In harm's Way?

Toughening

A part of PTA Goal: Assured PNT

A discussion of Threats, Strengths, Synergies and Timing

- Views and comments are my own
- This audience is already familiar with much of this material – <u>but it does not appear in the national dialogue</u>
- A/J techniques and Data are from open literature
- Signal Powers (etc) are numbers for illustration and comp – i.e. May be +/- a few dB

Bradford Parkinson
Professor Emeritus (Recalled)
Stanford University

Attention Step:

Former High-Ranking DoD Official - A Visionary or ?

"I think that 20 years from now we won't be buying GPS satellites," he asserted. 'Twenty years from now everything you have that is manufactured for you, including your phone, will have, on the chip, a clock, a gyro and an accelerometer. ***It'll be set the moment it's manufactured and henceforth it will forever know what time it is, where it is, what its spatial orientation is. And it will never need a satellite."***

Headlines and Responses

- Press Headlines: ***GPS vulnerable!***
  - Jamming
  - Spoofing
  - FCC authorization Blunders
- USG response - Pursuit of ***Augmentations***:
  "We have to find a replacement/backup"
  - A reasonable activity - Studied for over 20 years (FAA-DME)

But, Current PNTAB Assessment:

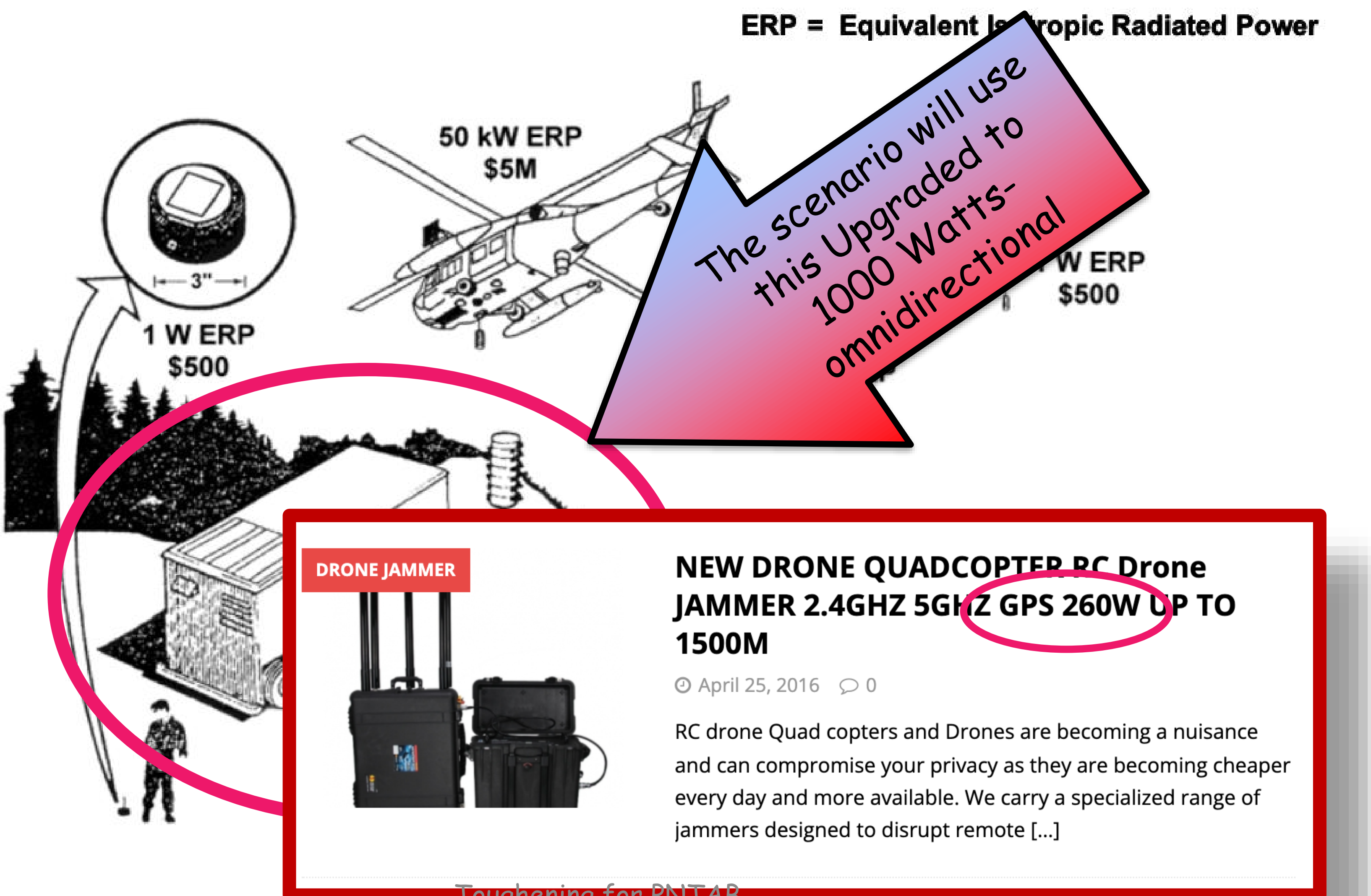
"No *current* or *foreseeable* alternative to GNSS (Primarily GPS) can deliver equivalent accuracy (to millimeters, 3D) and world wide 24/7 availability."

It is time to *increase* the emphasis on well established solutions to ensure GNSS-based PNT.

i.e., Toughen GPS

Background: Deliberate Jammer Alternatives

(Credit: Uncl. NATO Paper: Navigation Sensors and Systems in GNSS Degraded and Denied Environments)



Rockwell Collins GDM (1978)
One of the Phase One User Sets
(used over 10 kW of power)

Demonstrated over 100 dB of J/S!

- Apparent to me in 1973 that signal s to Jamming was an important issue
- We sponsored and encouraged AFAL Hi-A/J receiver with cooperation fr (JPO)
- Major Roger Brandt (AFAL) stepped up as Program director and selected Collins Radio to develop set.
- ***Field test Showed that a Hi-A/J GPS receiver could fly directly over a 10 KW jammer with no effect***
- Result was forgotten for at least 20 years…

Repeating my Point: Much of what I have to say has been known and verified for over 40 Years – I think we need to balance the search for "Replacements" with a vigorous pursuit of Toughening

Historical Review :

A single Decibel (dB) = Ratio of 1.26

- Logarithmic ratio scale
  - dB is 1/10th of a Bell (which is a multiple of 10)
  - So $10^{1/10} = 1.26$. and $1.26^{10} = 10$.
- Definition originated in measurement of transmission loss and power in telephony (early 20th century) in the Bell System
- Named in honor of Alexander Graham Bell, (but Bel is seldom used.) Instead, dB used in science and engineering:
  - prominently in acoustics, electronics, and control theory.
  - Electronics, the gains of amplifiers, attenuation of signals, and signal-to-noise ratios

I will use dB – Jamming to Signal Power - as the ***fundamental measure*** of receiver effectiveness assuming a nominal L1C signal Power of -157 dBW
But: I will use that J/S value to calculate the Jamming/Denial range of the selected (hypothesized) 1 Kw Ominidirectional Jammer

Capabilities of State-of-art GPS receivers with no Augmentations

Full Accuracy – State 5. Reduced Accuracy State 3

1.4 * 10^{-16} Watts

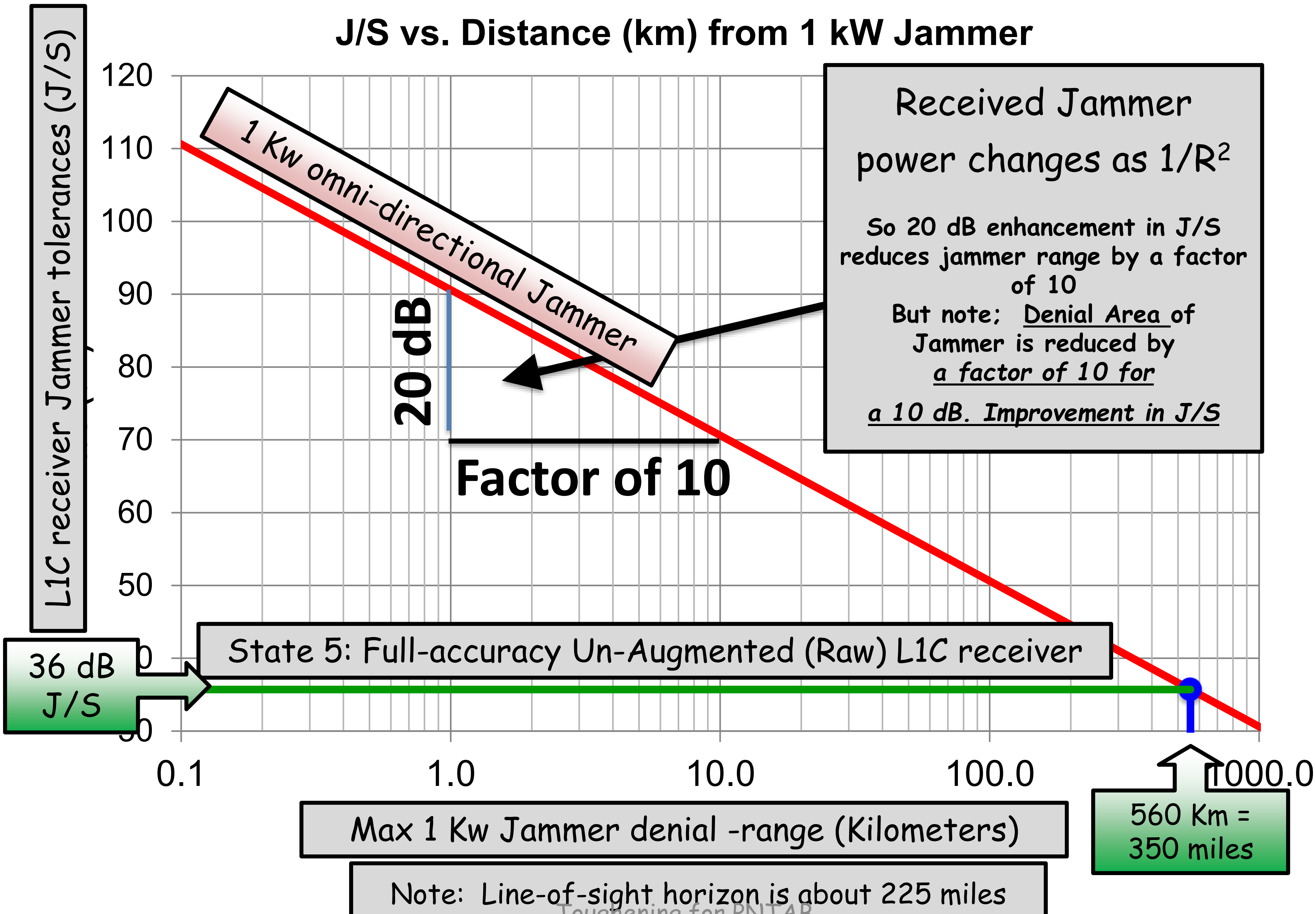
	in Received ower GPS III (dBW)	State 5 Data Tolerable J/S (dB)	State 3 Track Tolerable J/S (dB)
C/A	-158.5	34.0	44.7
L1C	**-157.0**	**35.7**	**52.7**
L2C	-158.5	39.2	47.7
L5	**-154.0**	**45.6**	**57.1**

State 5 = Code track, carrier track, data demodulation

State 3 = Code track only

Aside: Note that a Jammer's **denial area** for L5 Full accuracy tracking is 93% less than for L1 C/A Full tracking accuracy

Translation from J/S (dB) to Maximum Jammer-Denial Range

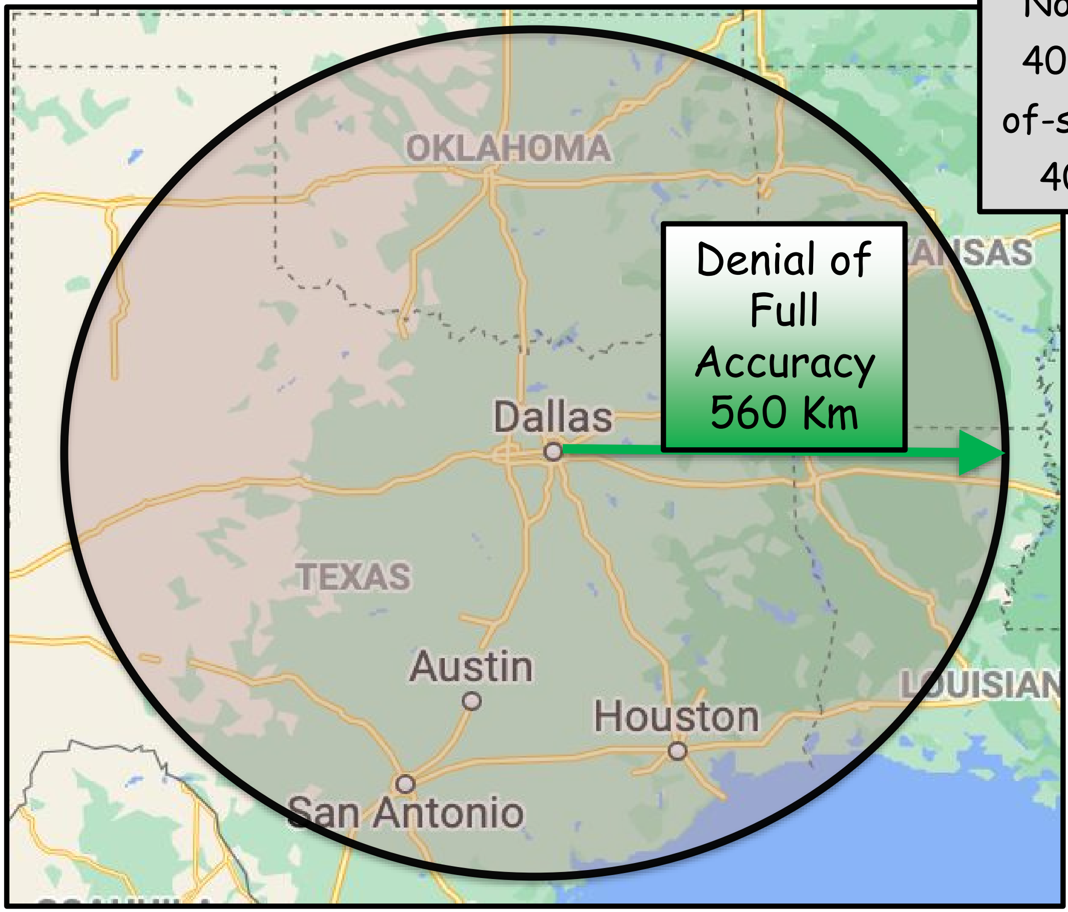


Denial Areas 1 Kw Jammer Located at Dallas Airport for unaugmented GPS L1C receiver

State 5 Full Accuracy

(Assuming Line-of sight)

Note: For Aircraft at 40,000 feet, the Line-of-sight horizon is about 400 km or 250 miles



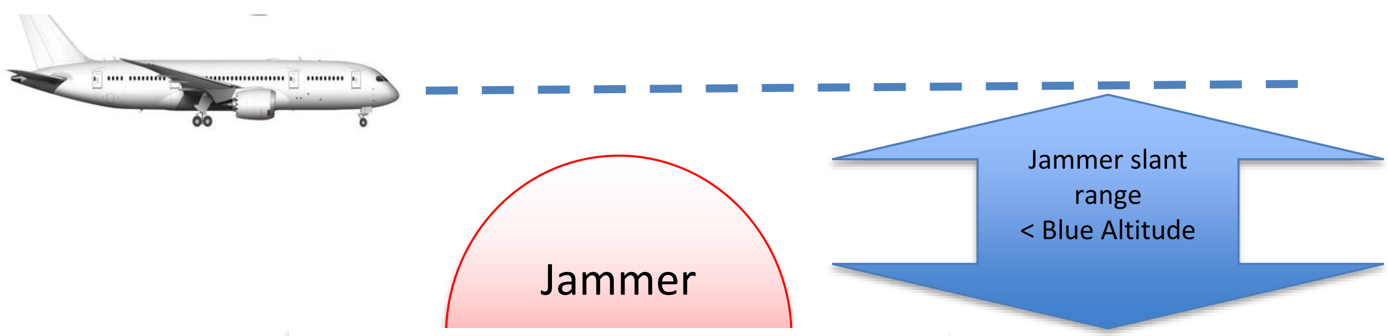
Scenario and Score Card

- Consider a Commercial Aircraft with full RTK accuracy (Code 5 tracking)
- Approaching and Landing at Dallas Fort Worth (DFW)

