"Toughening"

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.***"

Preamble: Headlines and Responses

- Press Headlines: ***GPS vulnerable!***
  - Jamming
  - Spoofing
  - FCC 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."

- **So why don't we *also* emphasize the well-established solutions to ensure GNSS-based PNT?**

i.e., Toughen GPS

Toughening

A part of PTA

Our Goal: Assured PNT

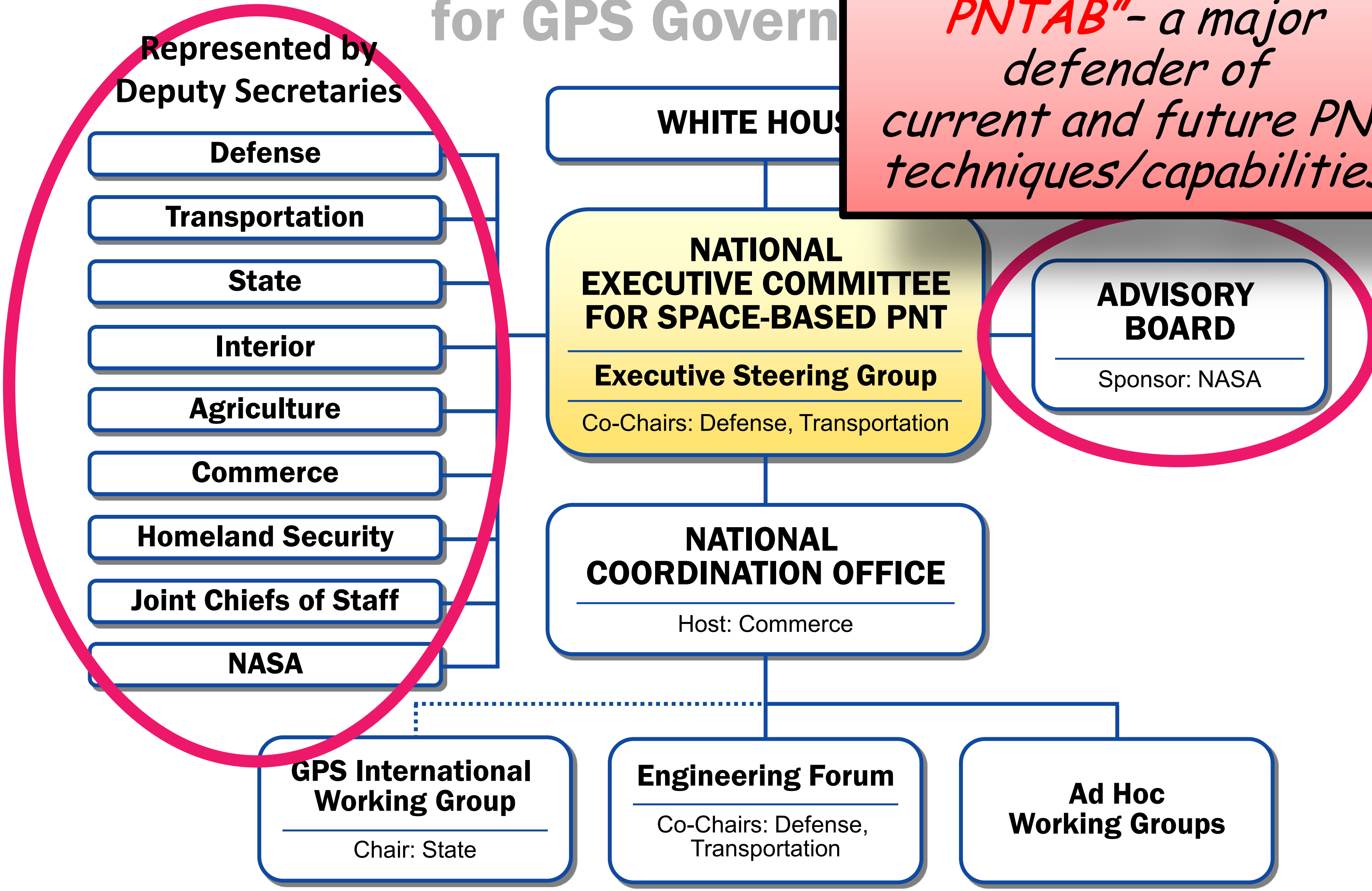
A discussion of Strengths, Synergies and Timing

