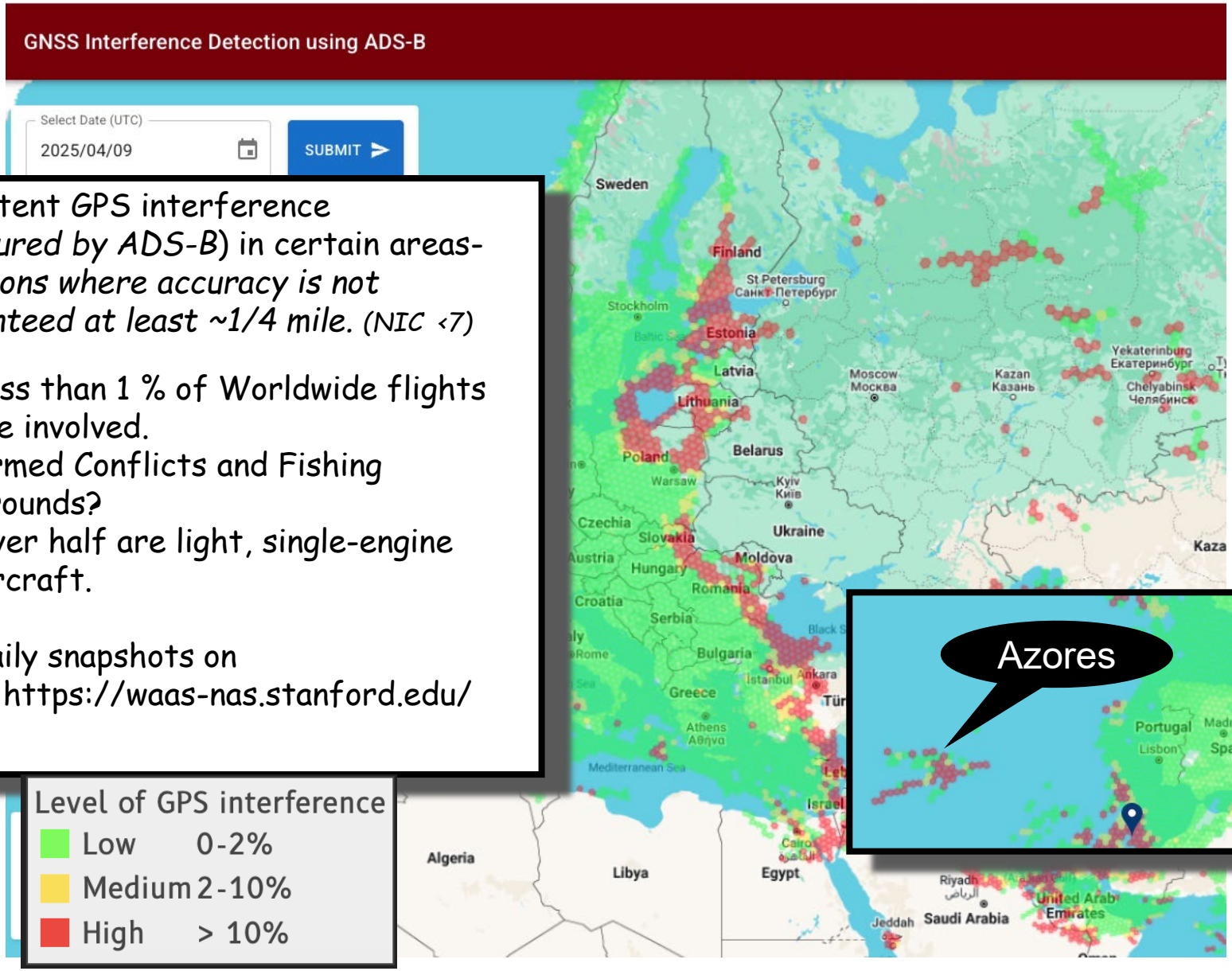


Interoperable

Other Constellation can augment with *calibration*

Major Threats to the Availability of *Assured PNT* from GPS/GNSS

- Signal Interference
  - "Jamming" - Natural, Inadvertent, or Deliberate
  - "~~Spoofing~~" → **Denial**
- Physical Attack
  - Satellites
  - Ground Control and Infrastructure
- Cyber Attack – System or Receivers
- Operator Errors – e.g. erroneous uploads to satellites



Persistent GPS interference (*measured by ADS-B*) in certain areas- *Locations where accuracy is not guaranteed at least ~1/4 mile.* (NIC <7)

- Less than 1 % of Worldwide flights are involved.
- Armed Conflicts and Fishing Grounds?
- Over half are light, single-engine aircraft.

Daily snapshots on
https://waas-nas.stanford.edu/

Media Responses

- **Headlines: GPS vulnerable!**
  - Jamming
  - Spoofing
  - FCC Allocation Blunders
- **Pursuit of Augmentations:**

  "We have to find a replacement/backup"
  - A reasonable activity - Studied for over 20 years (e.g. FAA-DME)

But, Current PNTAB Assessment:

"No *current* or *demonstrated* alternative to GNSS-type systems (Primarily GPS) can deliver equivalent dynamic/static accuracy (to millimeters, 3D), integrity and worldwide 24/7 availability." (Particularly Categories A and B)

- **Conclusion: We must *also* allow and encourage deploying well-established solutions to *toughen* *GNSS-based* PNT.**

i.e., Make GPS more Robust and Resilient

Outline: PNT AB Strategy:

PTA – Protect, Toughen, and Augment GPS to ensure that it ***continues to provide Economic and Societal Benefits***

- **Protect** the Clear and Truthful Reception –**7 steps**
  - **3 Pre-actions - Legal/Law Enforcement/FCC**
  - **4 Re-actions when interference/spoofing occurs – DOD/DOT/DHS/FCC/FBI/DOJ**
- **Toughen User's Receivers**
  - **Diversify -** *All GNSS signal* receivers (with vector feature and acceptable integrity)
  - **Increasing *Jam resistance*** – use well established techniques
- **Augment** or substitute PNT sources
  - **Densify and Diversify satellites –**
    - Use All Signals/Constellations but ***With adequate integrity***
  - **Non-GNSS PNT Sources**

Assured Availability of PNT - "PTA"

First Strategy Area : Protect.