  (DFW has more than 15 GPS Approaches!)
- "Domesticated", 1 kW Jammer

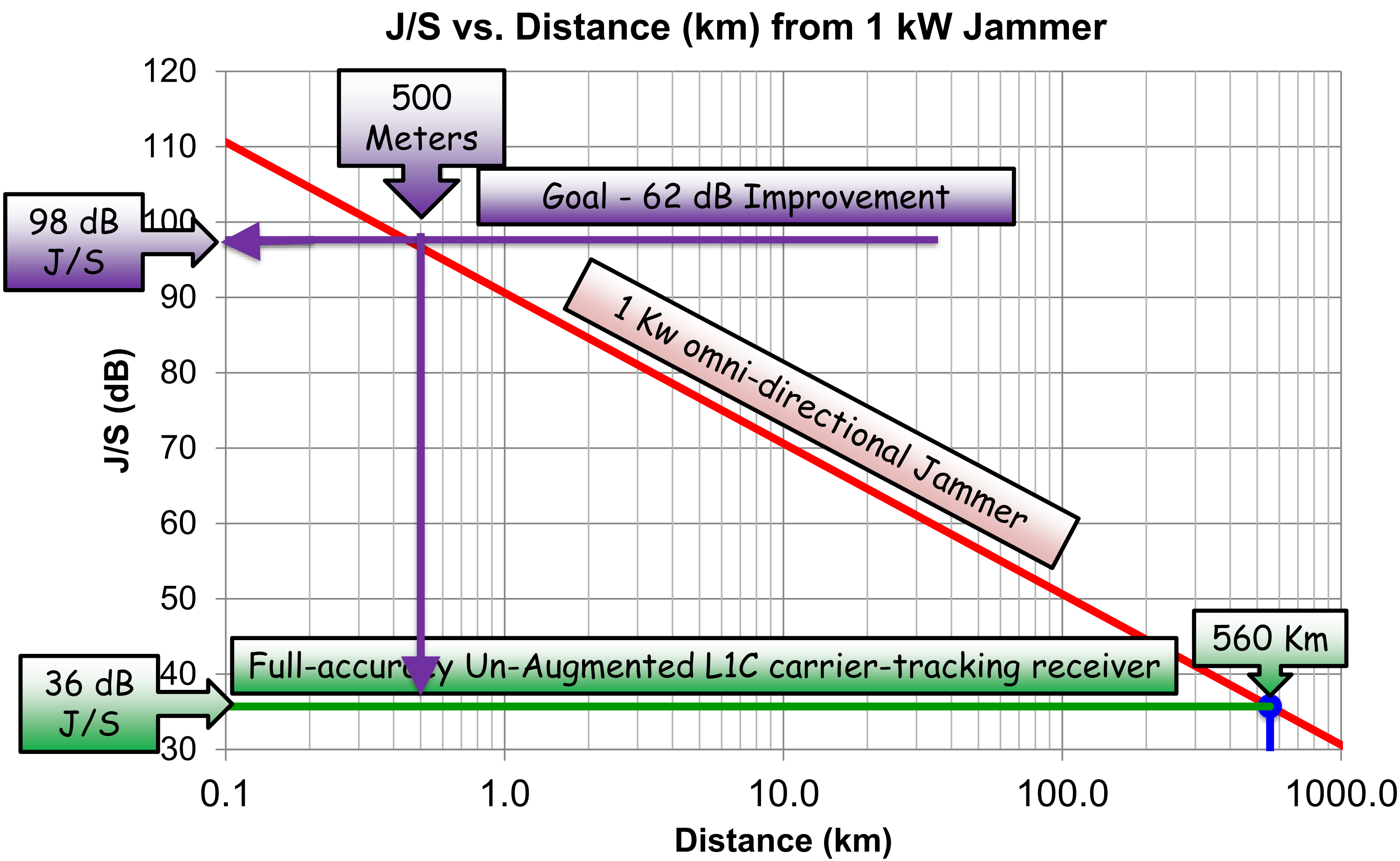
(Reciver Data from Aerospace Corp. (Tom Powell & Phil Dafesh) for <u>L1C signal and capability</u>)

- "Raw" L1C Receiver-
  - Full Accuracy (state 5) signal Track J/S = 36 dB,
  - State 3 Code Tracking Accuracy J/S = 53 dB
- Minimum Satellite Earth Coverage power (L1C) = -157 dBW*



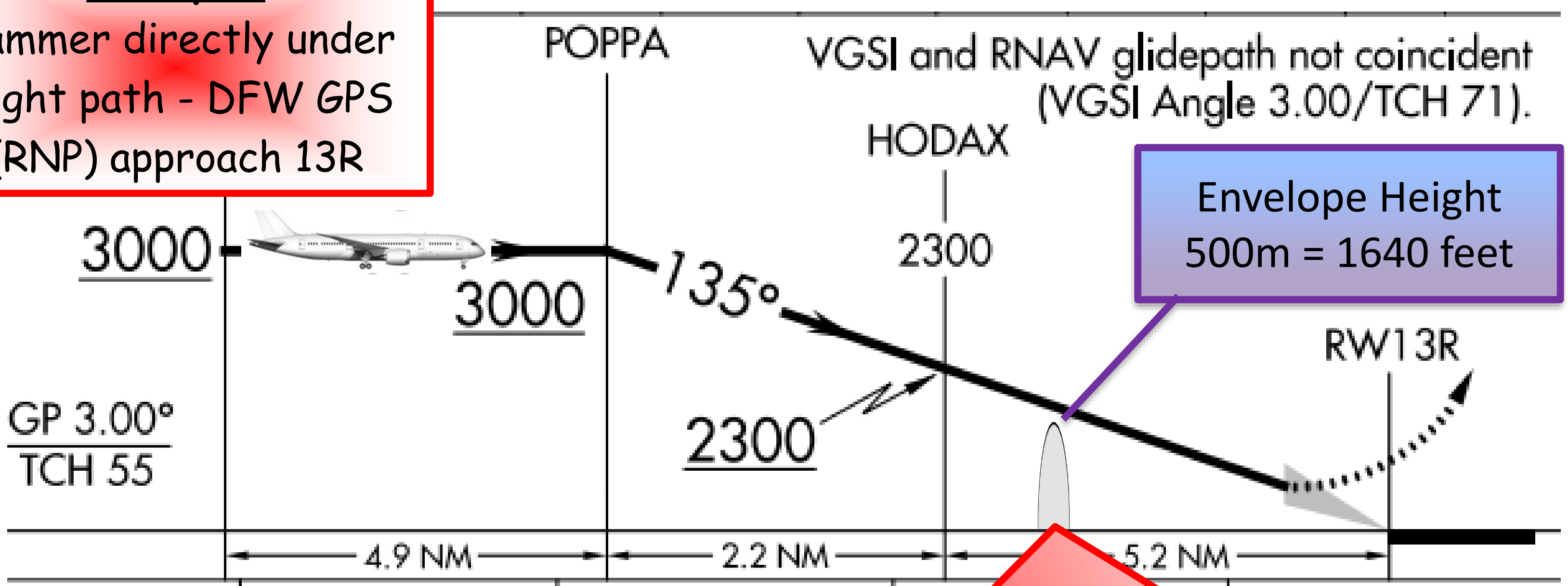
One of over 15 Certified GPS-based Approaches to DFW (RNAV (RNP) Z RWY 13R)

The Goal to limit Jammer-Denial range to 500 meters



Our Goal: Use Receiver enhancements to reduce effective envelope of 1 kW jammer against L1C receiver to less than 500 meters

Example:
Jammer directly under flight path - DFW GPS (RNP) approach 13R



Jammer envelope if L1C Receiver Total J/S = 98 dB. [required enhancement of 60 dB for Full accuracy (State 5) tracking or 45 dB for reduced accuracy (State 3).]

Achieving 62 dB of improvement in J/S
Well-known Techniques for "Toughening" an L1 C/A receiver

- **Category 1: Signal Processing**
  - Signal Modulation (L1 C/A or L1C)
  - Tracking mode (State 5 – ***full accuracy*** or State 3 ***reduced accuracy***)
  - With or without "Vector Processing"
- **Category 2: Inertial Meas. + Low-phase noise User Clocks**
  - MEMS – up to hi-grade IMU
  - Quartz to CSAC clocks '(Low Phase Noise) in user receivers
- **Category 3: Controlled Reception Pattern Antennas** (CRPAs)
  - Elements/Footprint – (4, 7, Many)
  - Beam/Null steering or combinations
- **Category 4: Satellite Enhancements**
  - Additional/Alternative Signals (Galileo, GLONASS (?), BeiDou (?))
  - Additional Frequencies (L5, L2, Galileo)

"Toughening" – nibbles and upgrades:

Category 1: Signal Processing

	Technique	Range of improvement			Estimated Time to Field
		Low	High	Example	
Receiver Techniques	L1C Code tracking (State 3)	10 dB	17 dB	17 dB	When L1C Operational
	Aircraft Shading	2 dB	4 dB	0 dB	Now
	Vector Receiver	4 dB	6dB	0 dB	Now to 5 yrs
	Totals – Signals and Processing	16 dB	27 dB	17 dB	Now to 5 years

Note: Modern receivers automatically revert to State 5 (Code Tracking) with the implication of reduced accuracy. I have made that step a part of "nibbles"

Takeaway

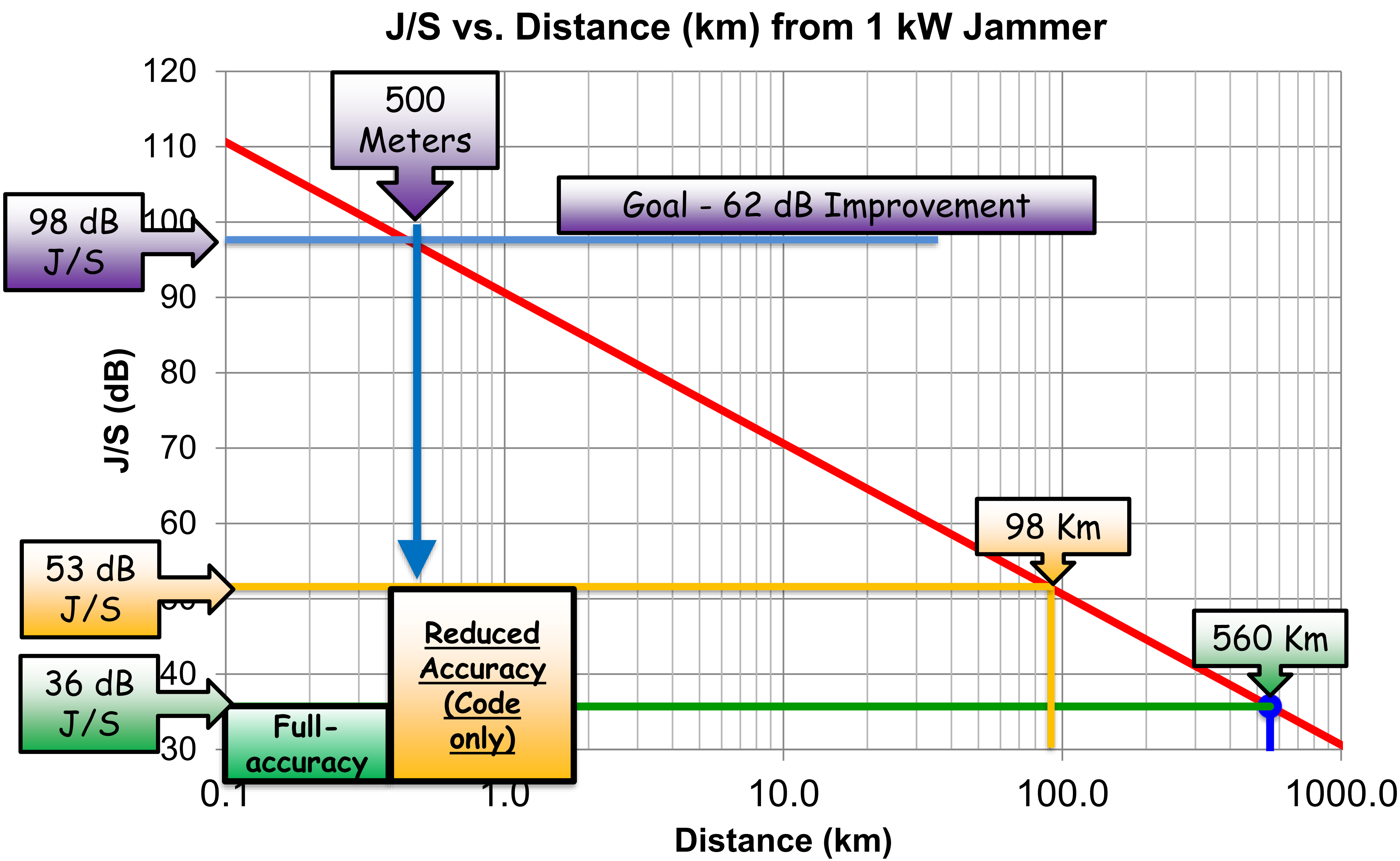
These nibbles could produce a useful 10 to 27 dB of improvements against Goal of 62 dB improvement

Example will assume this "nibble" Category is 17 dB

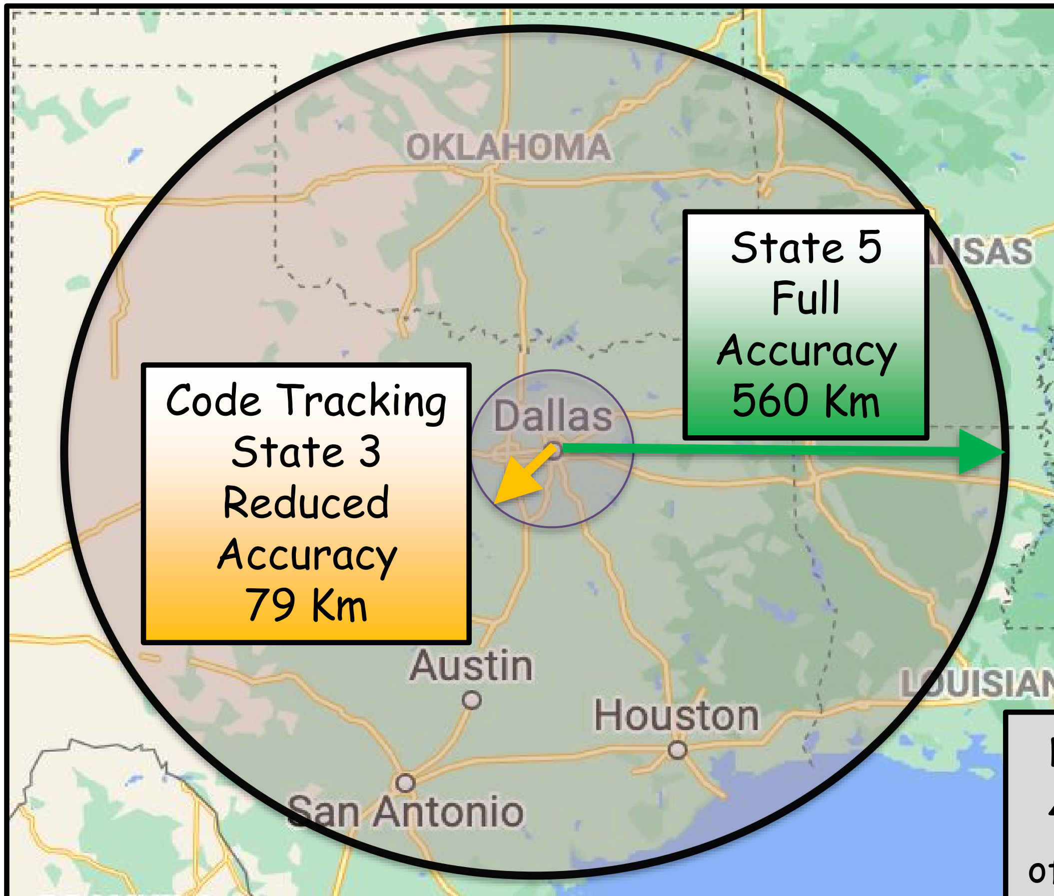
This will be categorized as "Reduced Accuracy" or Code Tracking

Save the Aircraft shading and vector receiver for "Margin" against our goal

Using Code Tracking to reduce Max Jammer Denial Range



1 Kw Jammer at Dallas Airport
denial areas for GPS L1C receiver
Effect of switching to Code Tracking (State 3)
(Assuming Line-of sight)



Note: For Aircraft at 40,000 feet, the Line-of-sight horizon is about 400 km or 250 miles

<u>**Category 2**</u> *Nibbles: <u>Inertial</u> Synergies –*

Well-Known Benefits

- Supports Longer Averaging Time for GPS/RF signal
  Best with "Tight-Coupling"
- Provides "Fly-wheeling" through outages
  - GPS to <u>**calibrate**</u> inertial components during valid reception periods
- Enable powerful <u>*spoofing detection*</u> and mitigation techniques – e.g.:
  - Velocity Verification
  - Enhances dual antenna heading verification
- If equipped with directional (beam) antenna: Provides accurate orientation measurements to enable precise beam steering during vehicle maneuvers

"Toughening" - nibbles and upgrades - Category 2 Inertial Synergies

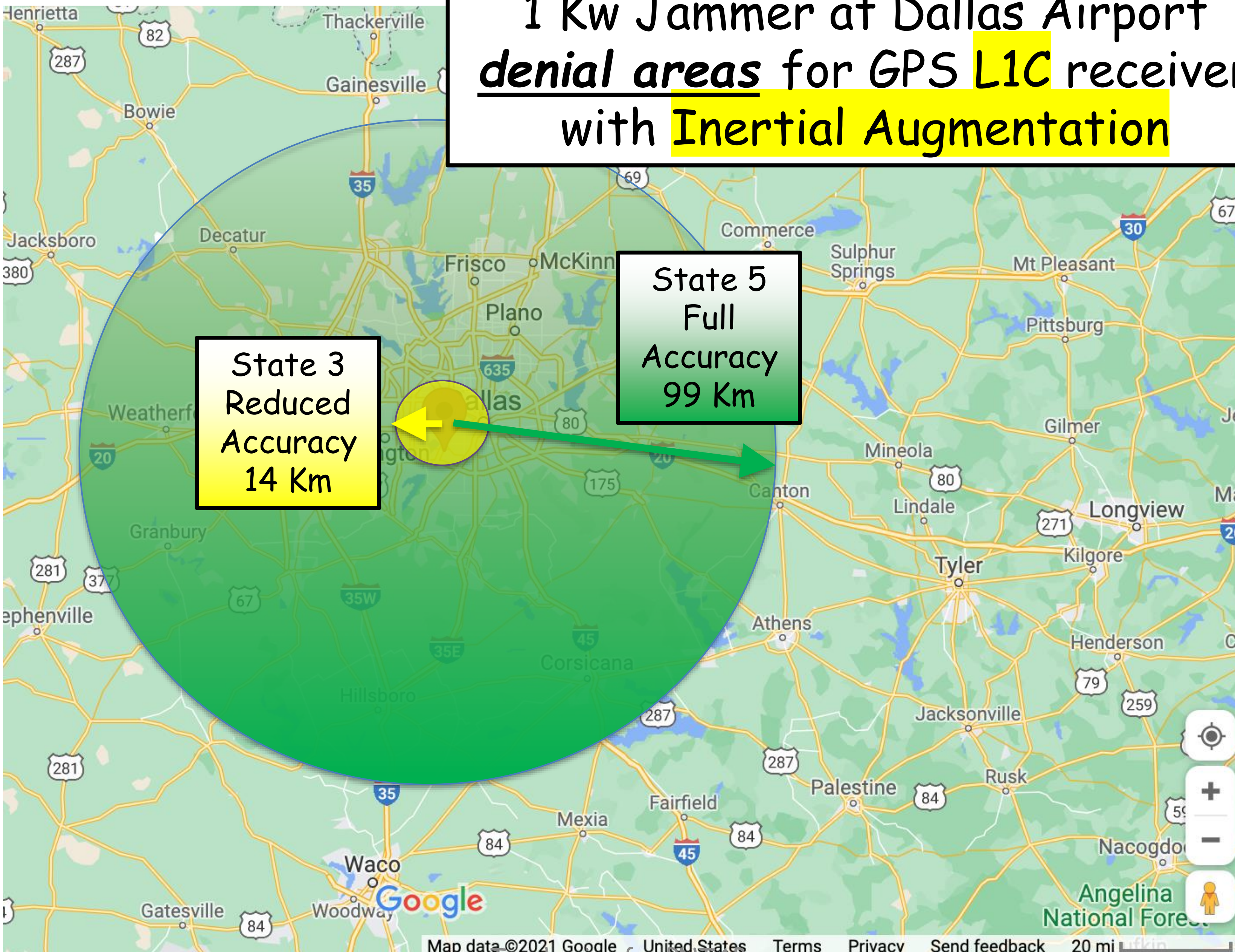
	Technique	Range of improvement			Estimated Time to Field
		Low	High	Example	
Receiver Enhancement	Inertial & Averag. (MEMS, CSAC)	8 dB	20 dB	15 dB	Now