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

Bradford Parkinson
Professor Emeritus (Recalled)
Stanford University

U.S. Organizational Structure for GPS Govern

PNTAB"- a major defender of current and future PNT techniques/capabilities



The PNTAB Strategy:
PTA

"We must

Protect, Toughen, and Augment GPS

to ensure that it

continues to provide Economic and Societal Benefits"

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

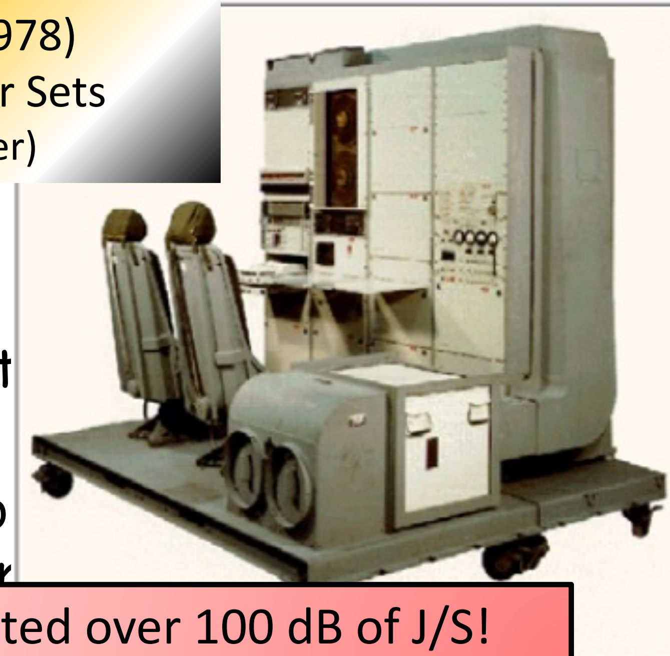
- **Augment or substitute PNT sources**
  - Densify and Diversify satellites - Signals/constellations
    - Worldwide Integrity Monitoring
  - Use Complementary PNT Sources - e.g. DME, eLoran, LEOs

Focus on Main "Toughening" Techniques

- **Category 1: Signal Processing**
  - Tracking mode
  - Narrow Filtering
  - Vector Processing
- **Category 2: Inertial + Very Stable User Clocks**
  - MEMS – up to hi-grade IMU
  - Quartz to CSAC clocks 9in user receivers
- **Category 3: Controlled Reception Pattern Antennas** (CRPAs)
  - Elements/Footprint – (4, 7, Many)
  - Beam/Null steering or combinations
- **Category 4: Satellite Enhancements – may require Receiver Mods**.
  - Additional Signals (L1C, Lm, Galileo)
  - Additional Frequencies (L5, L2, Galileo)
  - Earth Coverage Power Increases
  - Regional Gain: Beam Antennas/RMP

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

Anc...



- Apparent to me in 1973 that signal st... to Jamming was an important issue
- I sponsored and encouraged AFAL to ... A/J receiver with cooperation from r...
- Major Roger Brandt (AF... 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…

Demonstrated over 100 dB of J/S!