- Protect the Clear & Truthful Signal-

  1. Pre-actions -before interference occurs – Legal/Law Enforcement/FCC:

  Protect Spectrum/Enact strong Penalties/suppress Jammer sales

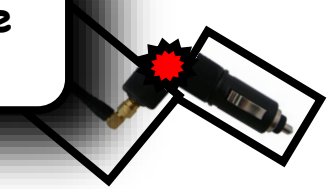
Assured Availability of PNT - "PTA"

Protect the Clear and Truthful Signal-
2. The *Reactions* - "DIEP"

D. *Detection* – Rapid Location of Jammed Receivers

I. *Identification* & Location of Jammer within < 2 hours

E. Physical *Elimination* of the Jammer



P. *Prosecution* of the Offender

Work with DOT and Enforcement to improve timeliness and accuracy of interference identification

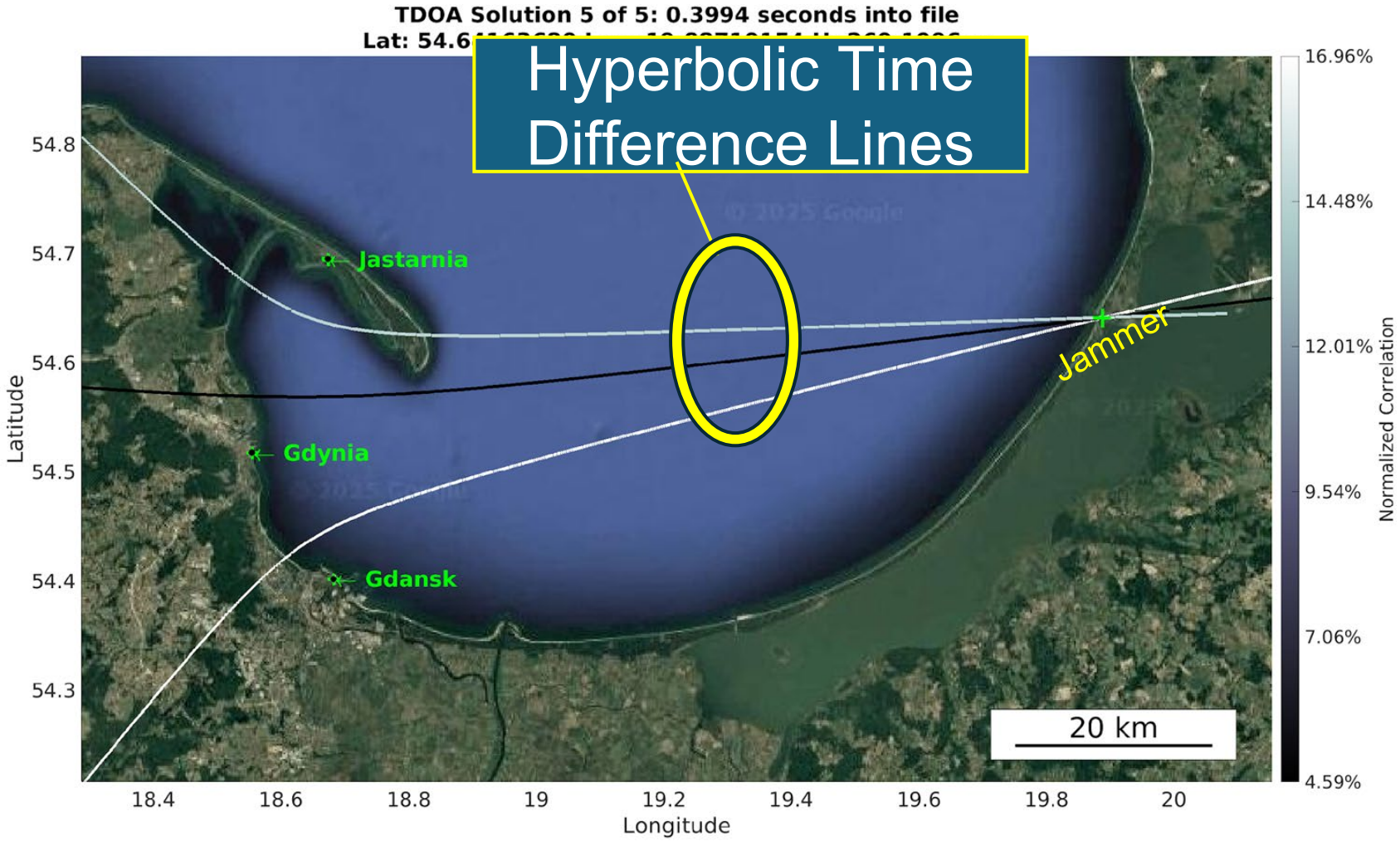
(e.g. crowdsourcing, every cell phone a detector?)

"Develop means to detect, measure, locate, and mitigate radio interference or jamming in support of the National Security Infrastructure."

GIDL: GENERALIZED INTERFERENCE DETECTION AND LOCALIZATION SYSTEM (A real example)

Professor Dennis Akos et.al.

Experiments by Colorado University and Polish Maritime Institute



Assured Availability of PNT - "PTA"

Strategy #2 of PNTAB

Toughen

- **Toughen GNSS Users' Receivers**
  - Employ multiple, well-known techniques to ensure *spoofing* can never create HMI
    - Increase Jam resistance – use demonstrated receiver A/J techniques
    - Diversify – use *All integrity-certified GNSS signal* receivers (with vector feature)
    - *Toughen Constellation by proliferating low-cost satellites*

Existence Proof from 47 years ago:
Rockwell Collins (now BAE) GDM (1978)
One of the Phase One User Sets

Unaffected flying over 10kW of jamming at 10,000 feet.

Demonstrated over 100 dB of J/S!

(J/S = 10,000,000,000. – **10 Billion to One**)

Main "Toughening" Techniques. (Factors Multiply)

Basic C/A receiver J/S factor of ~2,500 (full state 5)

- **Group 1: Signal Processing**
  - Tracking mode
  - Narrow Filtering
  - Vector Processing

Additional J/S factor of ~10

- **Group 2: Inertial + Very Stable User Clocks**
  - MEMS – up to hi-grade IMU
  - Quartz to CSAC

Additional J/S factor of ~31

- **Group 3: Controlled Reception Pattern Antennas** (CRPAs)
  - Elements/Footprint – (4, 7, 19, Many)
  - Beam/Null steering or combinations

Additional J/S factor of up to ~1,000,000

- **Group 4 Satellite type *Augmentations*:– may require Receiver Mods.**
  - *Additional GPS Satellites (Also a defence against anti-GPS satellite attacks)*
  - *Additional Signals and Frequencies (L5, L2C, L1C,)*
  - *Additional GNSS Constellations (Galileo)*
  - *Earth Coverage Power Increases*
  - *Regional Gain: Satellite Beam Antennas/RMP*