Takeaway

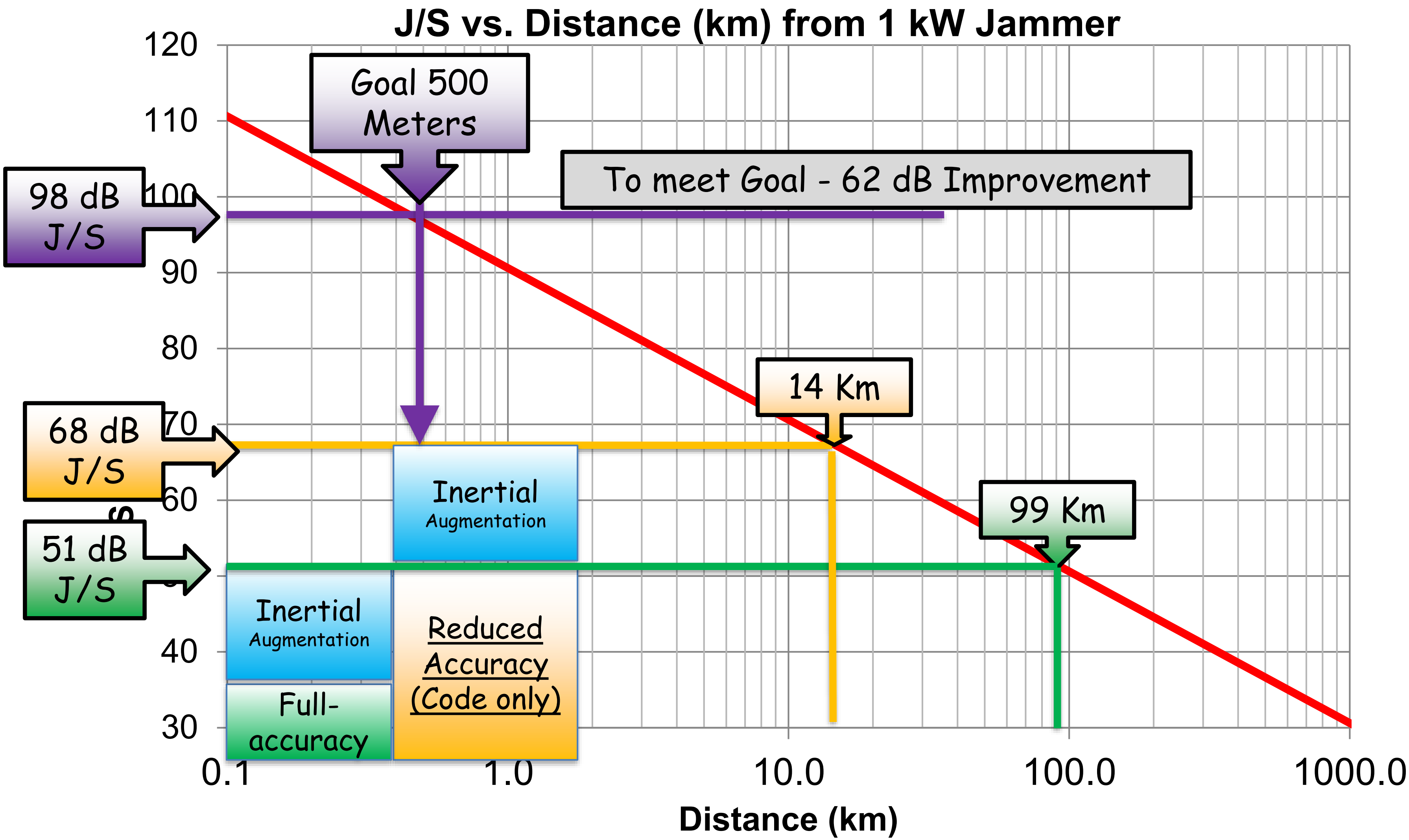
An unclassified Draper Paper, written for NATO, suggests Inertial synergies could improve J/S as much as 20 dB.

Will use 15 dB in our example

1 Kw Jammer at Dallas Airport ***denial areas*** for GPS L1C receiver with Inertial Augmentation



Adding Inertial Augmentation J/S (dB) to reduce Max Jammer Range



Further Observations regarding Inertial Measurement Systems

I advocate inertials but - *Inertial fly-wheeling is limited in accuracy*:

- **Inertials are** <u>inherently vertically-unstable</u>
- **Accelerometers** <u>do not measure acceleration</u>
- **"Down" does not exactly* point to center of the Earth – and locally deviates from models**
- **"g" is <u>not just gravity</u>**

<u>So: Errors grow in Proportion to Time or Time^2</u>

Elaboration -

The simple view of Inertial Navigation

- Double integrate *vector acceleration* and you have *vector position* (i.e. 3D)

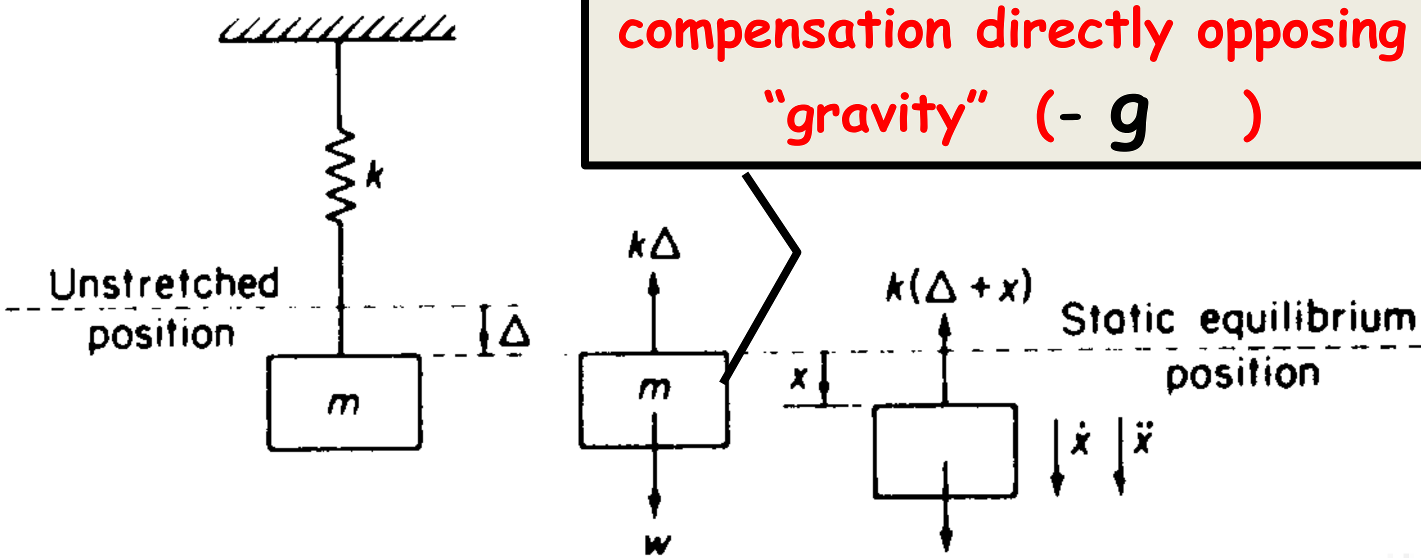
$$\vec{\boldsymbol{P}} = \int\int \vec{\boldsymbol{a}}\ d^2t$$

- So with a perfect "accelerometer" you end up with perfect position??…

Absolutely not –

"Perfect" accelerometers: What does an "Accelerometer" actually measure?

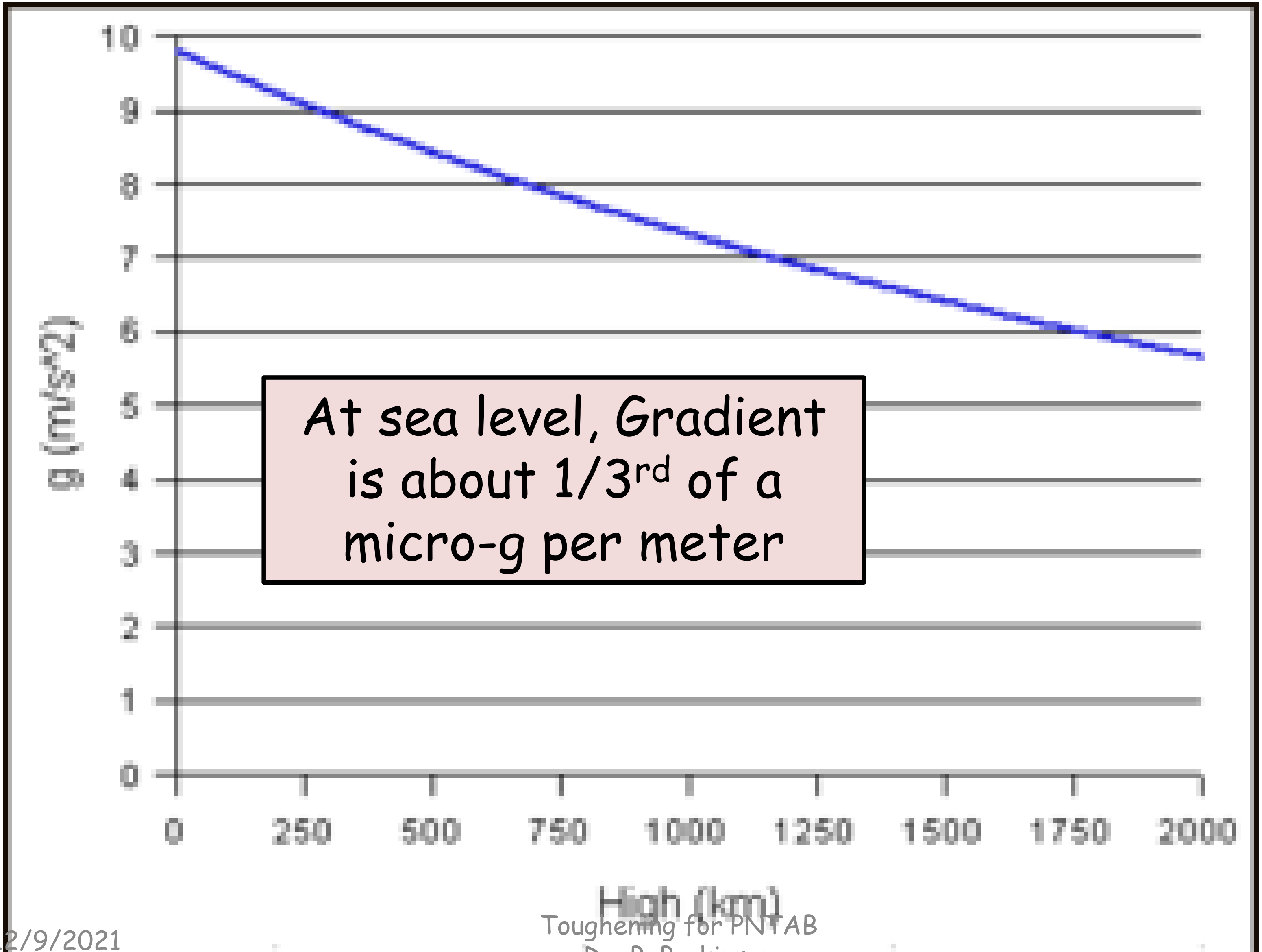
Clearly an ***un-accelerated*** "accelerometer" senses the lift to overcome gravity **An upward compensation directly opposing "gravity" (- g)**



$$\vec{f} = \vec{a} - \vec{g}$$

$$\vec{a} = \vec{f} + \vec{g}$$

Gravity changes with altitude above the earth

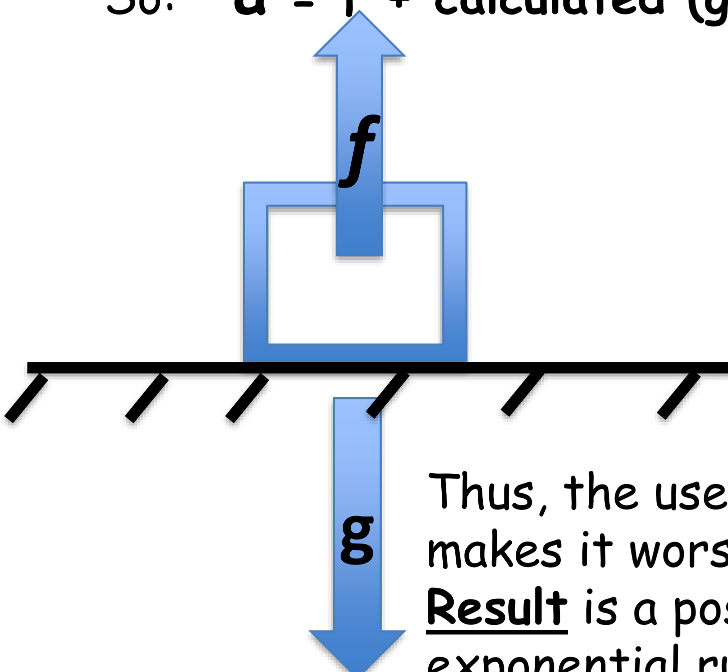


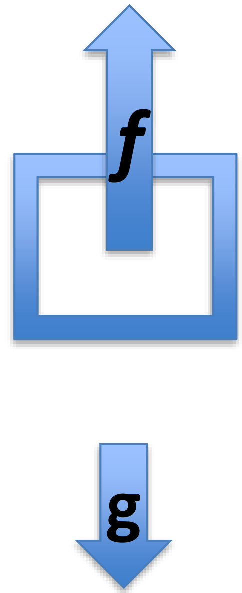
The vertical dimension is ***inherently*** exponentially unstable

True location -

$$f = -g$$

So: **a = f + calculated (g) = 0**





Assumed location -

If true would be

$$f = 0.9 * g$$

But user uses the measured **f = 1.0 *g and adds his calculated gravity of - 0.9 *g* and concludes:**

a = f + calculated (g) = 0.1*g

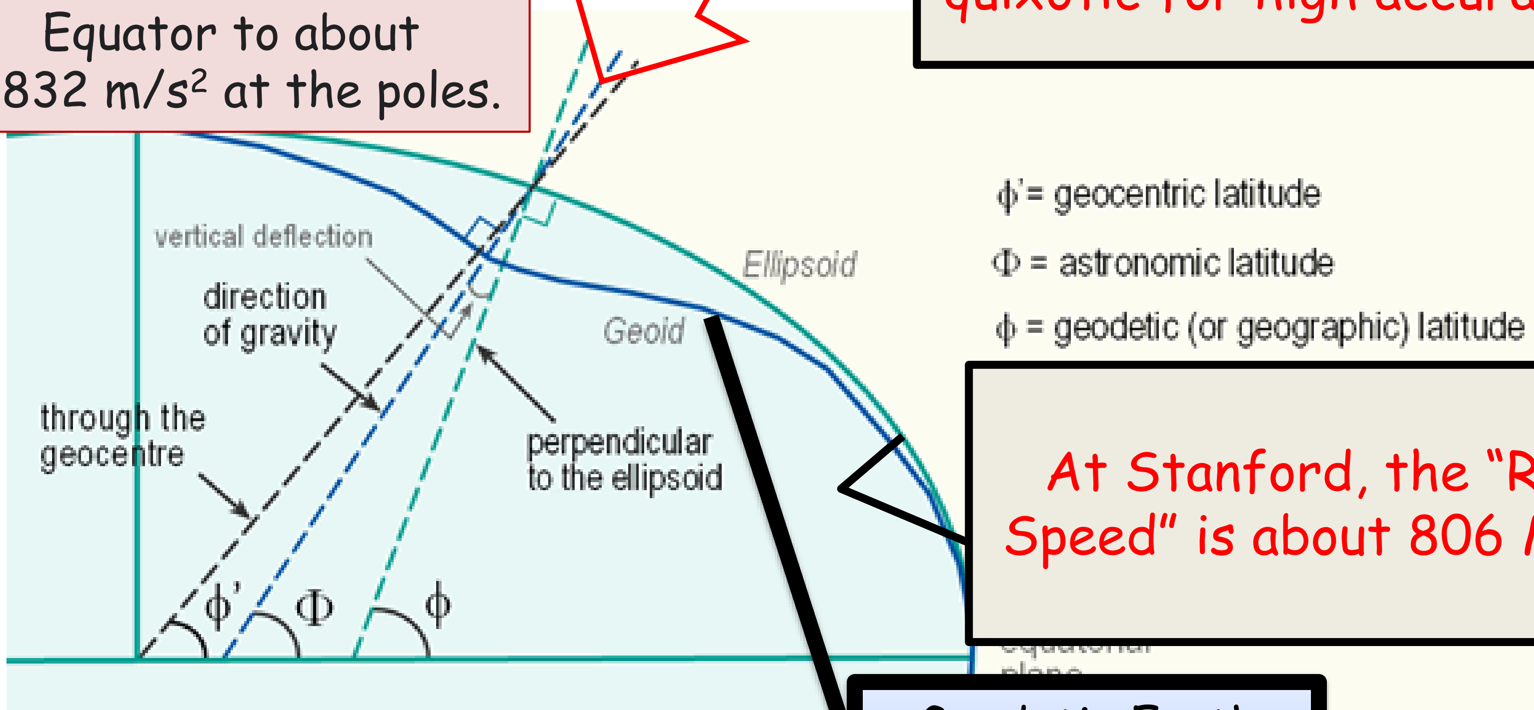
Thus, the user has a positive position error (up) and then makes it worse by using gravity for the assumed position. **Result** is a positive acceleration error which leads to an exponential runaway.