Additional J/S factor of ~14 – Similar to "M" Code

Receiver Toughening

L5 Authorized and planned over 26 years ago

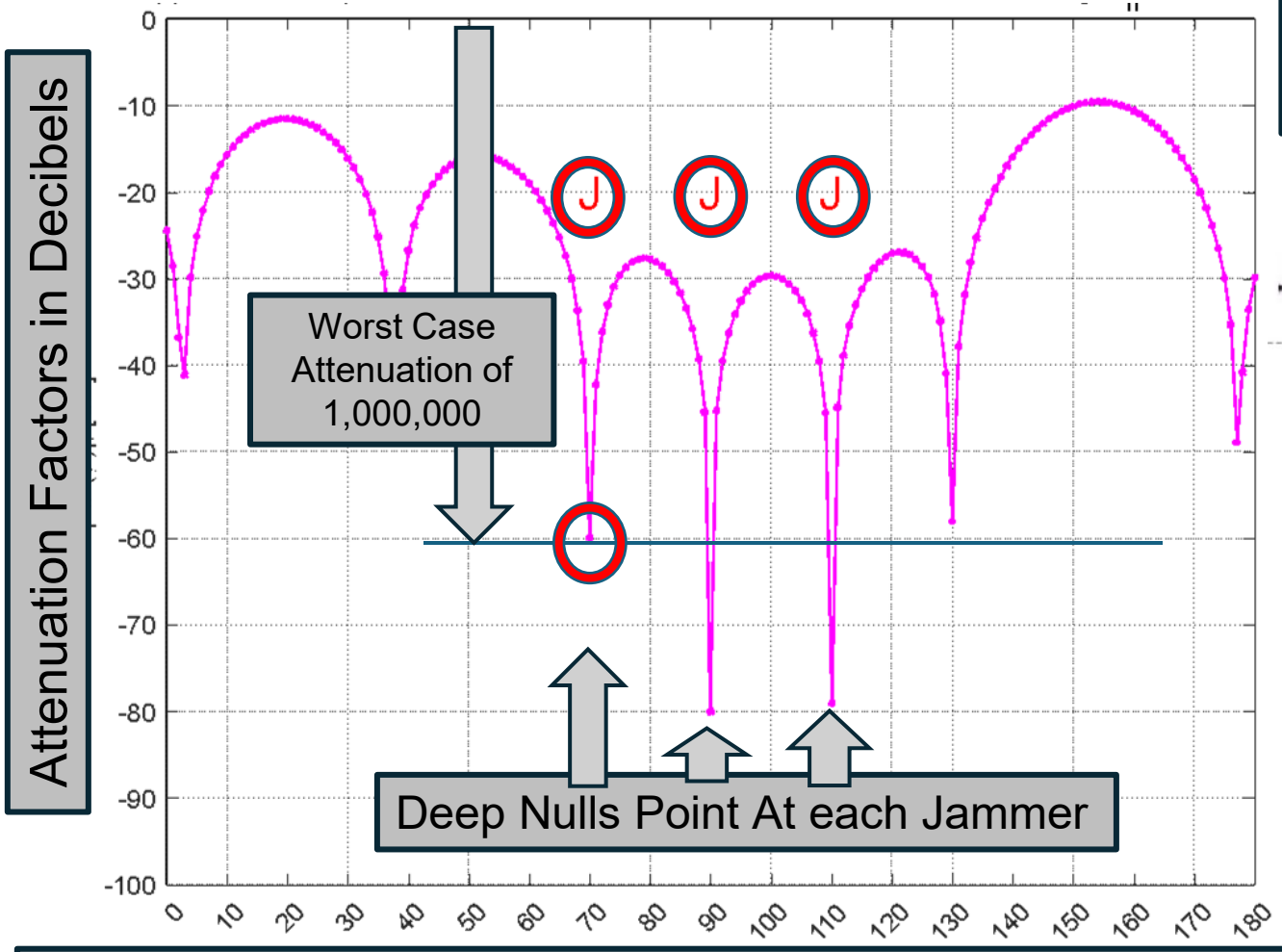
- White House Announcement – January 25, 1999 :

  "The third civil signal will be located at 1176.45 MHZ, within a portion of the spectrum that is allocated internationally for aeronautical radio navigation services and will be implemented beginning with a satellite scheduled for launch in 2005. "

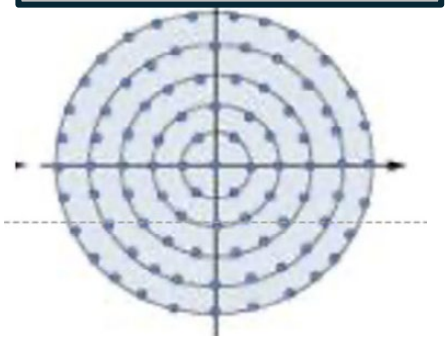
- **But message still set "Unhealthy" (April 2025)**

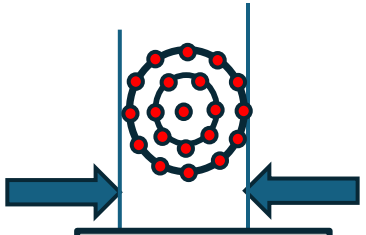
Additional J/S (Jammer Attenuation) Factor by Using 3 Ring version (19 Element) Phased Array

(Against three Jammers on horizon)



Possible Antenna Configurations (1 to 91 element)



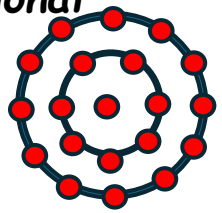


19 element – Diameter about 19 inches

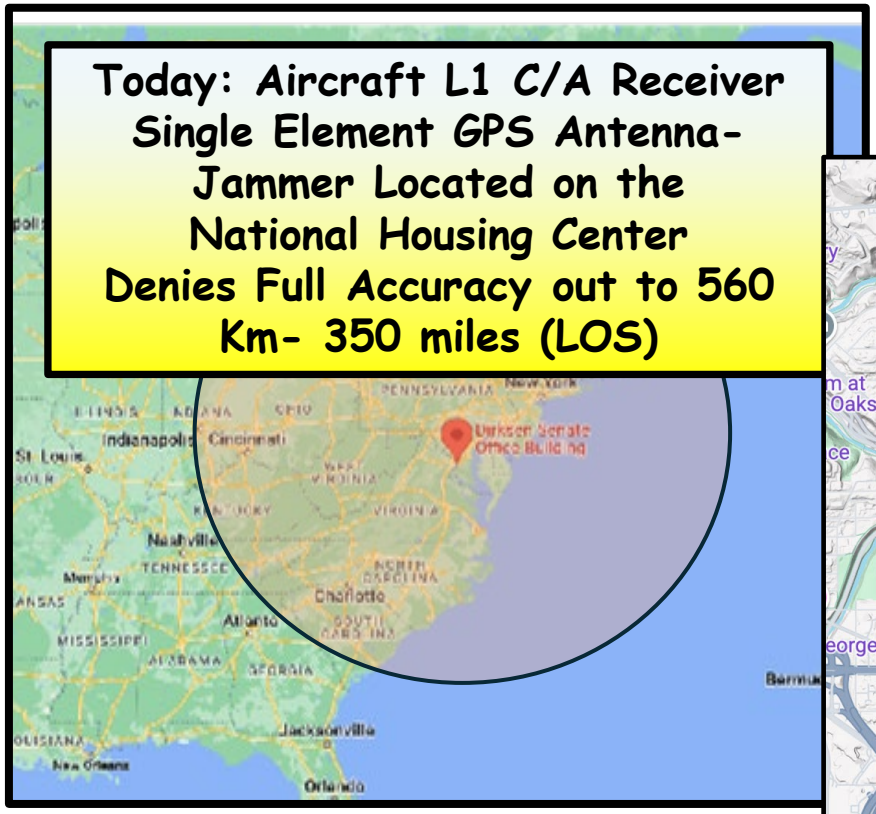
Using L5, Inertial aiding, and Digital Beam/Null-steering Antennas

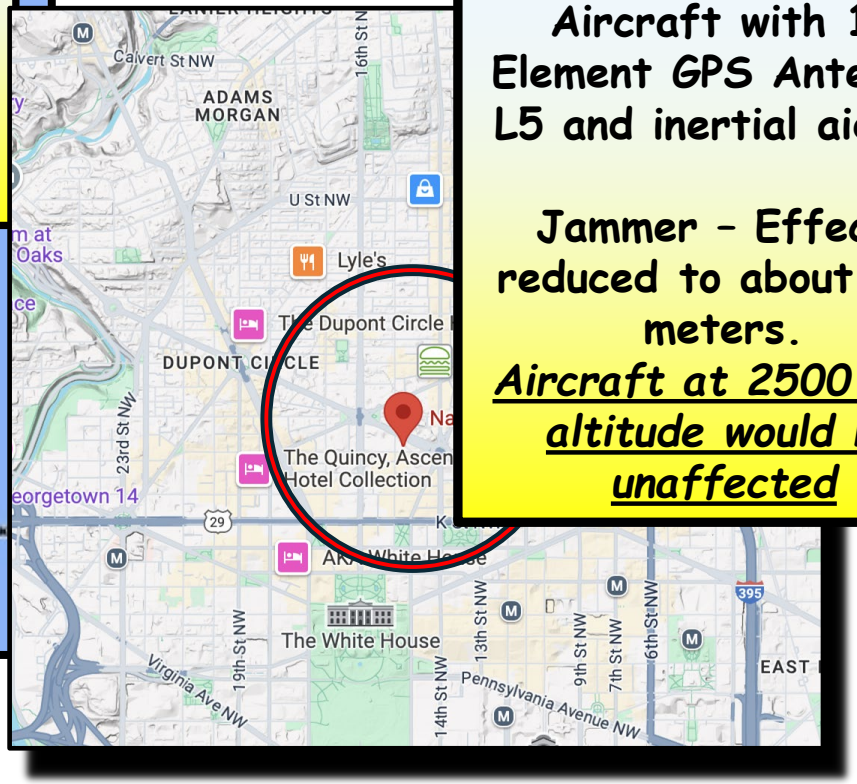
Denial Range of a 1 Kilowatt GPS Jammer – Located on top of National Housing Center

19 Element – 48 cm diameter - ~19"



Today: Aircraft L1 C/A Receiver Single Element GPS Antenna- Jammer Located on the National Housing Center Denies Full Accuracy out to 560 Km- 350 miles (LOS)





Aircraft with 19 Element GPS Antenna, L5 and inertial aiding.

Jammer – Effects reduced to about 600 meters.

Aircraft at 2500 foot altitude would be unaffected

Caution:

Are civil GPS receivers currently available in the US with these types of Antennas?: NOT YET

- *US ITAR* has forbidden more than 3 elements in US civil GPS antennas (*hopefully eliminated soon!*)
  - Although the technology at L band (radars) has been known and used for over 60 years
  - Inexpensive A/D devices are off-the shelf
  - A Turkish company (TUALCO) is selling a GNSS antenna with 16 elements

    *(and claimed at least **100,000 times** improved Jam resistance above GPS natural resistance of 2,500 J/S)*

Selected Recommendations to Toughen

- **Remove all restrictions on Phased Array Antennas for PNT**
- **Gain formal authorization to use all GNSS that have Satisfactory Integrity**
- Develop Industry (ICAO?/RTCA/RTCM) standards for improving Interference resistance
  - Deep Inertial integration
  - Directional antennas
  - Vector Receivers (All GNSSs)
- **Foster and help stimulate Manufacturers to develop and offer interference resistant GPS receivers, especially for safety-of-life applications such as commercial air, positive train control, and maritime."**
- Encourage users to move to tougher receivers

Assured Availability of PNT - "PTA"

Strategy #3 of PNTAB - Augment

- **Augment or substitute PNT sources (>TRL 6)**
  - **Use additional GPS Signals L5, L2C, L1C**
  - **Densify and Diversify with GNSS satellites –** Signals/constellations
    - **Independently verify integrity**
    - **Worldwide Integrity Monitoring**
  - **Use Complementary PNT Sources –**
    e.g. LEO-Comm, DME, eLoran, TV signals, Optical fiber
- Note: There are some intriguing new LEO Proposals that are not yet demonstrated as a system (TRL less than 7) such as Xona (cooperative) or Starlink (signal of opportunity)

Repeat Strong Caveat: All "Augmentations" should have careful estimates of **Integrity** – i.e. how often is the **signal untrustworthy?**

eLoran Characteristics

Characteristic		eLoran	
		Non-Differential	Differential
System Availability		Regional	Local only – e.g. Harbor Area
Accuracy	Horizontal	50m to >500m	10m to 20m
	Vertical	No Vertical (Use Baro?)	
Time to First Fix		1 to 2 Minutes (?)	
Vulnerability to Interference		Nearly Invulnerable	
Cost		$20 + Display& Ant	$20 + Display& Ant

- **Un-jammable**. (virtually)
- **Regional** – But not currently deployed in US
- **Horizontal Only**. No third dimension (Baro.?)
- **Accuracy over landmass subject to time delay variability**

  Speed of light – variations up to $\frac{1}{4}$ mile at longer range
- **Can Achieve 10/20 meter differential accuracy in small areas** (within about 5 miles of calibration point) must use continuous updates of Differential Corrections
- **Time transfer** Differential test data ~ 0.1 μsec (GNSS Reference)

Aside: Can eLORAN be configured to be one-way ranging?

LEOs – Altitudes of ~200 to- 1000 n.mi.