In the short term, a baro-altimeter can help, but in the long term, without an accurate altimeter – it is unstable

The gravity vector – "Down" is only Local

The force of gravity varies with latitude and increases from about 9.780 m/s² at the Equator to about 9.832 m/s² at the poles.

The gravity vector, near the surface, is quite quixotic for high accuracy



At Stanford, the "Rim Speed" is about 806 MPH

Geodetic Earth Surface

The user has to know the Initial Position and Velocity

- So we have:

$$\vec{P} = \int\int \vec{a}\ d^2t + \overrightarrow{V_0}\,t + \vec{P}_0$$

Current position is known no better than Initial position and the error increases with time if initial velocity is not perfectly known---

Where does an Inertial Measurement Unit find initial position?

(Hint: Frequently GPS!)

Another complication for inertial components

- To Navigate system must be accurately oriented to a known reference frame
- This converts the physical vectors to measurements that orient to E, N, and Up (or equivalent
- $$\begin{bmatrix} P_E \\ P_N \\ P_U \end{bmatrix} = \underline{\boldsymbol{P}} = \int\int \left(\underline{\boldsymbol{f}} + \underline{\boldsymbol{g}}\right) d^2t + \underline{\boldsymbol{V}_0}\,\boldsymbol{t} + \underline{\boldsymbol{P}_0}$$
- Note vector arrows have been replaced with underlines (indicating a coordinate system)

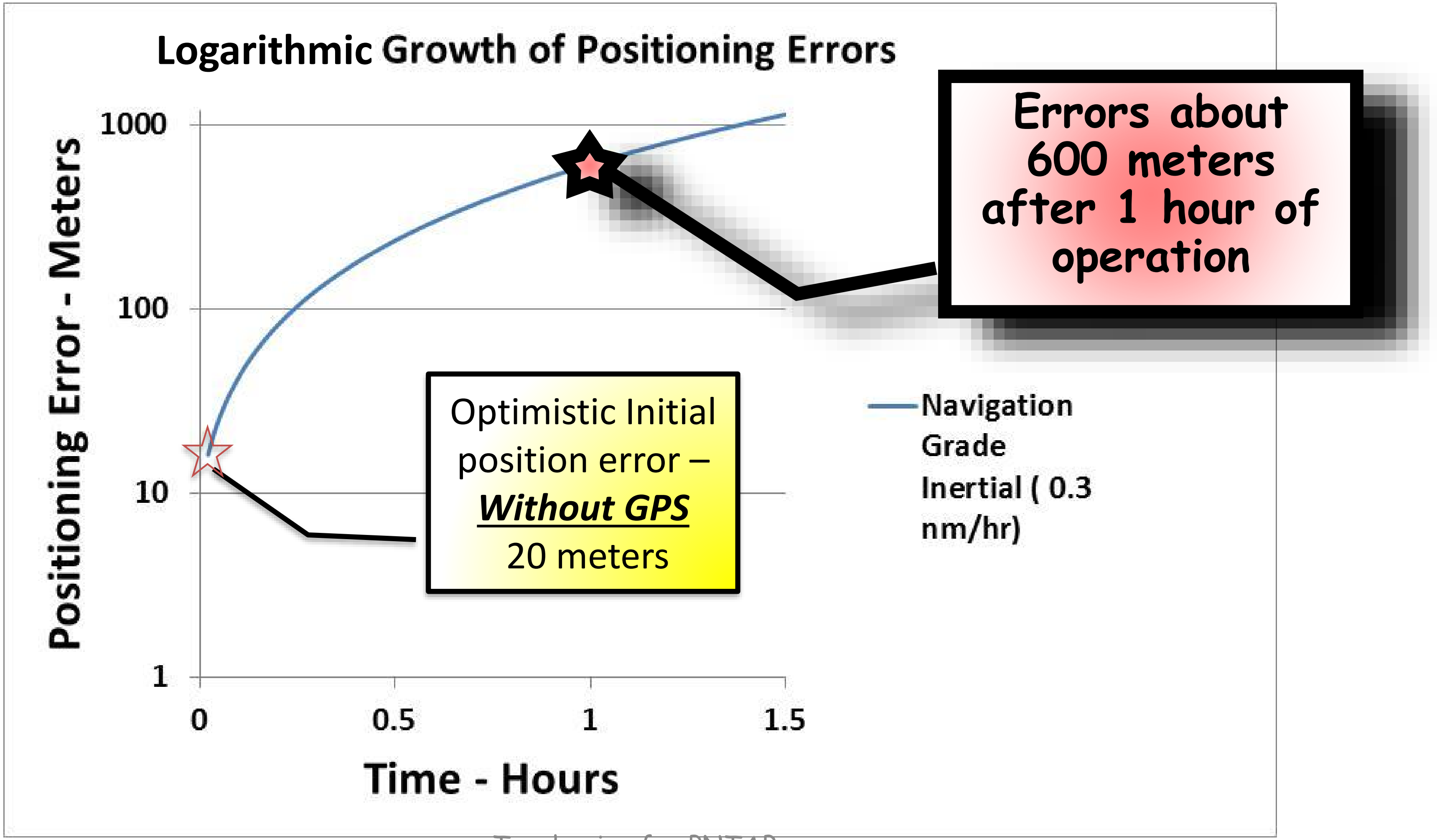
Wrap-up: Even Perfect "Accelerometers" can only be perfect *non-field force* sensors: They sense $\vec{f} = \vec{a} - \vec{g}$ not $\vec{a}$

Thus total accel.: $(\vec{a} = \vec{f} + \vec{g})$

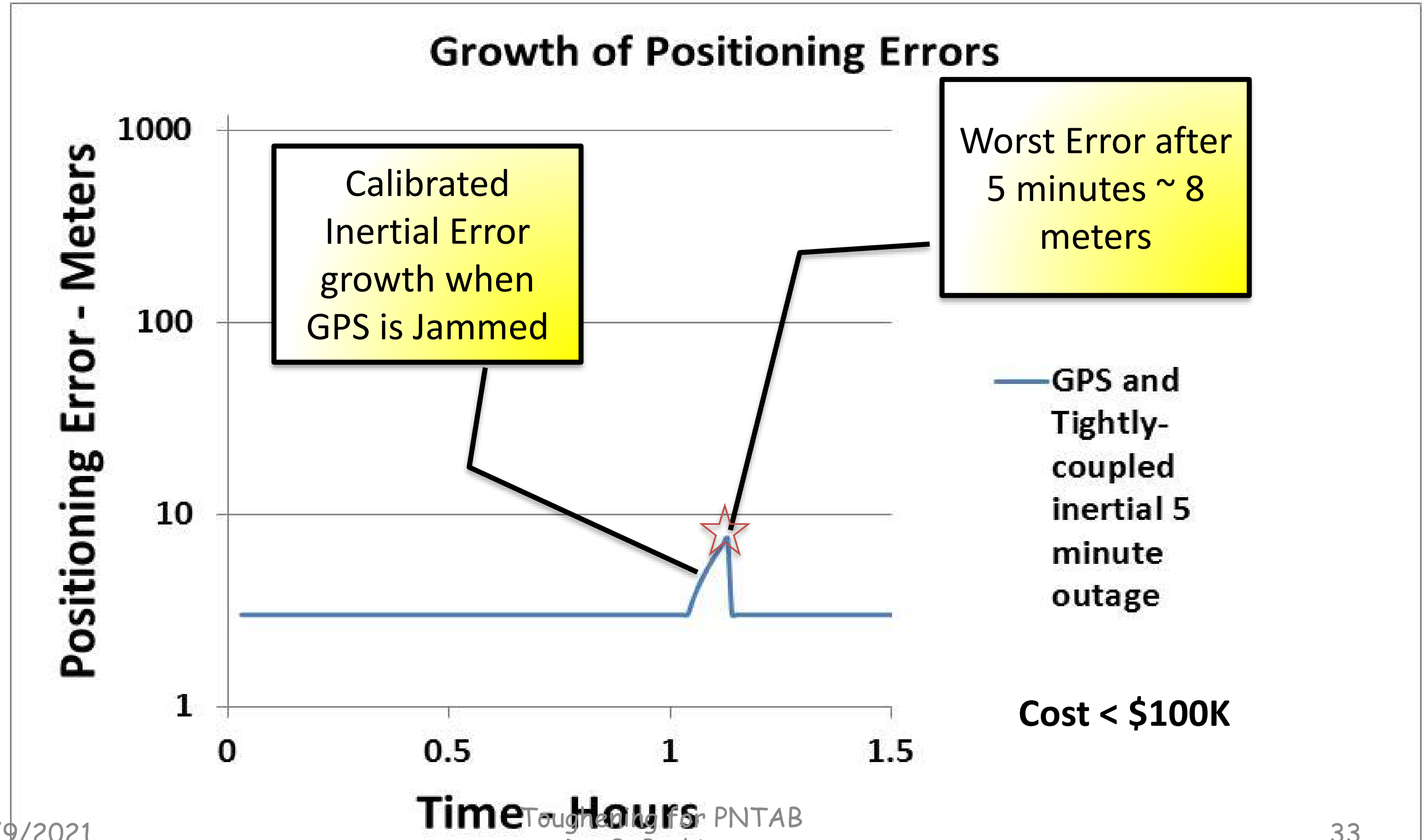
- So PNT system has to accurately both Measure $\vec{f}$ *and* calculate .. $\vec{g}$
- Initial Alignment errors within "local" coordinate frame propagates errors
- Inertials are unstable sensors of ***altitude*** – i.e. 2 Dimensional only

For fully robust receivers, all Inertial Systems benefit enormously with GNSS synergy

Summary: Hi-Performance Inertial Navigator without GNSS (error growth at 0.3 nm/hour)



Synergy -
GPS and ***Tightly-coupled*** Inertial
(Regains GPS accuracy after 5 minute outage)



Former High-Ranking DoD Official - A Visionary or ?

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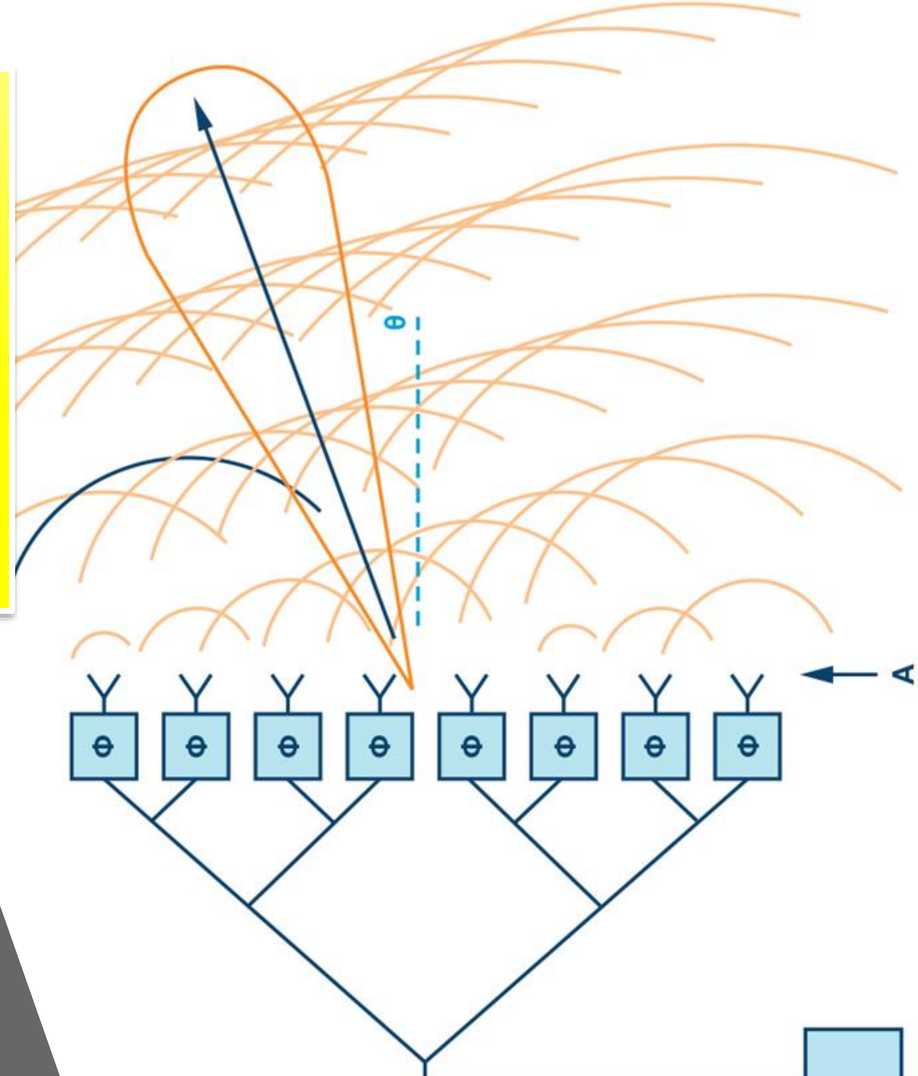
Category 3 Nibbles: Digital Beam and Null steering antennas

- GPS CRPAs well known for >40 years
  - Incorporated In Early, JPO Demo (1974 to 1978)
  - Many Journal Articles
  - *Internationally* well understood
  - Digital components readily available
  - Many manufacturers have developed and are selling CRPAs
- **ITAR has limits on # of Elements in exported Receivers**
  - Chinese and Russians probably do not adhere…
- Great striving to make small footprint but…
  - Hi-value (e.g. military vehicles/civilian Aircraft/ Maritime/long-haul trucks) mostly have both vehicle real estate and power
- Cost should greatly decrease with continuing advances in digital electronics, and large-scale use, ***and with equipage when vehicle is manufactured***

One Caution:
Because the beam is formed with variable phase delays, both Code and Carrier tracking receivers must calibrate and account for this. JPALS program has successfully demonstrated the calibration techniques.



Basic Concept of Phased Array

Digital Antenna results from Bartone and Stansell public paper

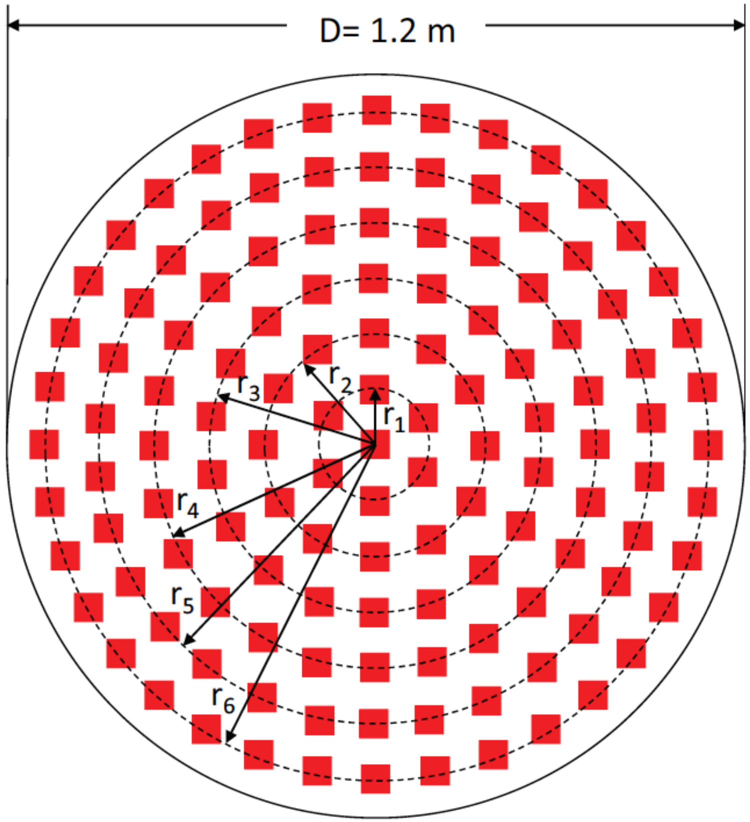


Figure 1: 127-element L=Band CRPA Configuration

- Authors studied many configurations - up to 127 inexpensive antennas
- Analyzed the # versus performance tradeoff
- ***Currently prohibited by ITAR for greater than 4 elements for civil use***