Promising PNT augmentation systems in various states of development

- Main categories: 1. ComSat with/wo dedicated Nav signal or
  2. dedicated Navigation Satellites
  - Major issues include funding the development and operations
- Tougher than GPS (without phased-array antenna):
  Up to 1000 times received GPS power
- Smaller single satellite coverage area requires more satellites
  (typically about 250 for 4 in view)
- Direct Ranging +
  - Doppler positioning can be used – gives 3D with 2 satellites but requires accurate user velocity. Also Doppler is less precise
- Iridium claims ~20 meters 2D and "indoor" reception
- **Needed: independent testing and assessment, including accuracy, integrity, and quantifying resistance to jamming.**

Augmentations to be Compared

(TRL 7 or Greater. Some promising Augmentations [e.g. Xona, Trustpoint] not yet at TRL-7)

- Additional GNSS Signals
  - GPS: L5, L2C, L1C
  - Other GNSS: Galileo, Beidou, GLONASS + Regionals)
  - GNSS with Regional Integrity/Correction Feature: WAAS (FAA), EGNOS (EU)
- LEO Satellites (Principally COMs, some proposed as dedicated)
  - With Tailored NAV signal (e.g. Iridium/Satellis)
  - Signal of Opportunity
- Inertials: Fly-wheeling with GNSS, Standalone
- eLORAN
- Cell Towers
- TV Stations

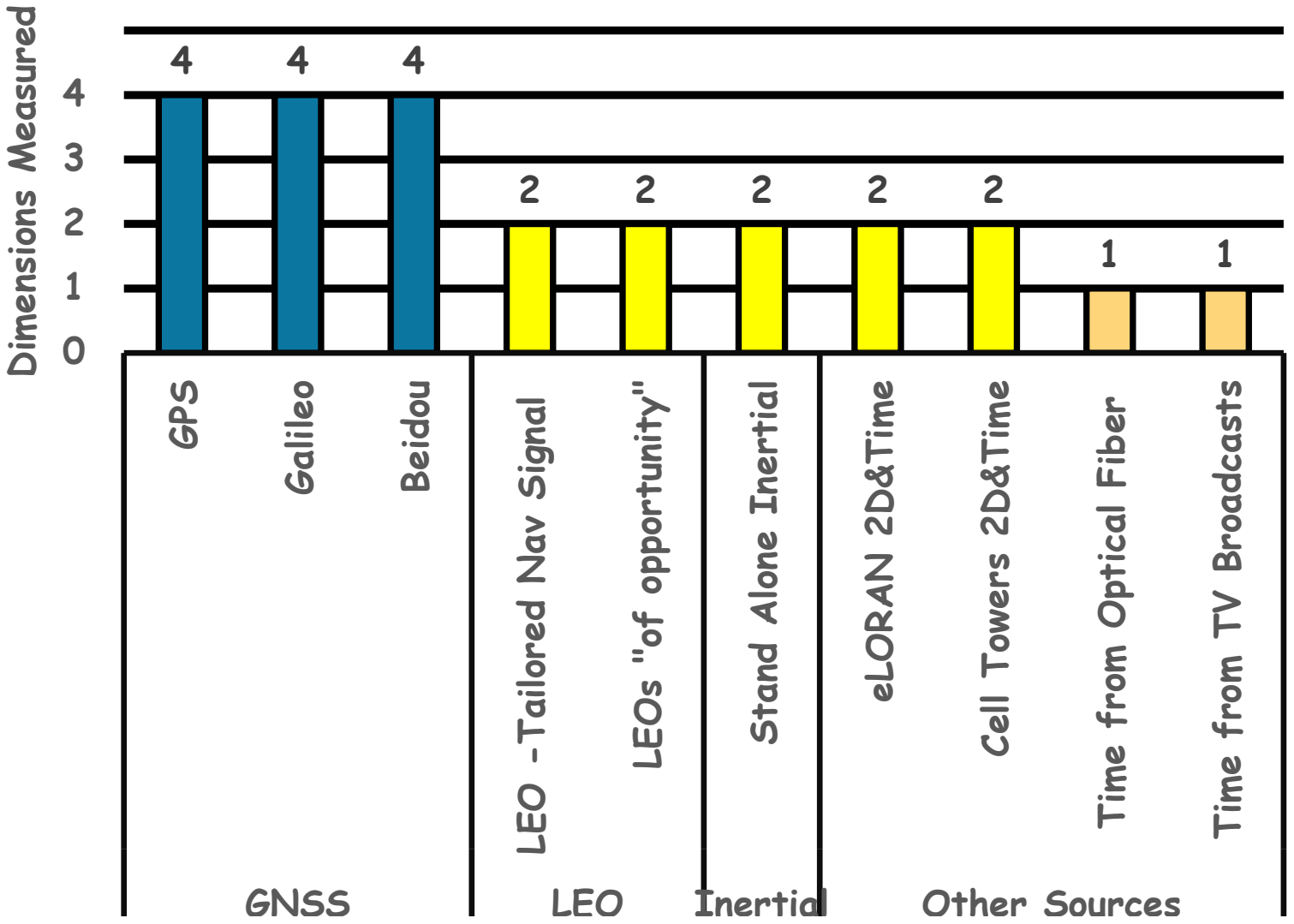
Using PNT Categories (ABCST) to Compare Augmentation Techniques: *Four Key Comparisons* –

1. Number of ***Dimensions*** Measured
2. ***Integrity*** – Samples for a single undetected hazardous fault (HMI)
3. ***Accuracy***
4. ***Robustness*** – 1 kW Jammer's expected range

Color Key:

Meets Cat A&B	Between Cat B&C	Meets Cat C	Does not meet Cat C	Cat T

Dimensions Measured by Demonstrated Systems



Preamble to Integrity Comparison:

Emphasizing – For many uses *(e.g. Aircraft and Safety of Life)*

Availability and Accuracy of the signals is insufficient

Integrity also must *be certified* for adoption

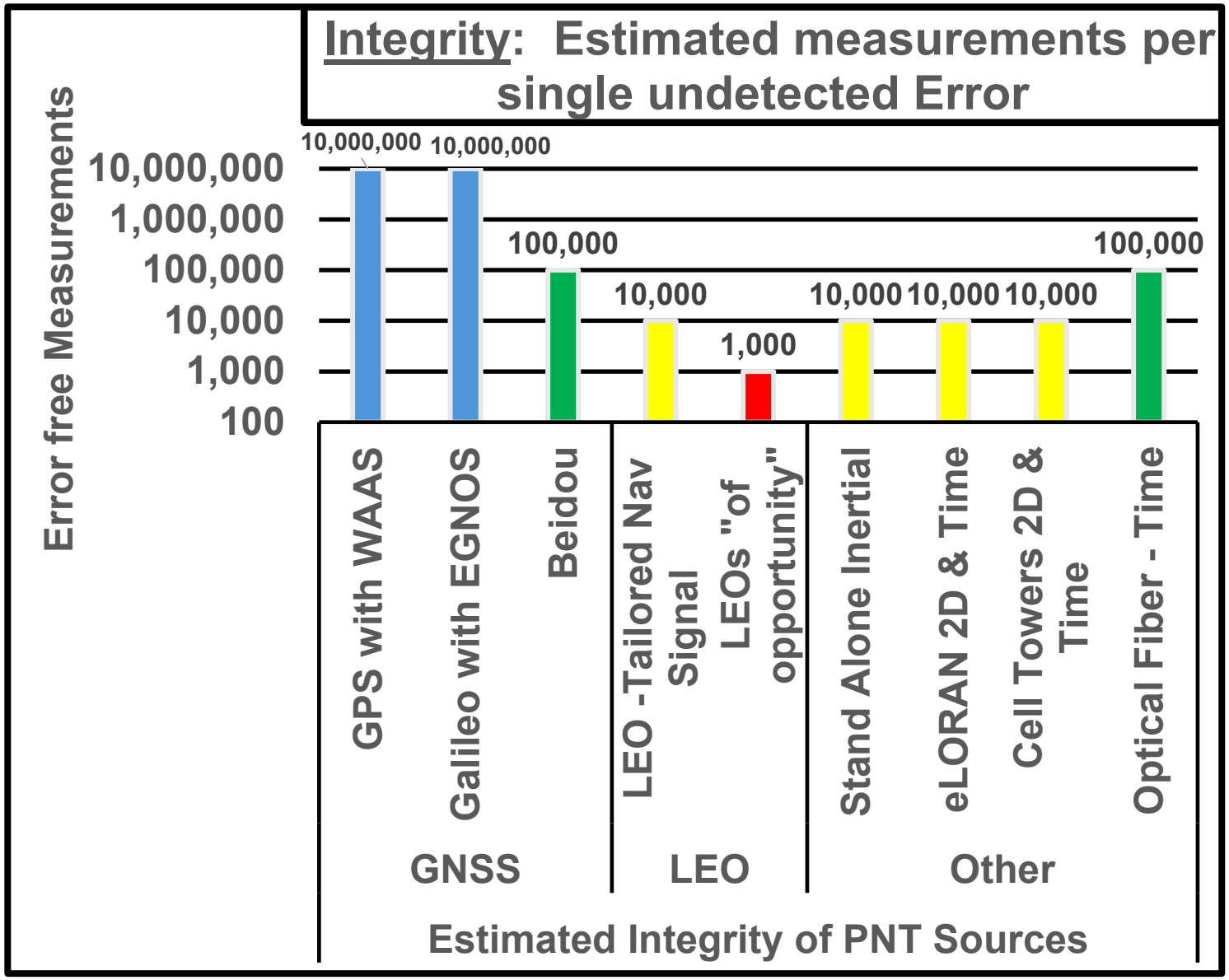
Integrity:

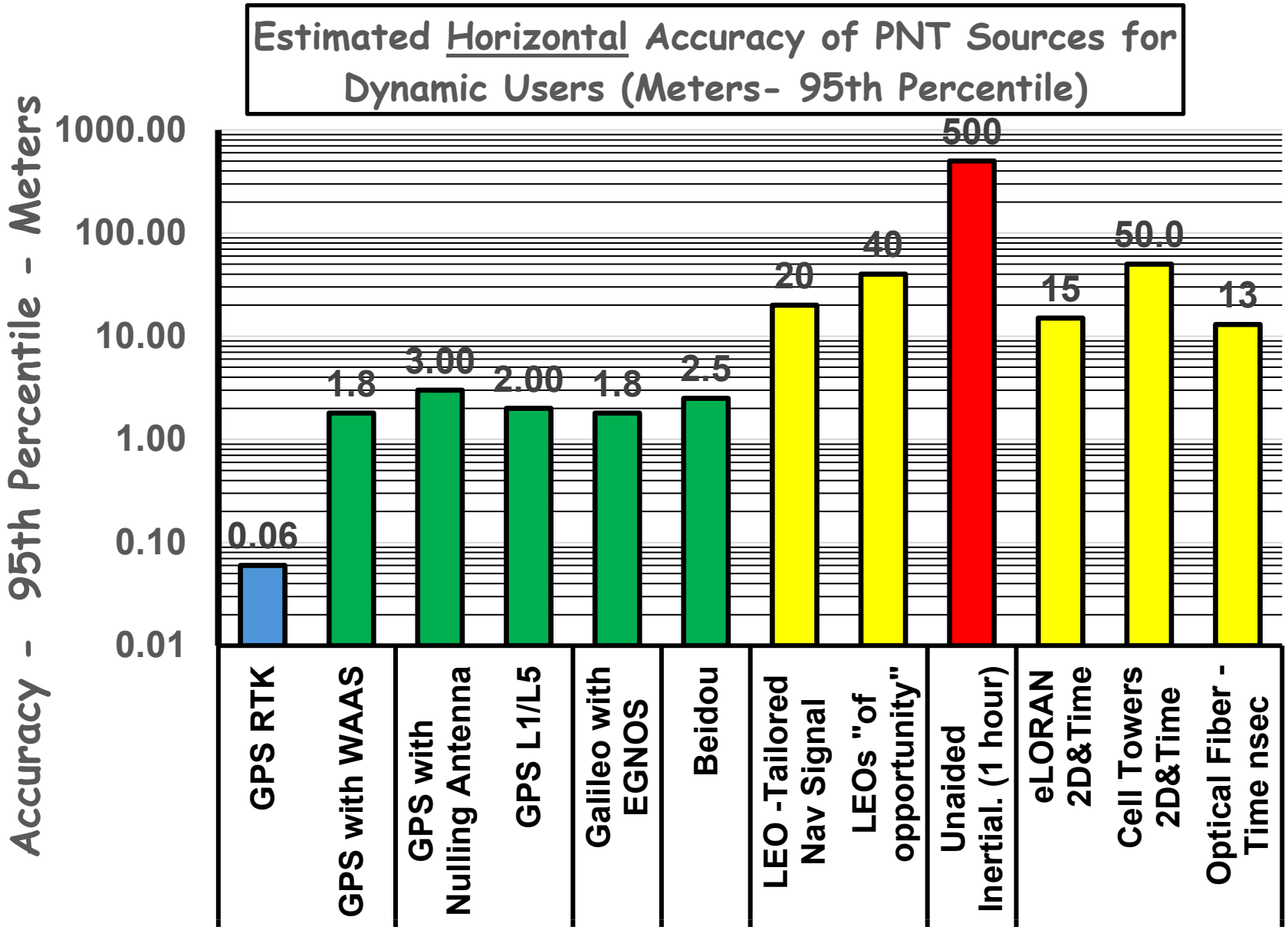
- **Probability that expected accuracy is not exceeded** –**Example – Cat III Aircraft Landing – better than 10^{-7}.**