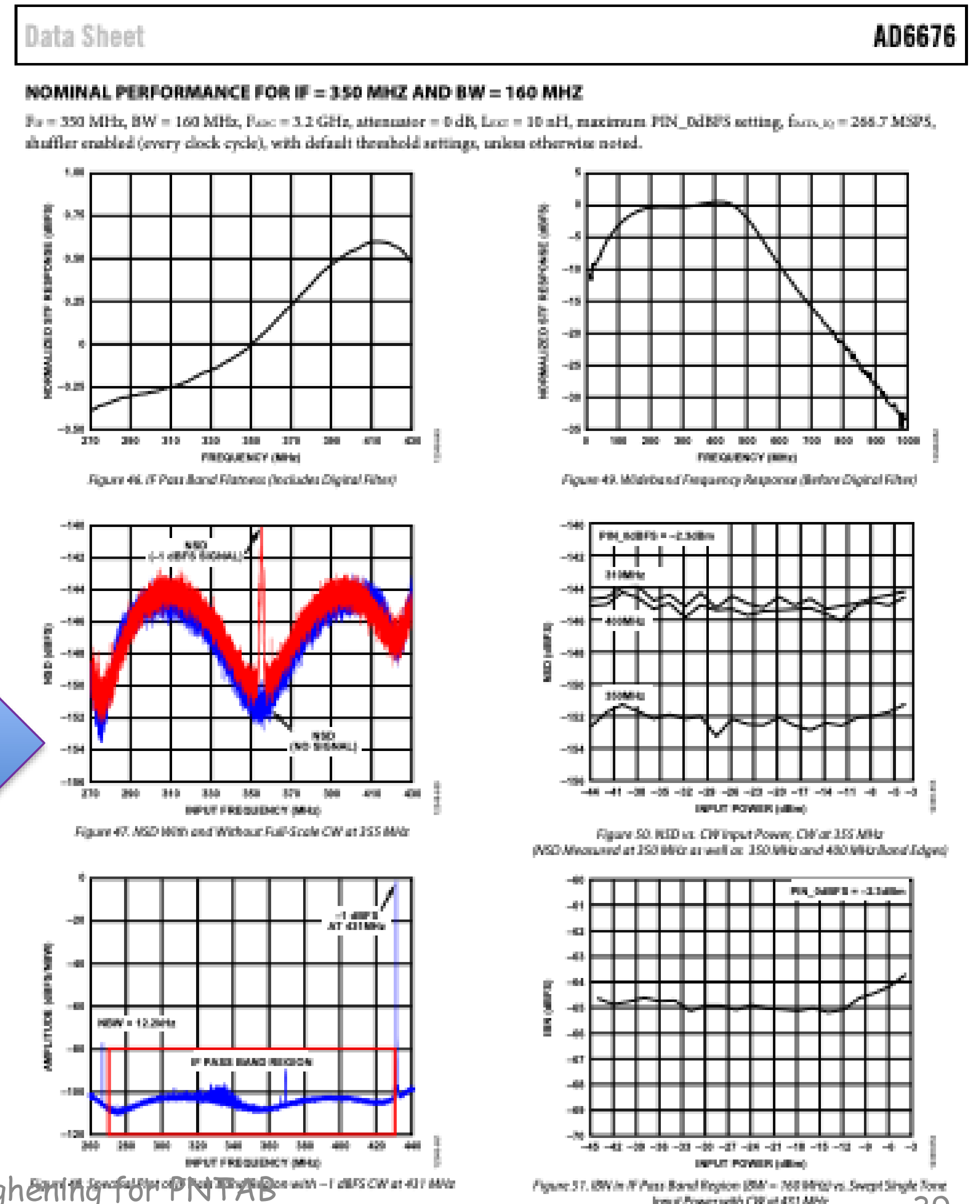
Comparing elements and footprints for various CRPA configurations

CRPA Configurations with Approximate Dimensions														
		Number of Elements in Each Ring										Mounting Ring Allocation [m]	Diameter (D)	
Rings	CE	1	2	3	4	5	6	Total # Elements	Directivity max [dB]	NB Signals Mitigated	r_i base on l_L1/2 [m]		D [m]	D [in]
0	1							1	2.0	0	0.000	0.095	0.10	3.75
1	1	6						7	14.5	6	0.095	0.170	0.36	14.19
2	1	6	12					19	19.0	18	0.190	0.170	0.55	21.65
3	1	6	12	18				37	21.9	36	0.286	0.170	0.74	29.18
4	1	6	12	18	24			61	24.0	60	0.381	0.170	0.93	36.68
5	1	6	12	18	24	30		91	25.8	90	0.476	0.170	1.12	44.18
6	1	6	12	18	24	30	36	127	27.5	126	0.571	0.170	1.31	51.68

Feasibility with ***off-the-shelf*** *componenets:*

"This antenna array can grow quite large in ground-based radar systems, with ***over 100,000 elements*** being possible."

Data Sheet for
330 MHz
16 Bit
A to D



Price: about $150 each

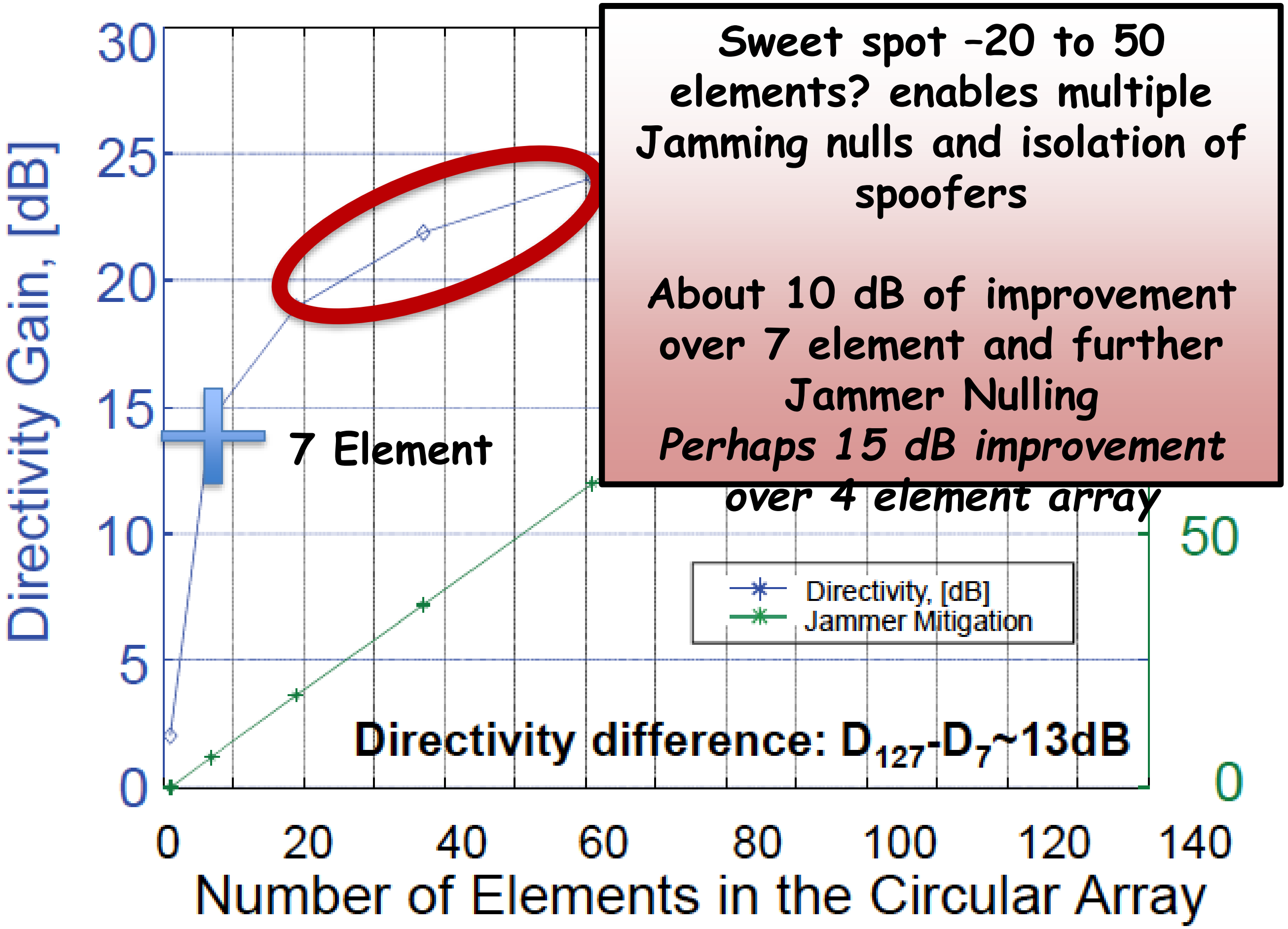
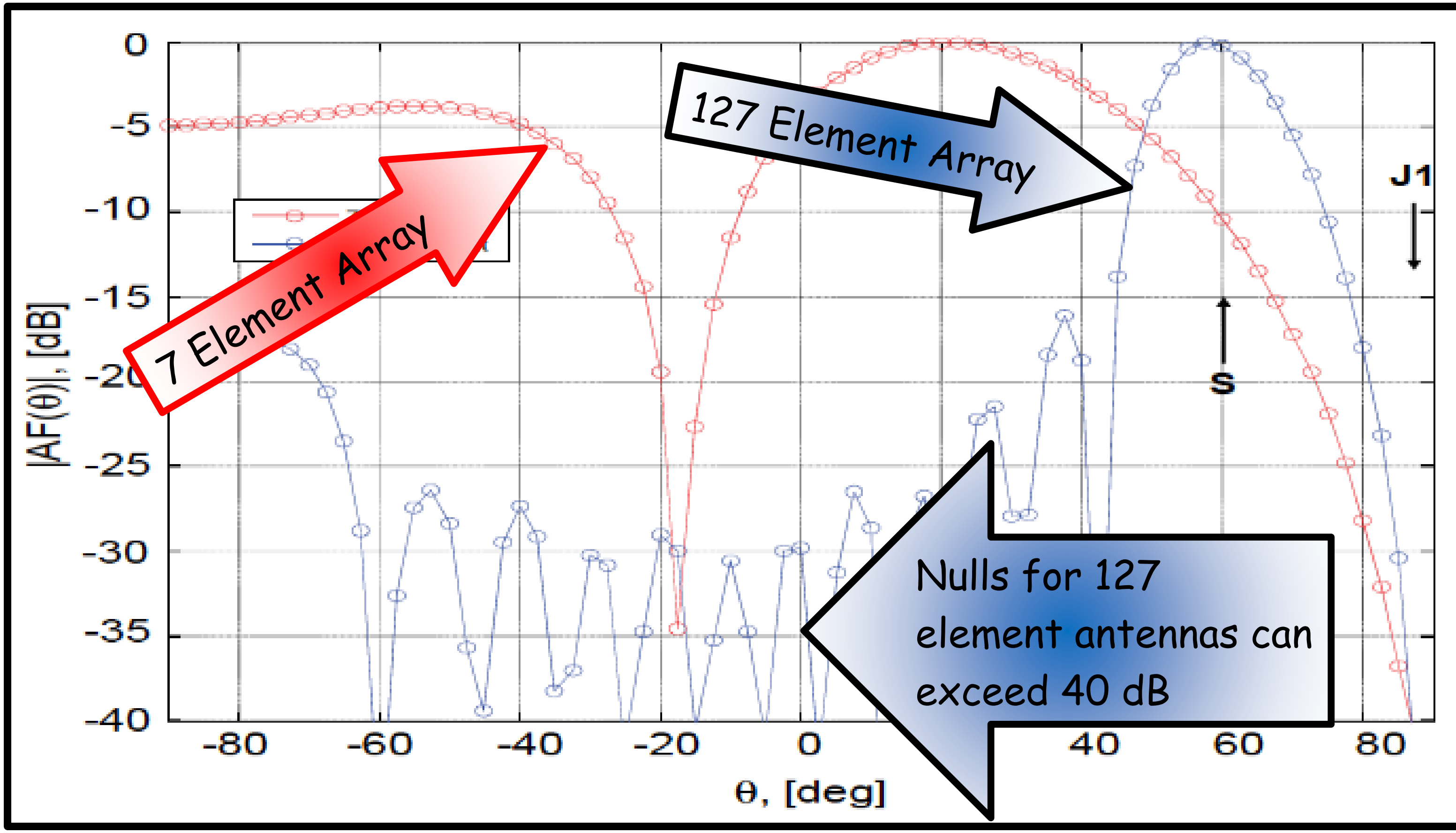


Figure 2: Directivity and Interference Mitigation Capability as a function of the Number of Elements in a 2D Planar Array

Additional Digital Elements Have high payoff and have become relatively cheap

Multiple Element Comparison
Large Element Arrays can easily create multiple adaptive nulls



Signal to Interference Noise Ratio for large element, 1.2 meter Antenna

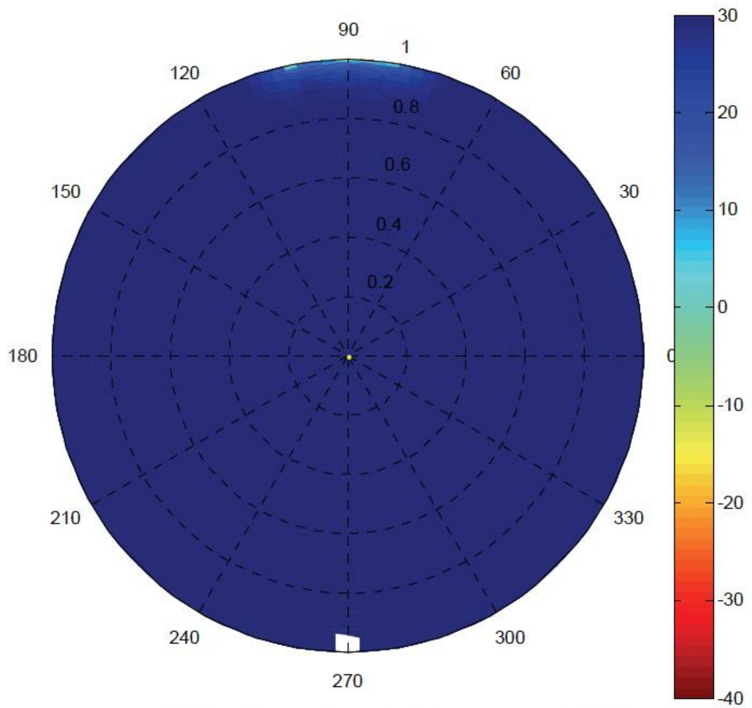


Figure 12: SINR Values for the 127-element CRPA with 5 Interference/Jammer Sources

- ***With Five sources*** of horizontal Interference
- Everywhere, at least 30 dB of Signal to (Interference plus noise) Ratio -or SINR

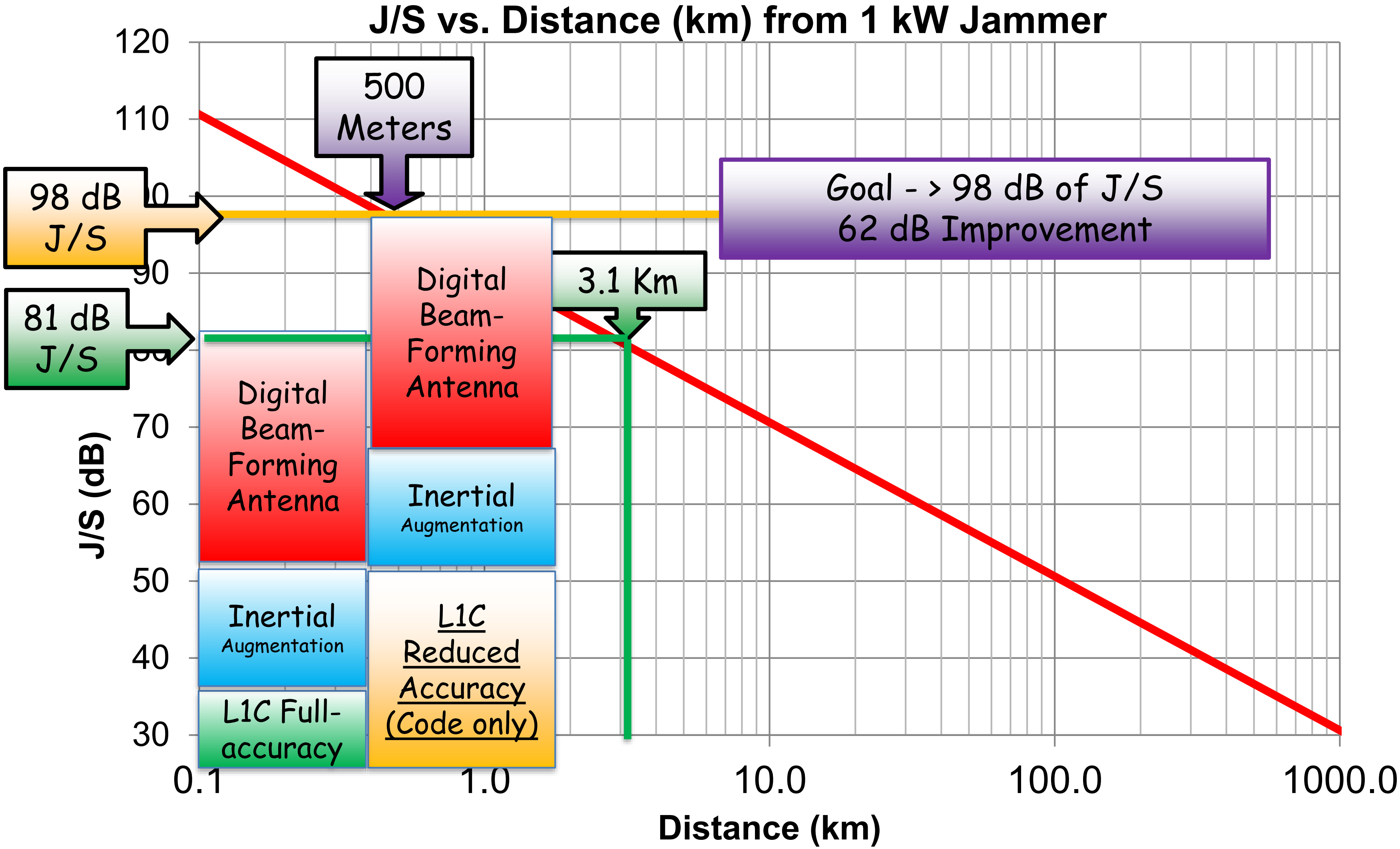
"Toughening" – nibbles and upgrades –
Category 3 Digital Beam Forming and Null steering

Technique	Range of improvement			Estimated Time to Field
	Low	High	Example	
Digital Beam Forming and Nulling Antenna	20 dB	45 dB	30 dB	Now to 5 Yrs

Takeaways:

- At least 30 dB of improved J/S_0 has been verified with hardware
- For good results, need about a 1-meter diameter Footprint
- Payoff exceeds penalty of finding space for certain users
- Also should enable enhanced situational awareness re: Jammers
- **At a median 30 dB improvement, this "nibble" alone can reduce Jammer effective area by 99.9%**

Adding Digital Beamforming Antenna plus Inertial Augmentation J/S (dB) to reduce Max Jammer Range



Denial Areas for 1 kW Jammers around DFW Airport for L1C Augmented Receivers with J/S = 98 dB

(Runways in Green)

A quick summary to this point - Improvements to the ***Receiver*** System

Improvement Group	Median Improvement
Signals and Processing	17 dB
Tightly coupled Inertial	15 dB
Digital Null and Beam Steering Antenna	30 dB
Total Receiver Enhancements	62 dB