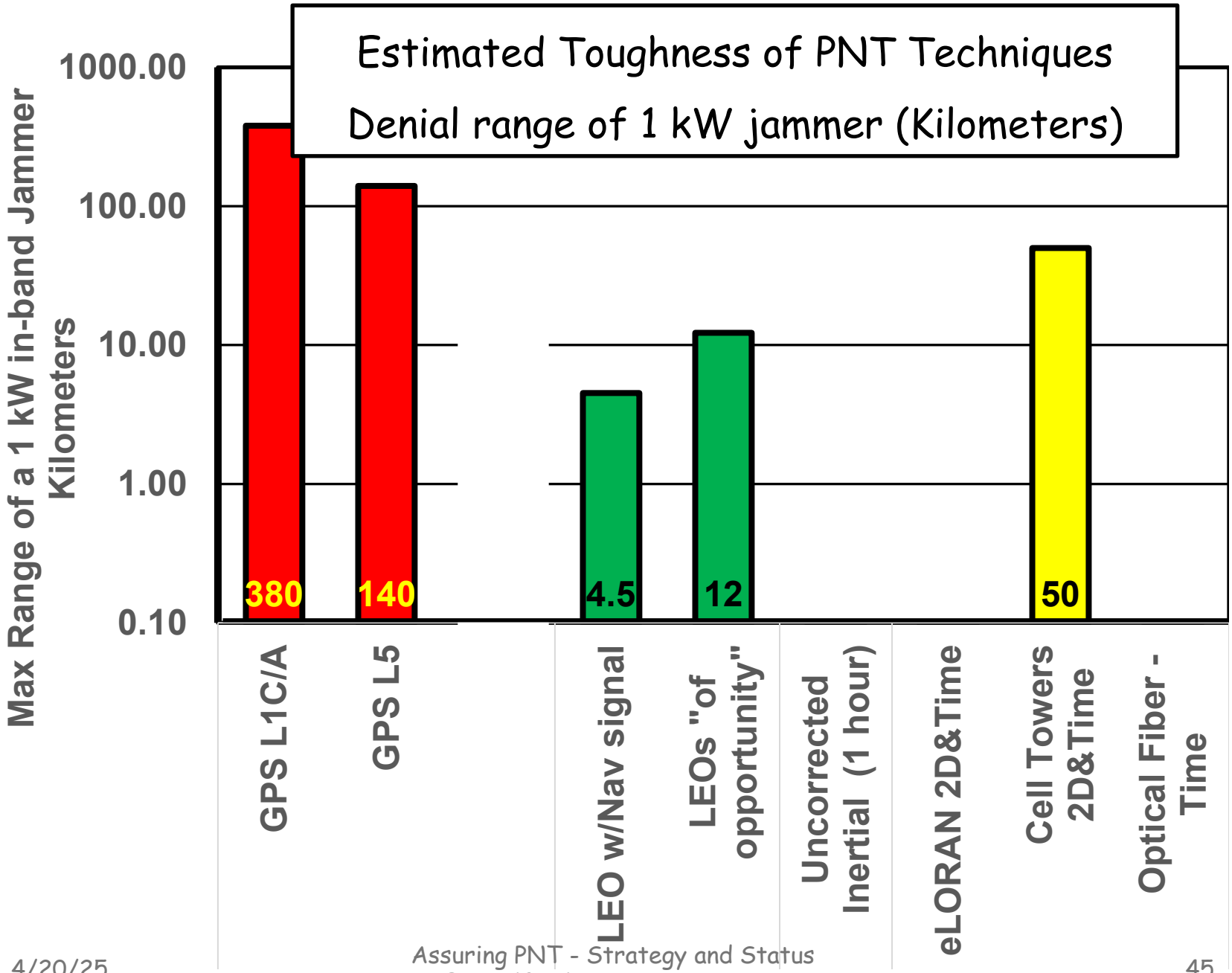
  [Hazardous or Misleading Information not more often than Once in 10 million cases]

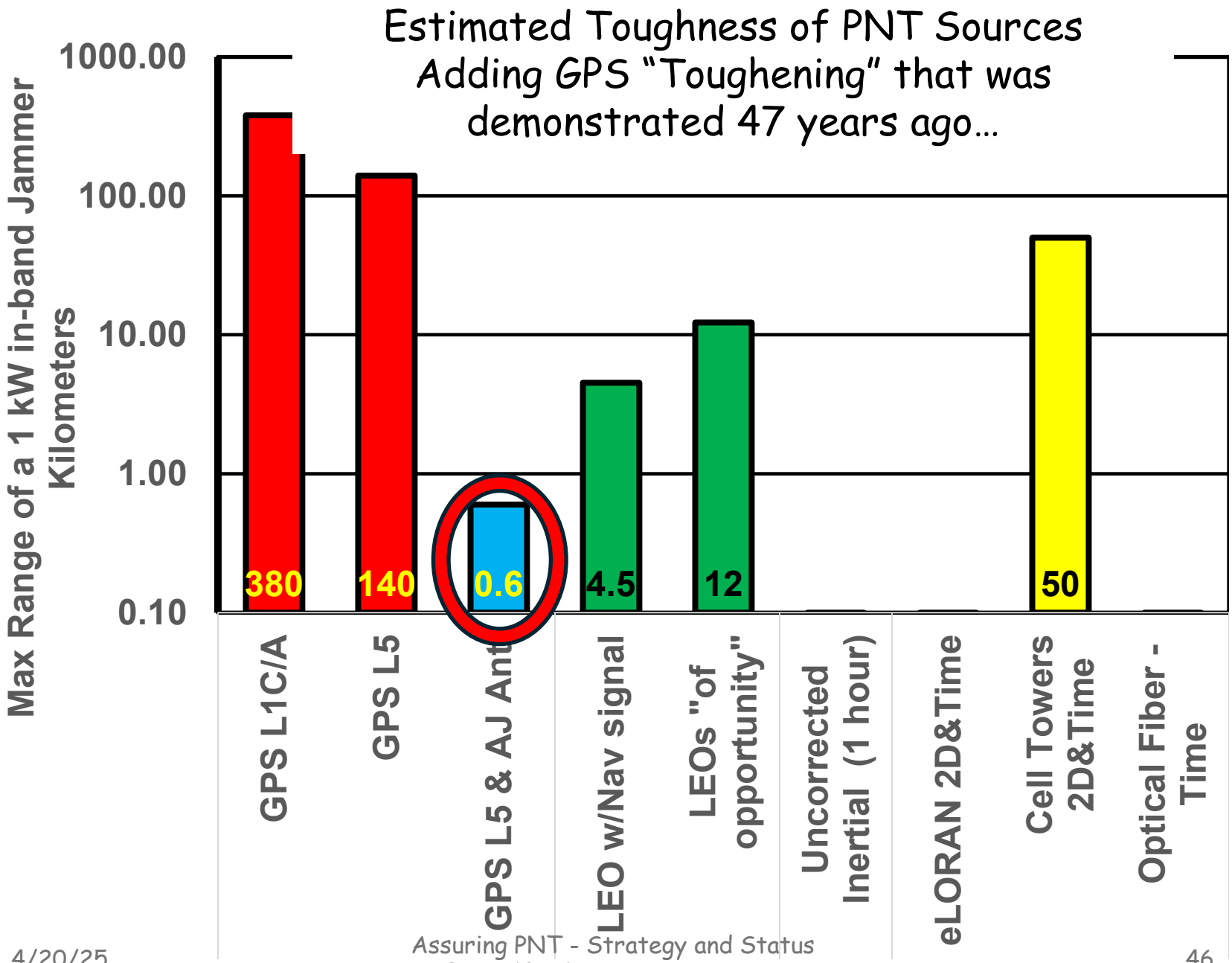
- **Can be estimated with help from WAAS and/or**
- **Using RAIM – Receiver Autonomous Integrity:**