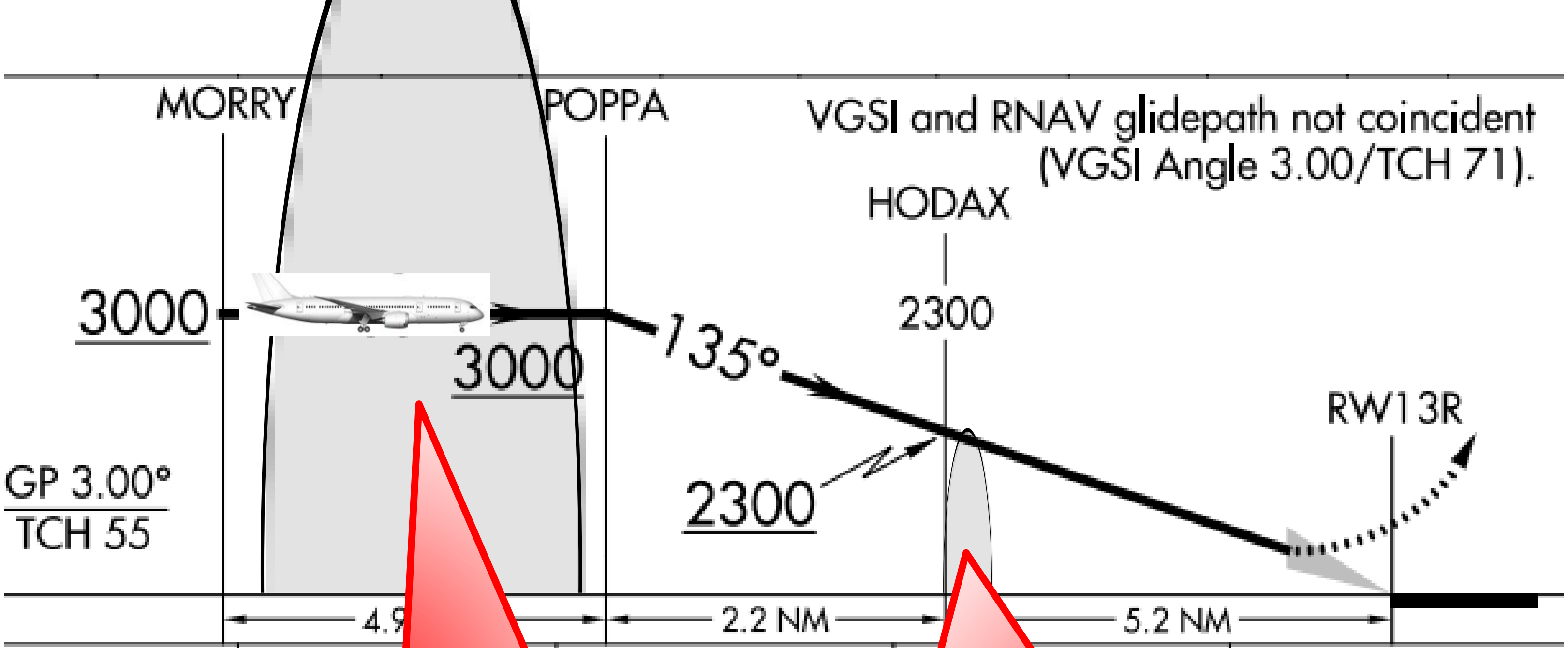
For Code Tracking L1C receiver, 36 + 62, or:

J/S = 98

- **This has been roughly verified with real hardware**
- **All of these Nibbles should be achievable in available users sets within 5 years**
- Impact on defeating ***1KW jammer***:
  - Denial Slant Range Reduced from 556 Km to 0.4 Km
  - Area of Denial Jamming reduced from 972,000 Km^2 to 0.6 Km^2.

Resulting 1 Kw Jammer Denial envelopes Receiver enhancements for L1C in state 5 (Full accuracy) or State 3 (Reduced Accuracy)

(Jammer directly under flight path - DFW GPS (RNP) approach 13R)



Full Accuracy (State 5) denial envelope for 1 Kw jammer and enhanced L1C Receiver
Total J/S = 81 dB.

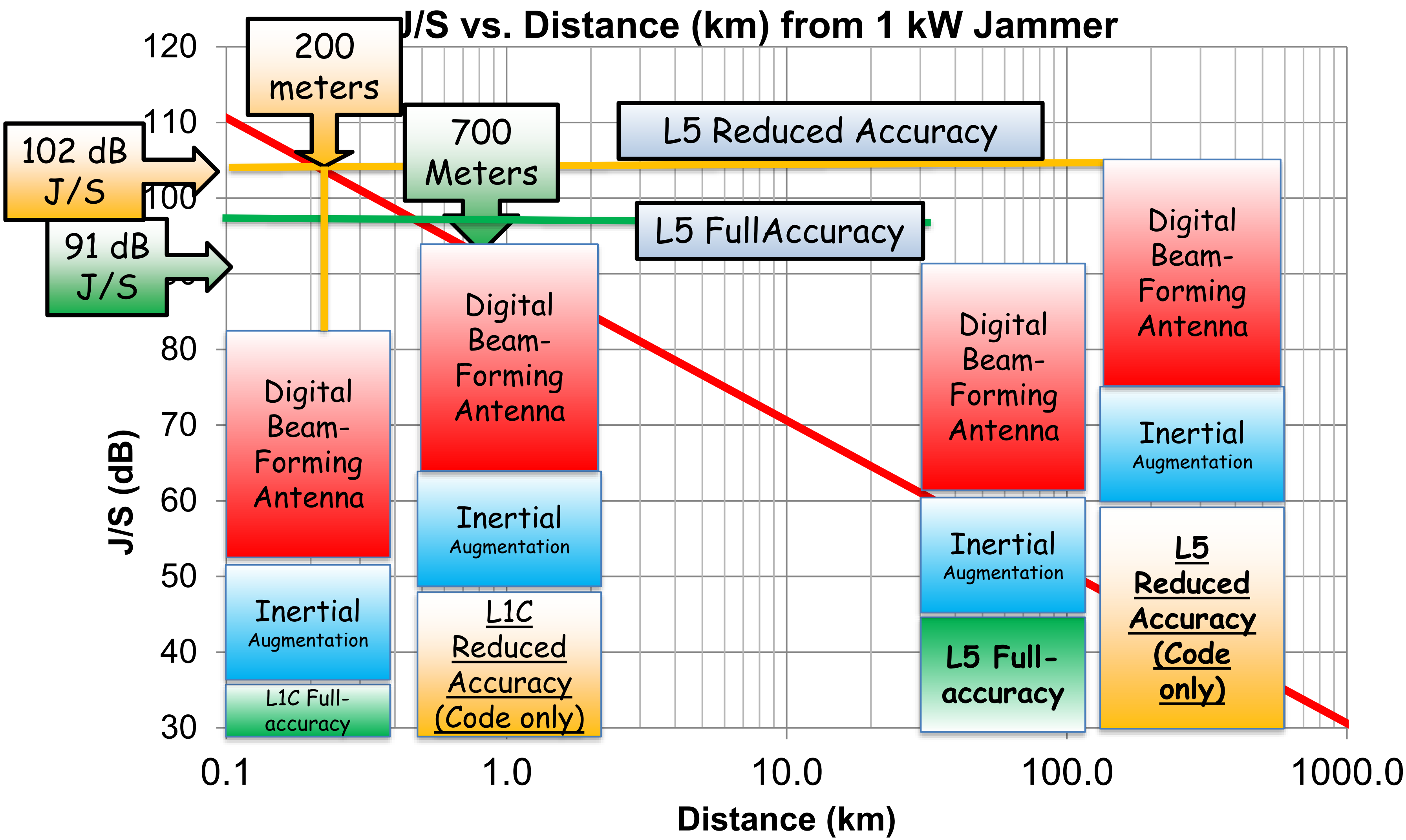
Reduced Accuracy (State 3) denial envelope for 1 Kw jammer and enhanced L1C Receiver
Total J/S = 98 dB.

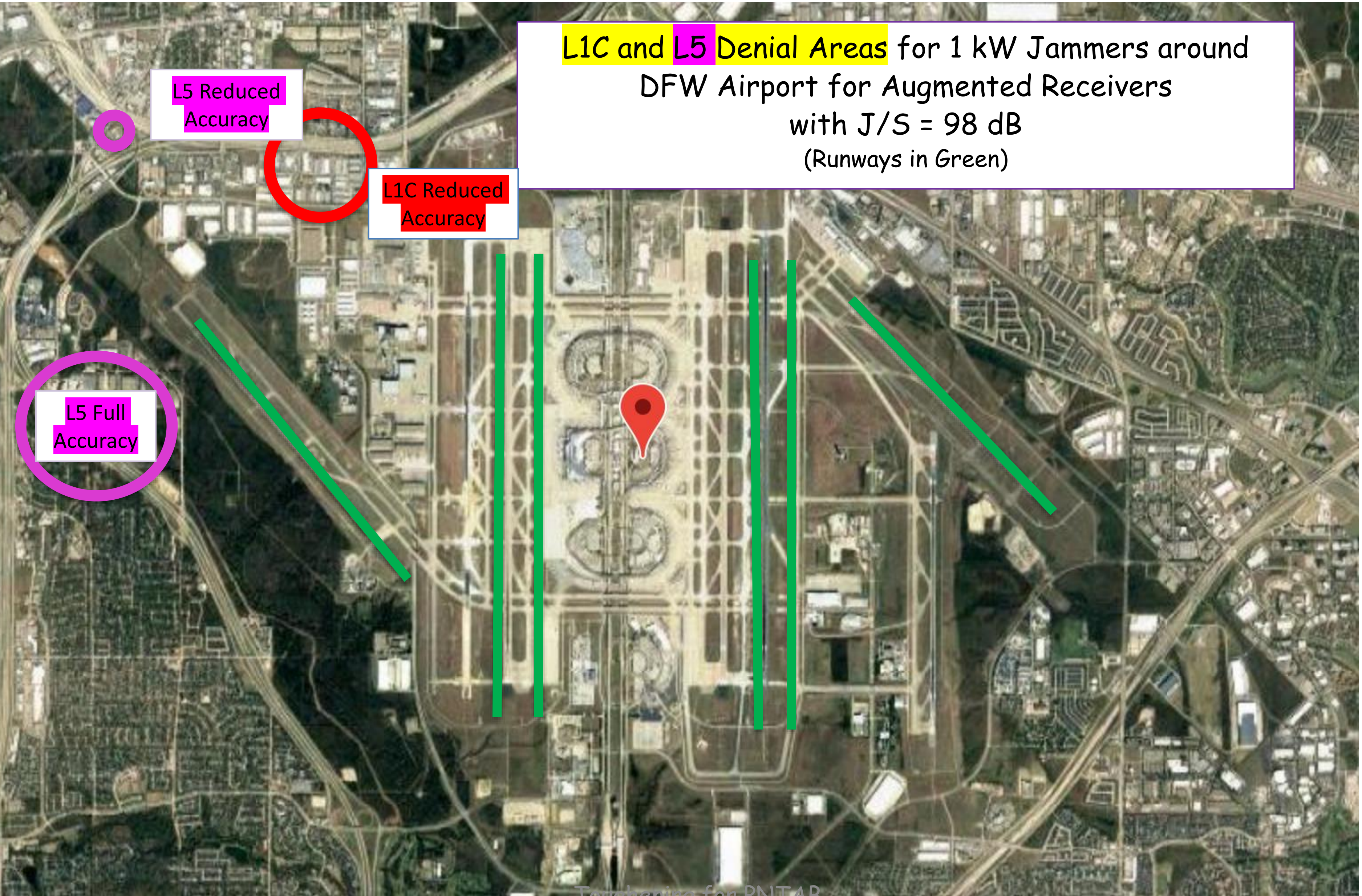
"Toughening" – nibbles and upgrades

<u>Category 4</u> : Satellite Enhancements

- Additional/Alternative Signals
  (Galileo, GLONASS (?), Beidou(?))
- Additional Frequencies (L5, L2, Galileo)

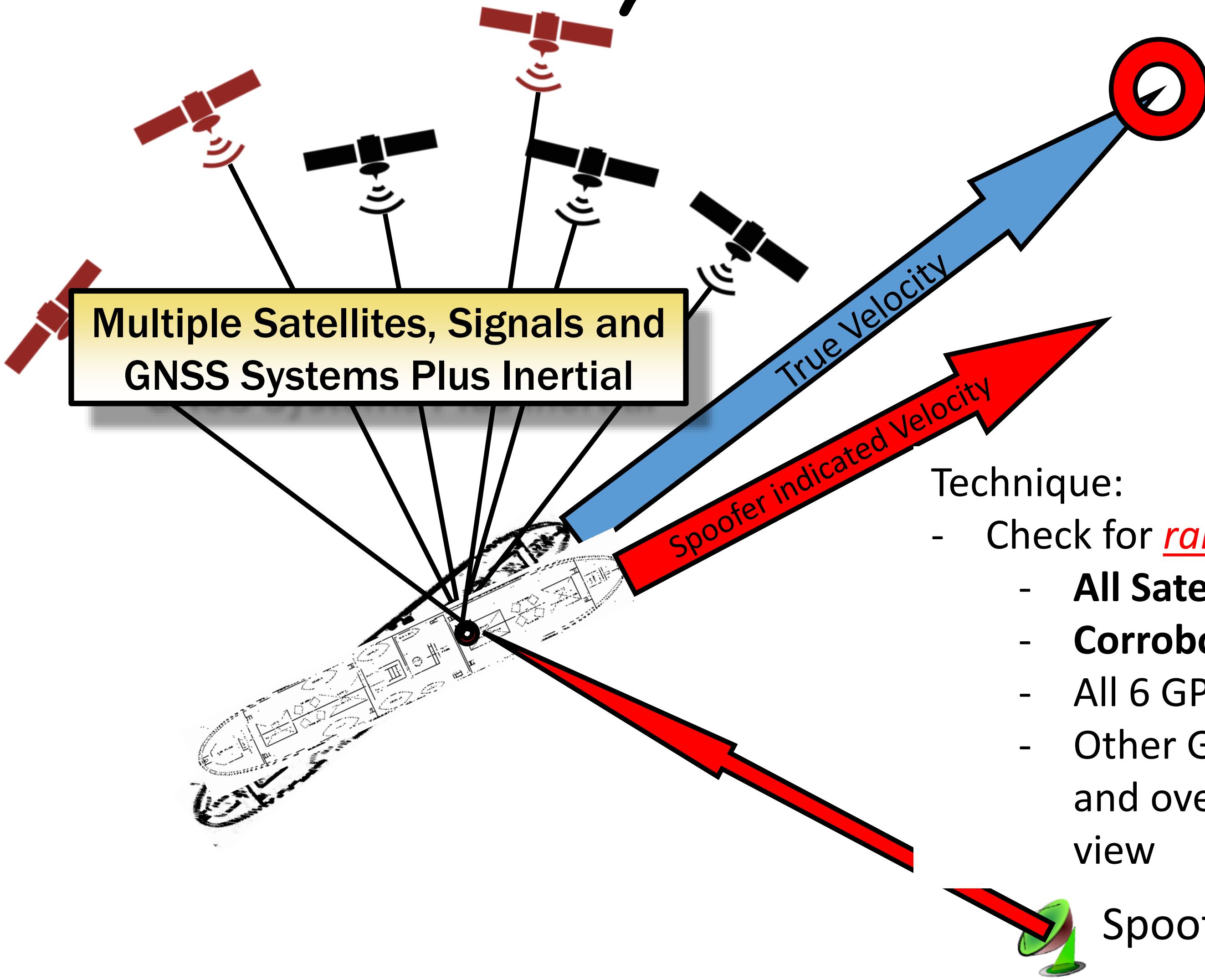
Comparing L5 and L1C based on Max Jammer-Denial Range
Note: FAA is pursuing L5, but apparently not L1C




L1C and L5 Denial Areas for 1 kW Jammers around
DFW Airport for Augmented Receivers
with J/S = 98 dB
(Runways in Green)
L5 Reduced Accuracy
L1C Reduced Accuracy
L5 Full Accuracy

Spoofing

Spoof Detection Example:
The Velocity Crosscheck



The Skeptical Circle – If velocity mismatch is outside, discard

Technique:
- Check for *range-rate* consistency
  - **All Satellites in view**
  - **Corroboration with Inertial**
  - All 6 GPS Civil Signals *
  - Other GNSS (11 more signals and over 20 addl. satellites in view

Additional observations re: spoofing- Additional Detection Techniques

- **Directional Antennas** can attenuate spoofing as well as reduce noise jammer interference
  - Amplify Valid Signal
  - Attenuate Spoofing input
  - Measure bearing of Spoofer
- **RF environment monitoring**: local, regional, national
  - Input Power above normal
- **External Detection and Notification** – FAA's WAAS? (J911)
- **Other System Crosschecks**
  - **Inertial Navigation** Components
  - Other RF Systems – ***LEOs, eLoran or FAA's DME***
  - **Eyeballs**/ Magnetic Compass etc.

Summary reminder:
The Jammer Threat is real and growing

Chinese - engineers from Tsinghua University in Beijing

Also: https://ctstechnologys.com/low-altitude-gps-spoofing-system-drone-defense-anti-drones-device.html

Summary and Conclusions

"GNSS (GPS) cannot be matched with any terrestrial system in terms of accuracy, 3D, Worldwide 24/7, but must be protected against Jamming"

- The civil jammer threat is very real and rapidly growing. Aviation, including RPVs are particularly threatened. Maritime is also very vulnerable.
- More emphasis should be placed on ***toughening*** GPS against high-powered Jammers: **Extreme resilience can be created with a modern Receiver *System***
  - The most important contribution Category is a Multi-element (>18) Digital Beam Forming and Null steering Antennas
  - These techniques are also powerful anti-spoofing tools
  - New improvements should be ready to field in the next 3 to 5 years if deemed urgent
  - Many companies are actively pursuing these techniques
- While Inertial Systems can flywheel through GPS outages, they must be periodically reset because of unbounded error growth –*even with perfect "accelerometers"*
- FAA can help by emphasizing Toughened GNSS Receivers, particularly using directional antennas.
  - ITAR antenna restrictions must be removed. They are only hurting the US, since the whole world knows the technique and has access to the commercial components.
- The L1C and L5 signals are much more robust than the L1 C/A. The FAA should rapidly enable aviation to use these signals, including WAAS, enhanced GPS, and the supporting MOPS etc.