– **"Continue to implement ARAIM & inertial for Integrity (+WAAS/EGNOS/MSAS + …)"** (PNTAB)









Summarizing GPS and Augmentations

		Capabilities of Alternative PNT Sources									
		GNSS				LEO		Other			
PNT CATE-GORIES	Discrim-inators	GPS + WAAS	GPS+ WAAS w/Phased antenna	Galileo + EGNOS	Beidou	LEO - Tailored Nav Signal	LEOs "of opportunity"	Stand Alone Inertial	eLORAN 2D & Time	Cell Towers 2D & Time	Optical Fiber - Time
A	3D, Dynamic, 6 cm	Local Base Stat	Local Base Stat	Local Base Stat	Local Base Stat			Not Contenders			
B	3D, Dynamic, 2.5 m										
C	3-D, Dynamic, 30 m					2D, 20m	2D (?) 30M	2D, 0.5 km/hr	2D, 15M Local		
S	3-D, Static, 0.1 mm			?	?						
T	Common View or UTC					100 to 200 nsec	Unknown				

KEY	Meets Req. including 1 kW Jammer	Meets Req., except resisting 1 kW Jammer	Initially Meets Req., but degrades w/time	Meets 2D req. in Local Region	Does not meet Category Req.	Not a Contender

		Capabilities of Alternative PNT Sources									
		GNSS				LEO		Other			
PNT CATE-GORIES	Discrim-inators	GPS + WAAS	GPS+ WAAS w/Phased antenna	Galileo + EGNOS	Beidou	LEO - Tailored Nav Signal	LEOs "of opportunity"	Stand Alone Inertial	eLORAN 2D & Time	Cell Towers 2D & Time	Optical Fiber - Time
A	3D, Dynamic, 6 cm	Local Base Stat	Local Base Stat	Local Base Stat	Local Base Stat			Not Contenders			
B	3D, Dynamic,										
C	3-D, Dynamic, 30					2D,	2D (?)	2D, 0.5	2D, 15M		
S	3-D, Static, 0.1 mm			?	?						
T	Common View or UTC					100 to 200 nsec	Unknown				
COMMENTS											

KEY	Meets Req. including 1 kW Jammer	Meets Req., except resisting 1 kW Jammer	Initially Meets Req., but degrades w/time	Meets 2D req. in Local Region	Does not meet Category Req.	Not a Contender

Capabilities of Alternative PNT Sources

PNT CATE-GORIES	Discrim-inators	GNSS: GPS + WAAS	GNSS: GPS+ WAAS w/Phased antenna	GNSS: Galileo + EGNOS	GNSS: Beidou	LEO: LEO - Tailored Nav Signal	LEO: LEOs "of opportunity"	Other: Stand Alone Inertial	Other: eLORAN 2D & Time	Other: Cell Towers 2D & Time	Other: Optical Fiber - Time
A	3D, Dynamic, 6 cm	Local Base Stat	Local Base Stat	Local Base Stat	Local Base Stat			Not Contenders			
B	3D, Dynamic, 2.5 m										
C	3-D, Dynamic, 30 m					2D, 20m	2D (?) 50M	2D, 0.5 NM/H	2D, 15M Local	?	
S	3-D, Static, 0.1 mm			?	?						
T	Common View or UTC					100 to 200 nsec	Unknown		UTC: 100 nsec		
COMMENTS											

KEY					
Meets Req. including 1 kW Jammer	Meets Req., except resisting 1 kW Jammer	Initially Meets Req., but degrades w/time	Meets 2D req. in Local Region	Does not meet Category Req.	Not a Contender

Summary 1: *Assured* PNT

- The degree of "Assurance" is driven by both the PNT technique and the user-class requirements.
- We have defined 5 broad PNT categories:
  ABCST
- Major discriminators are the old favorites: Accuracy, Availability/Coverage.
- Also critical for many are: Integrity and Robustness to Jamming

Summary 2: Assured PNT some emphasized points…

- **Integrity** of better than one undetected (HMI) fault in more than 1,000,000 is required for many safety of life PNT applications.
  (e.g. Train Control, autonomous cars, aircraft Landing, etc.)
- Only **GNSS-type space systems** have demonstrated Cat A&B PNT.
  - 24/7 worldwide dynamic accuracy to better than 5 cm (RTK) and Integrity: undetected Faults < 1 in 10,000,000 with WAAS)
- LEO Augmentations demonstrate reduced susceptibility to jamming and much better penetration of structures, ~ **jammer range about 3% of Raw GPS** they ~ meet PNT Category C, but usually in 2D. *Can meet many Category T requirements.*
  - Full 3-D LEO with accuracy probably requires 250 to 300 satellite constellation. Doppler would reduce the required constellation size, but with reduced accuracy.
- **Time Synchronization** is an important PN**T** application. GPS can be augmented with a variety of systems (eLORAN, LEO, TV, optical cable…), depending on requirements. Most trace back to UTC through GPS.
- **eLORAN** has 2-dimensional accuracy potentially 10 to 25m,in local Differential region and time transfer 1.0 to 0.1 microsec. (Probably Unjammable.)
- **Toughened GPS** with phased array antennas has demonstrated *reduced range susceptibility* to jammer of better than **0.2% of Raw GPS**
  (e.g. a 1 kW jammer range < 2500 feet)

Conclusions/Recommendations: PTA

- ***P**rotect*: Efforts to protect GNSS Spectrum should be a high priority effort of US Government
  - Need stronger central direction and resources
  - Proposed goal: pinpointing interference within 2 hours
- ***T**oughening*: With phased-array antennas, GPS resistance to jammer power can be increased by factors of 100,000 or more – decreasing jammer range by up to 99.7%. This largely exceeds the natural toughening of LEO supplements. The ITAR restriction on these antennas must be totally removed.
- ***A**ugment*: US should continue to pursue promising systems, while recognizing that ***none have demonstrated capability to meet PNT Categories A and B.*** In addition, time to achieve full augmentation likely exceeds 5 to 10 years. Many will require government sponsorship to close the business case.

Thank You

- Questions?