A recommendation

- That PNTAB forms a committee on "Toughening" focusing on, at least, countering both **jamming and spoofing**
  - Identify and project the civil threats
  - Identify mitigations and roadblocks to implementations
  - Create a report and recommendations to the EXCOM for USG actions
- Members ?
  - Tom Powell, John Betz, Frank Van Diggelen, Scott Burgett, et.al.
  - Advisors: Chris Hegarty, Ken Alexander, Karen Van Dyke

Let's re-emphasize "Toughening"
and develop affordable multielement antennas.

And remove them from the Munitions List
so Commercial airplanes can exploit, and the COTS prices drop.

L5/L1C

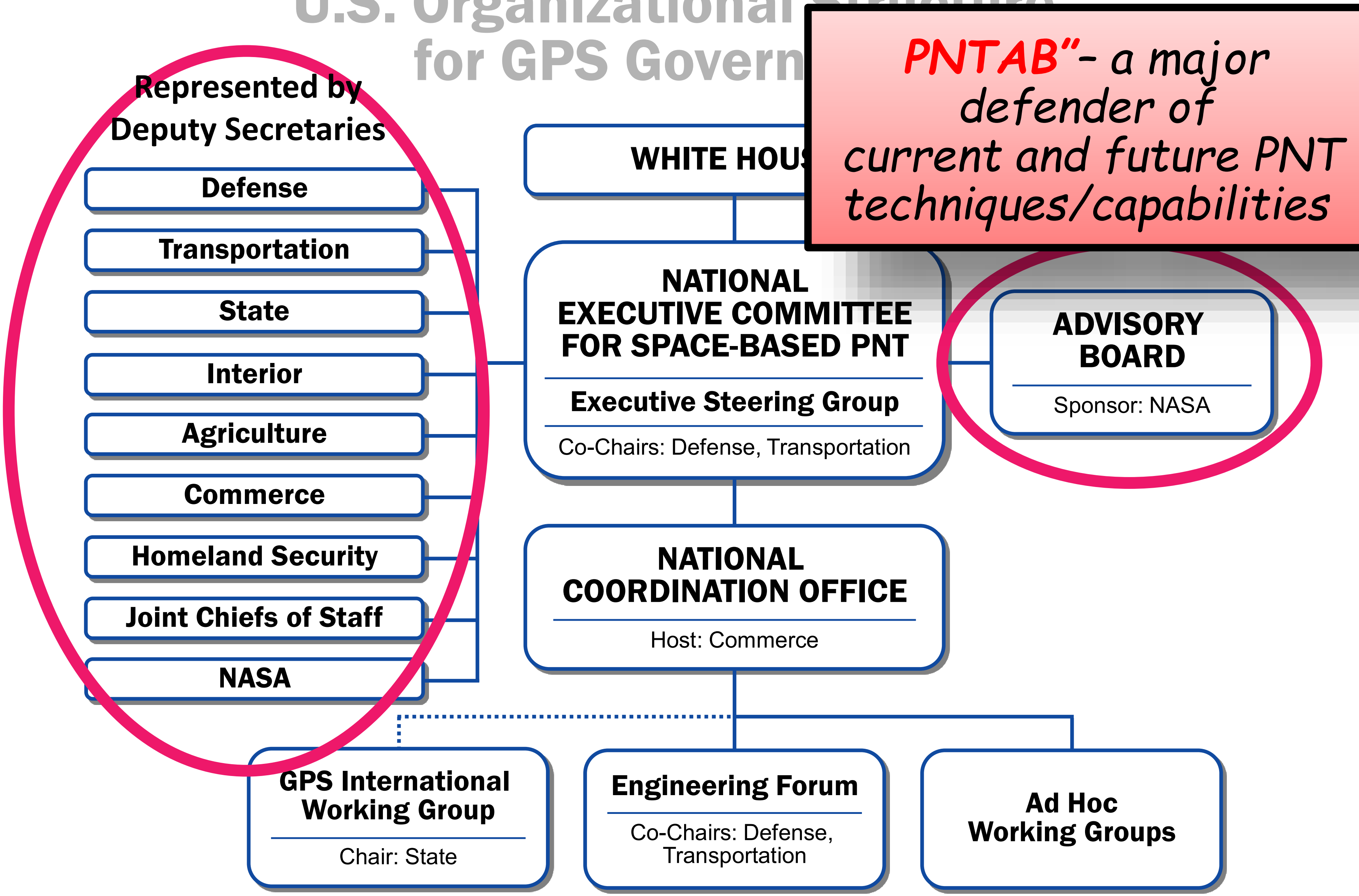
Tightly-coupled Inertials

Multi-element Antennas

Thank you

Backups

U.S. Organizational Structure for GPS Govern...



Assured Availability of PNT - the "PTA" Strategy

Three Strategy Areas:

PTA - Protect, Toughen, Augment

- **Protect the Clear & Truthful Signal-3 steps**
  - Advocacy – vigorously oppose any FCC repurposing that would jeopardize current and future GPS uses
  - Pre-actions – even before interference occurs - Legal/Law Enforcement/FCC:
    - Protect Spectrum/Enact strong Penalties/suppress Jammer sales
  - Re-actions - when interference/spoofing occurs:
    - Quick Knowledge of Jamming Area/Pinpoint Location/Apprehend Perpetrator/Prosecute as Appropriate

Assured Availability of PNT - the "PTA" Strategy

Three Action Areas:

PTA - Protect, Toughen, Augment

- Toughen Users' Receivers to use GNSS
  - Employ multiple, well known techniques to ensure *spoofing* can never create HMI
  - Increase Jam resistance – use well established techniques
  - Diversify - *All integrity-certified GNSS signals* receivers (with vector feature)

Assured Availability of PNT - the "PTA" Strategy

Three Action Areas:

PTA - Protect, Toughen, Augment

- **Augment or substitute PNT sources**
  - Densify and Diversify satellites – Signals/constellations
    - Worldwide Integrity Monitoring
  - Use Complementary PNT Sources – e.g. DME, eLoran, LEOs

Deliberate Spoofing has been Demo

Many examples of Spoofing recently, Real and Possible:

- Academic Demonstrations
- Possible Incidents for Military
- Will focus on "Civilian" Receivers
- Military has additional anti-spoofing techniques

"Professor fools $80M superyacht's GPS receiver on the high seas"

Humphreys conducted the test in the Ionian Sea in late June 2013 and early July 2013 with the full consent of the "White Rose of Drachs" yacht captain.

- Outline:
  - What is Spoofing?
  - How can it be prevented?
  - What actions might USG take?

Spoofing Definition and General Techniques

Spoofing:

- ***Deliberately creating False GNSS signals that lead to misleading Position, Time or Velocity***

Note: Not considering *inadvertent satellite errors* –an integrity problem, albeit has some of the same solutions

- ***A Few* *Examples*** *of Deliberate Spoofing* ***Techniques***

Technique 1. ***Create*** fictitious signals & broadcast to user

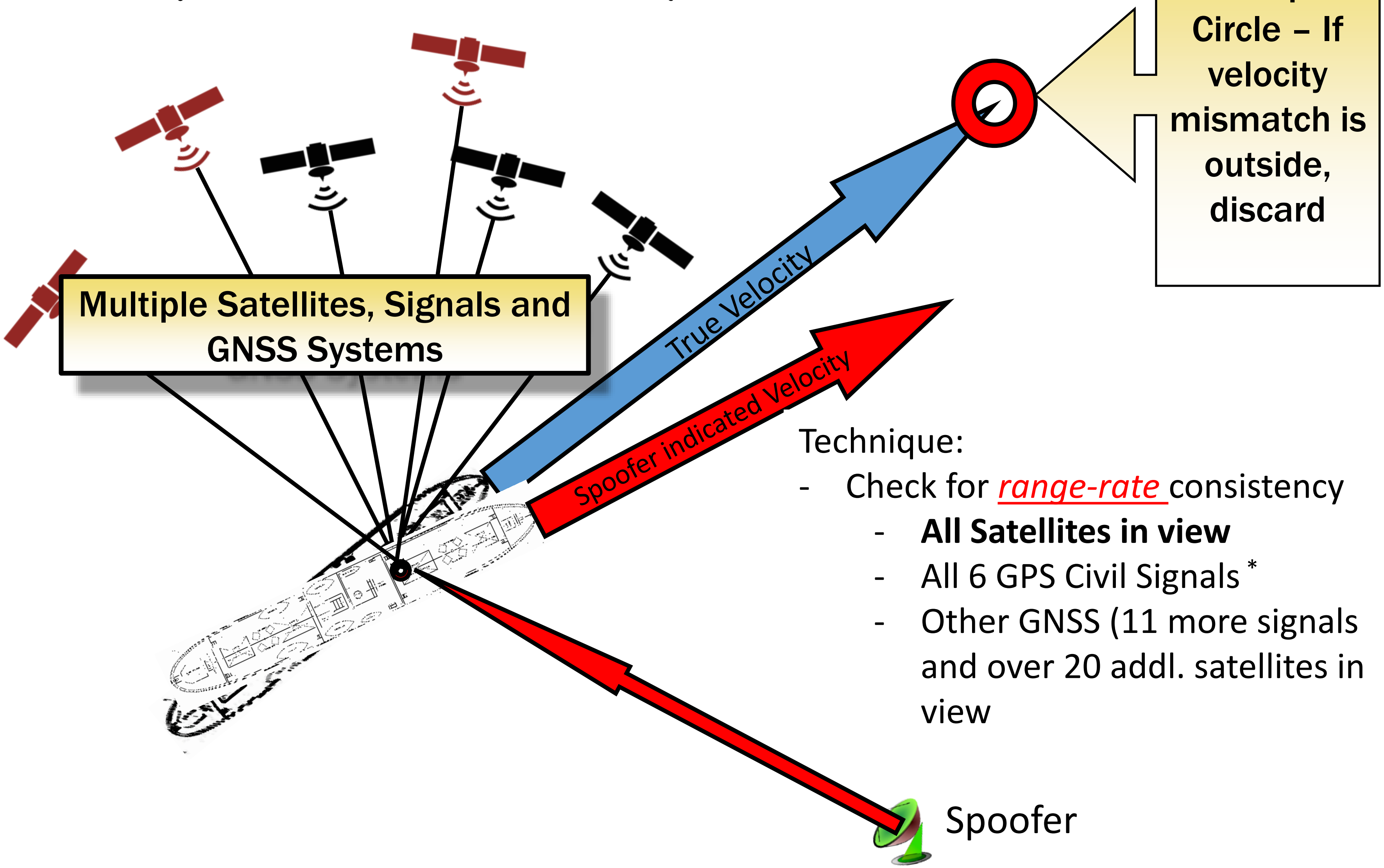
- Presumably Hazardous and Misleading Information ("HMI")
- Requires Knowledge of Signal Sequences
- Requires time synchronization

Technique 2. ***Rebroadcast*** GPS signals with >> Power

Arrives at user with delay – nanosecs to 10s of microseconds

Technique 3. Combination of 1 and 2.

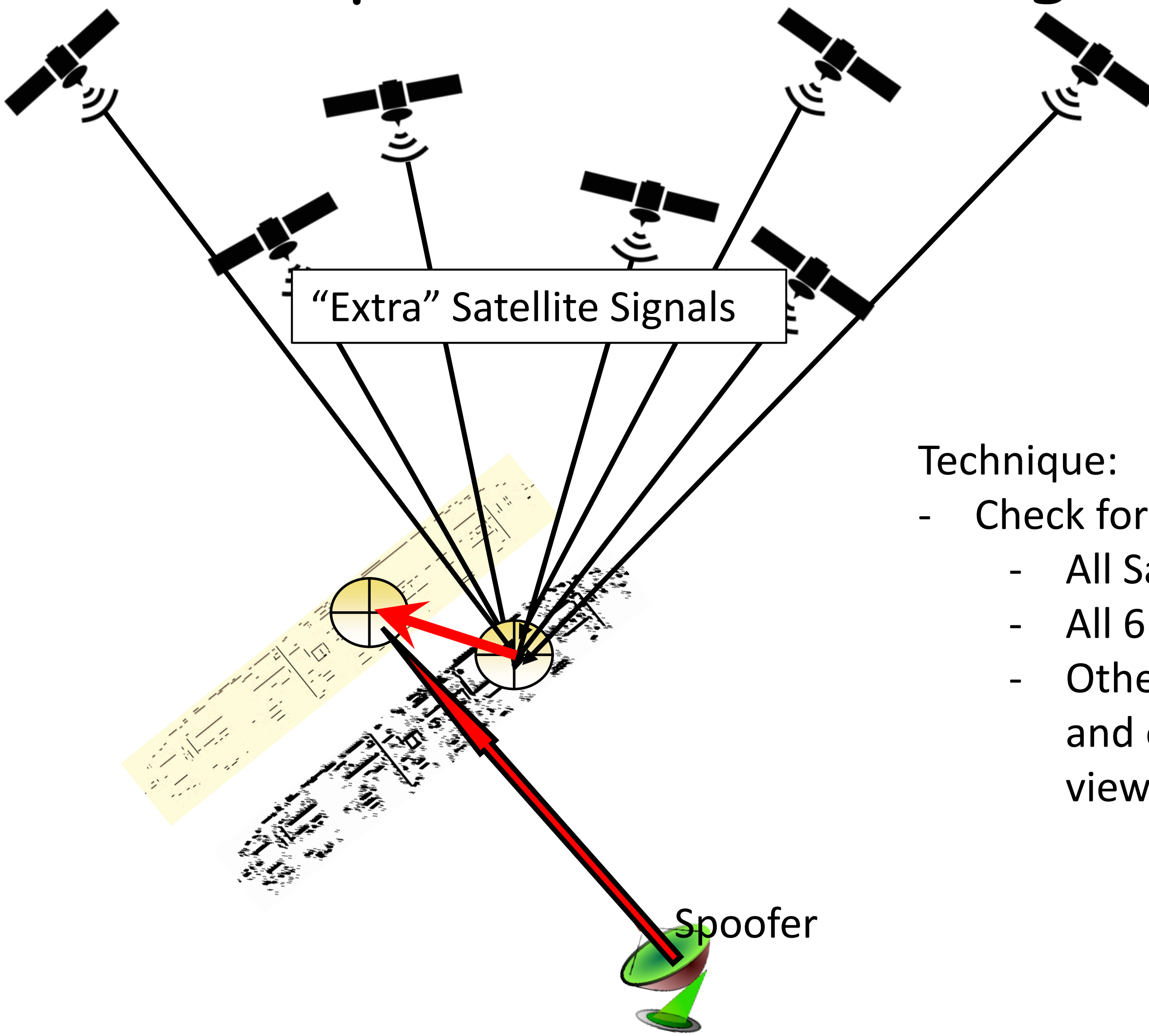
Example: The Velocity Crosscheck



Technique:

- Check for *range-rate* consistency
  - **All Satellites in view**
  - All 6 GPS Civil Signals *
  - Other GNSS (11 more signals and over 20 addl. satellites in view

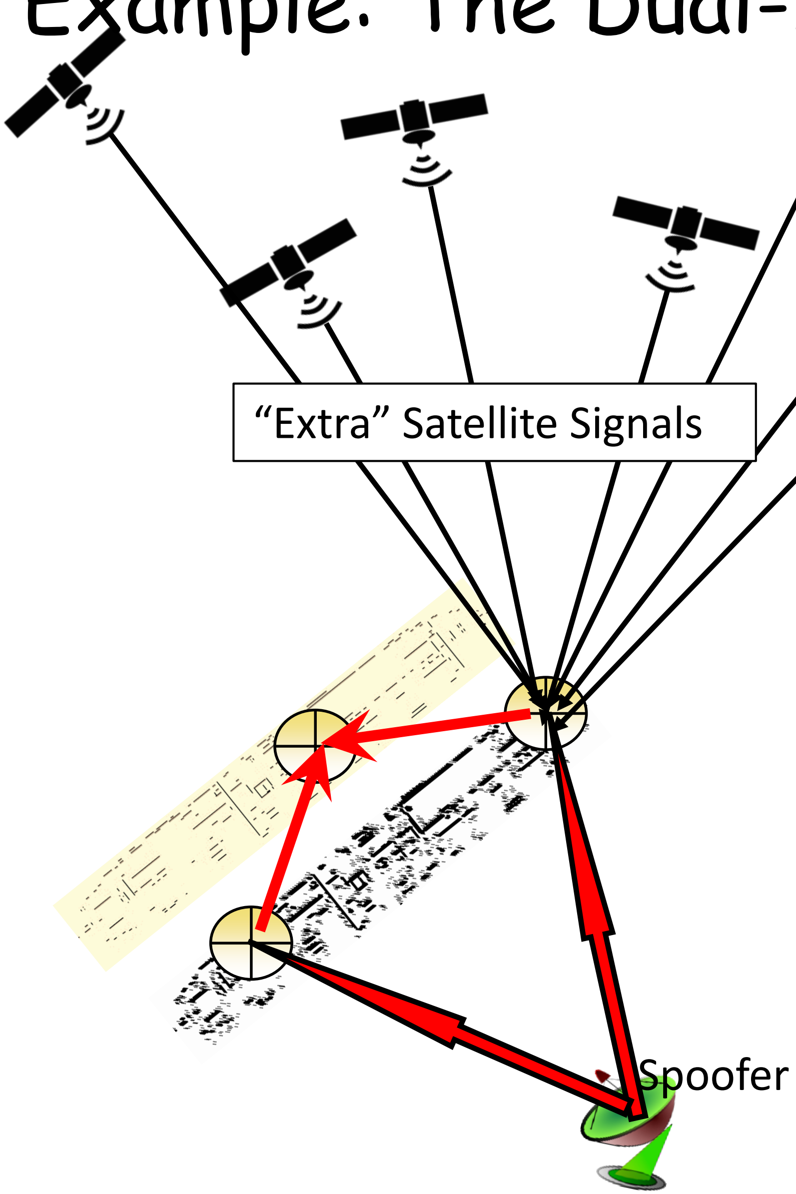
Example: The Positioning Crosscheck



Technique:

- Check for ***ranging*** consistency
    - All Satellites in view
    - All 6 GPS Civil Signals *
    - Other GNSS (11 more signals and over 20 addl. satellites in view)

Example: The Dual-Antenna Crosscheck



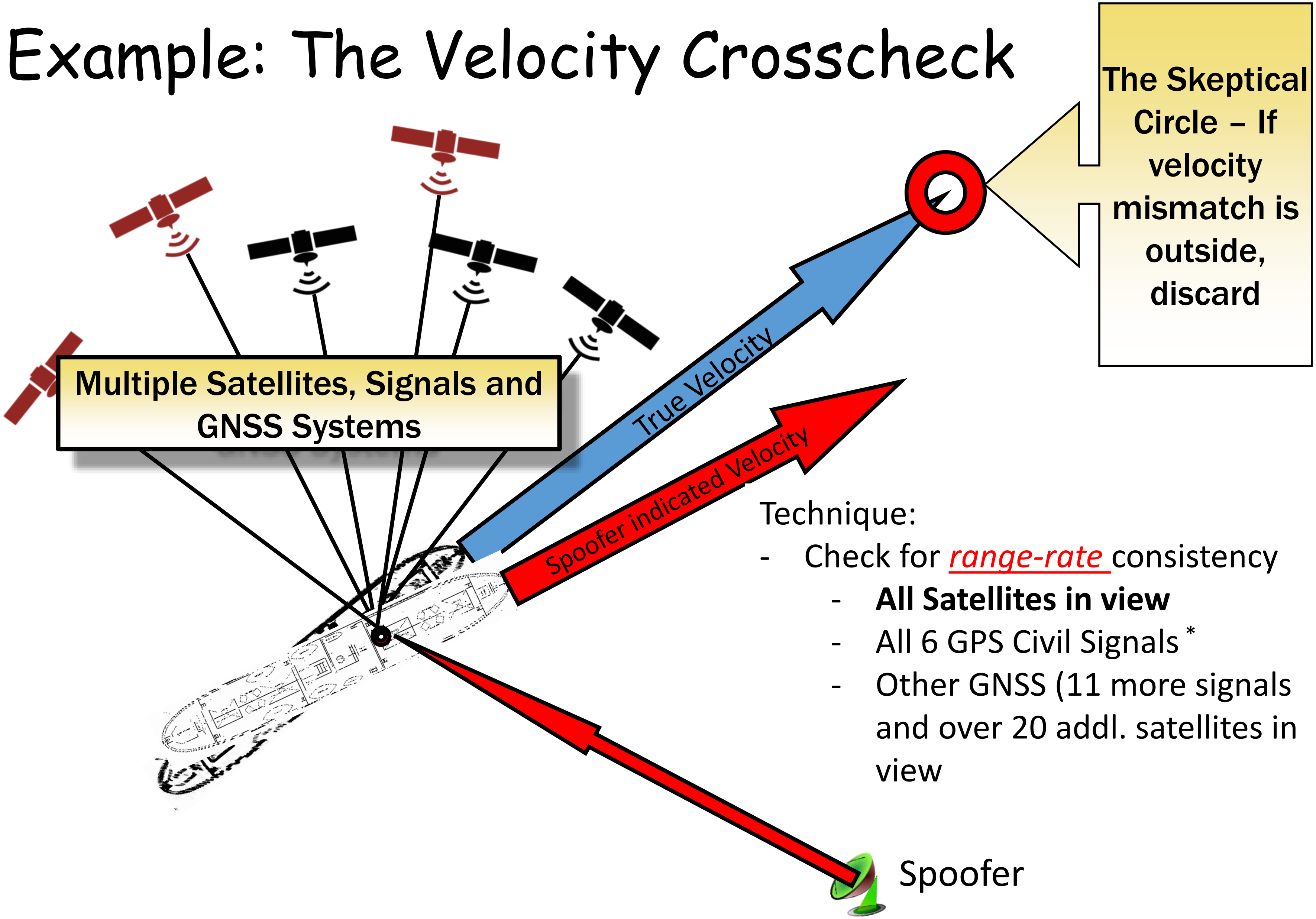
Vehicles can use dual antennas to get precise heading (0.1° or better)

But spoofer places both antennas at same location

Technique:

- Check for azimuth and relative antenna location
- If identical, must be a spoofing signal

Example: The Velocity Crosscheck



Technique:

- Check for *range-rate* consistency
  - **All Satellites in view**
  - All 6 GPS Civil Signals *
  - Other GNSS (11 more signals and over 20 addl. satellites in view

Spoofing Summary

- "Competent" (Skeptical) receivers should detect spoofing
  - At a minimum, cleanly stop providing misleading outputs
  - Consistency checking ("crosschecking" - a self-integrity monitor)
  - Many other techniques e.g. directional antennas
- Many Receivers should be able to "Operate Through"

Well-known defenses are beginning to be incorporated

Finding Initial Attitude for INS

- Null two cross axis accelerometers to find “level”
- Orient East/West gyro to sense no earth rate
- Typically takes 15 to 20 minutes to find orientation to about an arc minute
- **At 100km, an arc minute in azimuth is about 30 meters.**
- *Note:* **With GPS aiding, initial alignment can occur in the first 30 minutes of flight with no waiting on the flight line.**

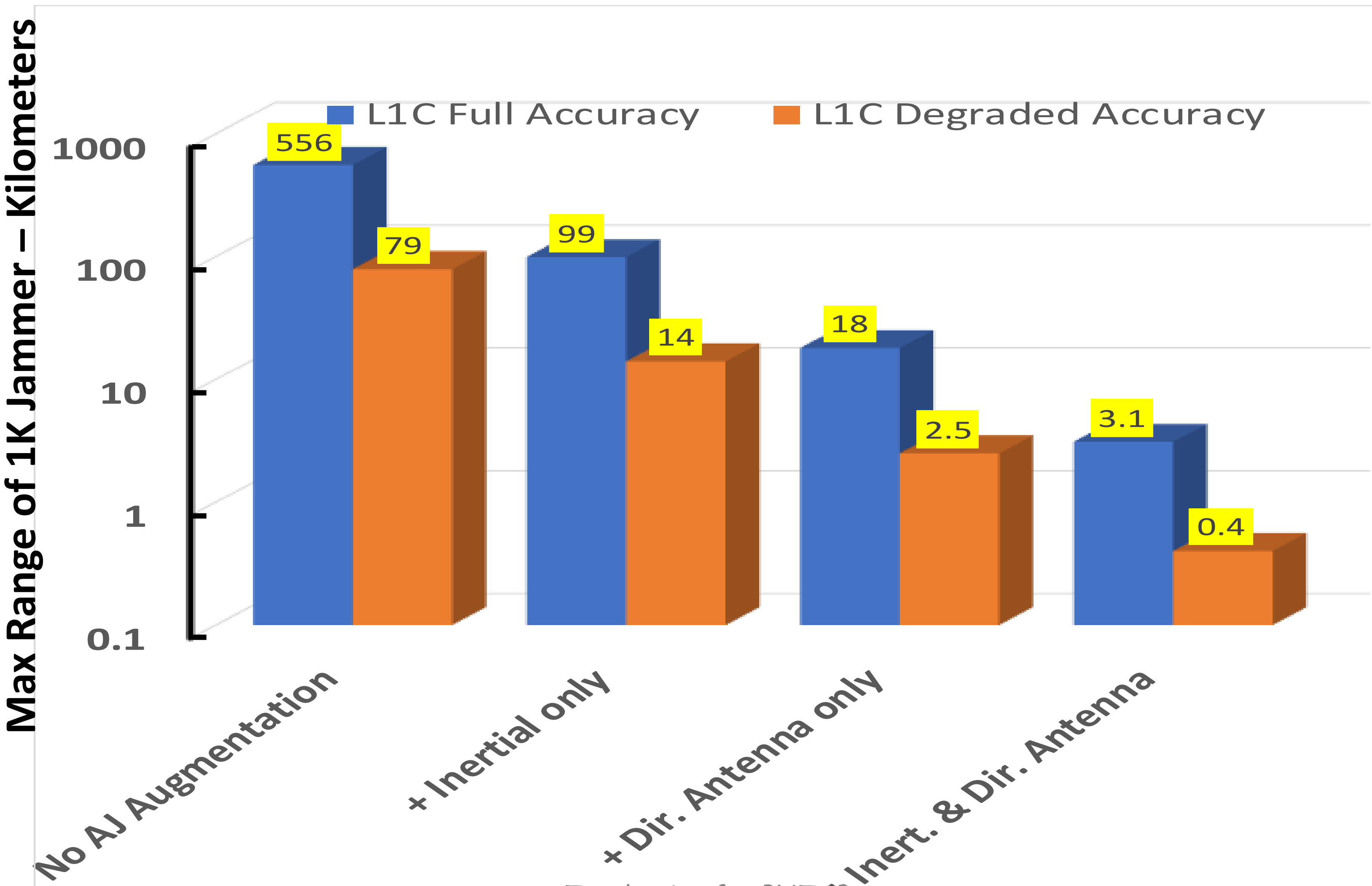
L1C A/J techniques against 1 kW Jammer

	State 5 Full Kinematic Accuracy			State 3 Code Tracking Accuracy		
	dB of J/S	Range (km)	Area (km^2)	dB of J/S	Range (km)	Area (km^2)
No AJ	36	556	972,000	53	79	19,390
+ Inertial only	51	99	30,731	68	14	613
+ Dir. Antenna only	66	18	971	83	2.5	19
+ Inert. & Dir. Antenna	81	3.1	31	98	0.4	0.6

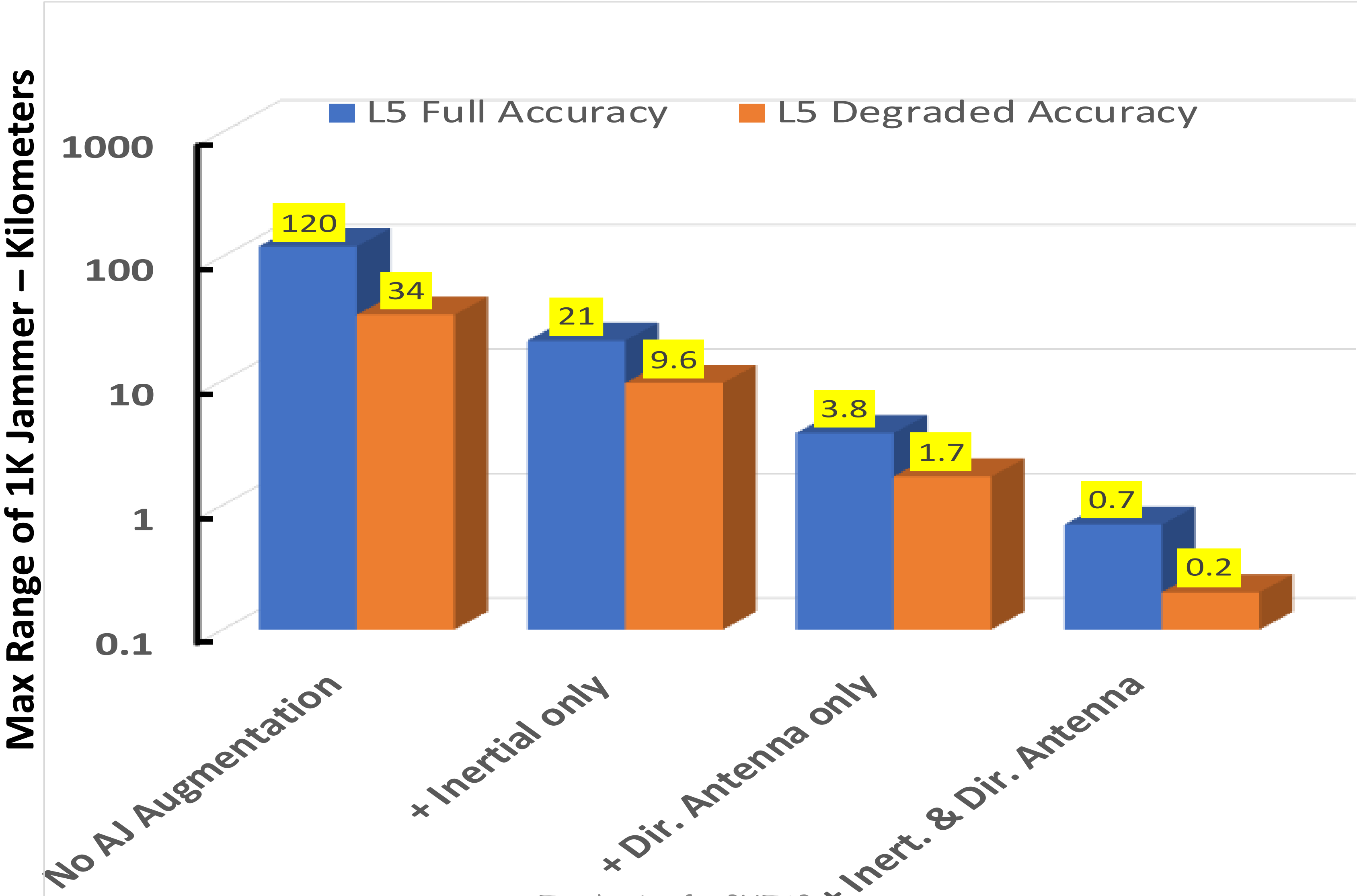
L5 A/J techniques against 1 kW Jammer

	State 5 Full Kinematic Accuracy			State 3 Code Tracking Accuracy		
	dB of J/S	Range (km)	Area (km^2)	dB of J/S	Range (km)	Area (km^2)
No AJ	46	120	45,454	57	34	3610
+ Inertial only	61	21	1437	68	9.6	287
+ Dir. Antenna only	76	3.8	45	83	1.7	9.1
+ Inert. & Dir. Antenna	91	0.7	1.4	102	0.2	0.1

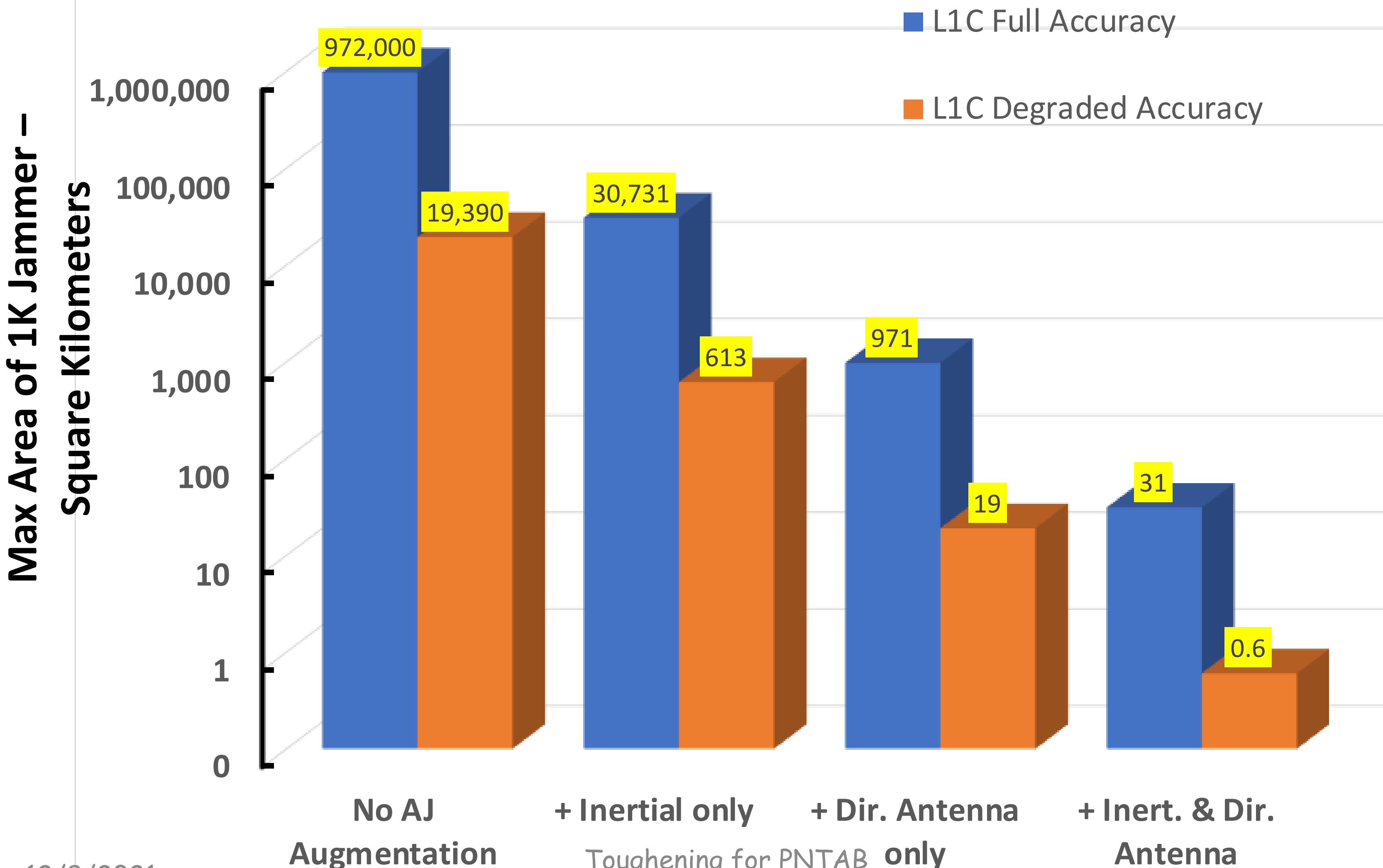
GPS L1C Receiver. Maximum Radius (Km) of 1K Jammer for Various A/J capabilities -



GPS L5 Receiver. Maximum Radius (Km) of 1K Jammer for Various A/J capabilities -



GPS L1C Receiver. Total Area (Km^2) of 1K Jammer for Various A/J capabilities -



L1C and L5 A/J Comparisons
Max Radius of 1 Kw Jammer