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

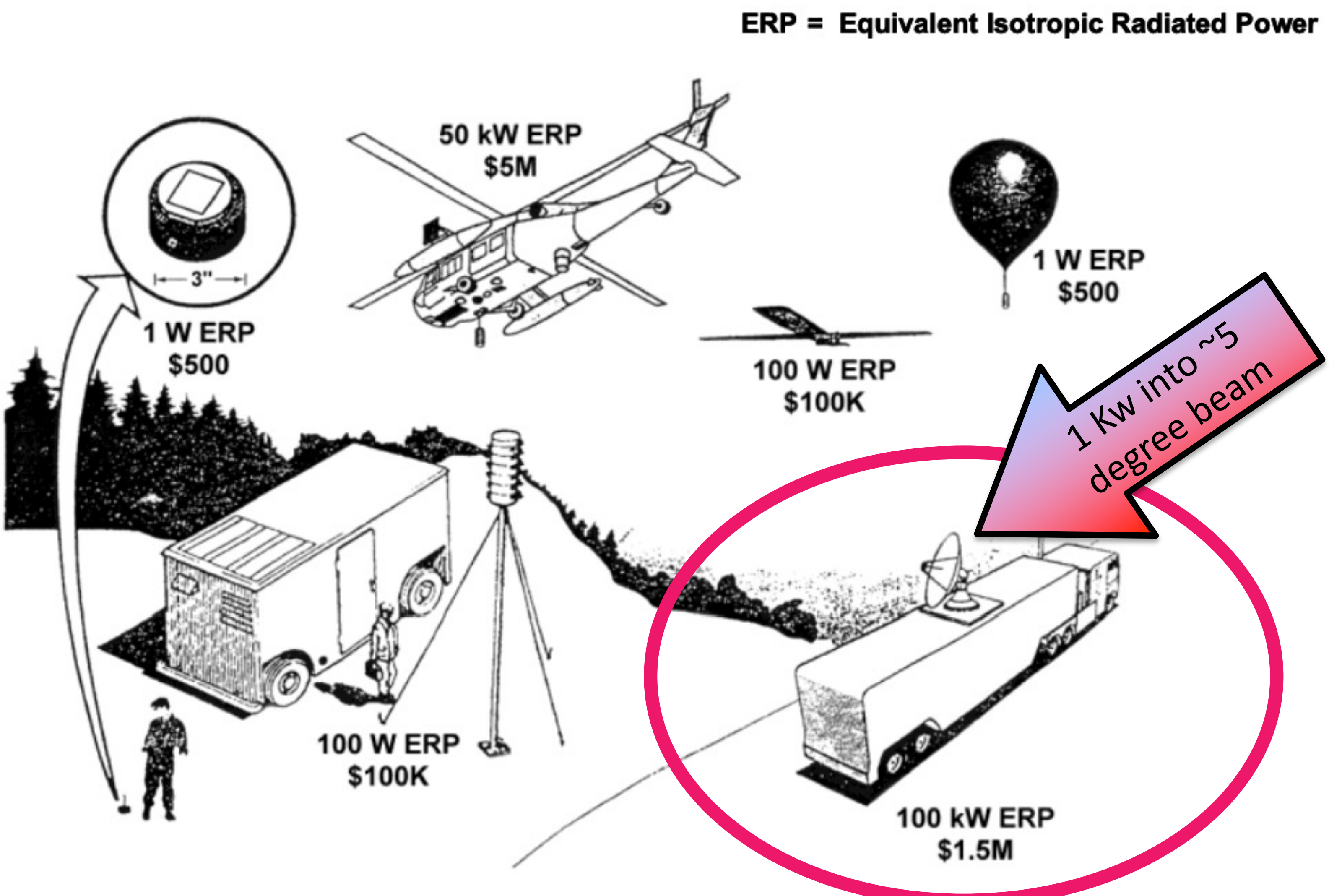
I will use dB as the ***fundamental measure*** of receiver effectiveness in operating in the presence of Jamming – J/S ratio,

assuming a nominal signal Power of -160 dBW

But: I will use that J/S value to calculate the Jamming range of a selected (hypothesized) Jammer with a certain effective radiated RF Power (ERP).

Background: Deliberate Jammer Alternatives

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



Scenario and Score Card

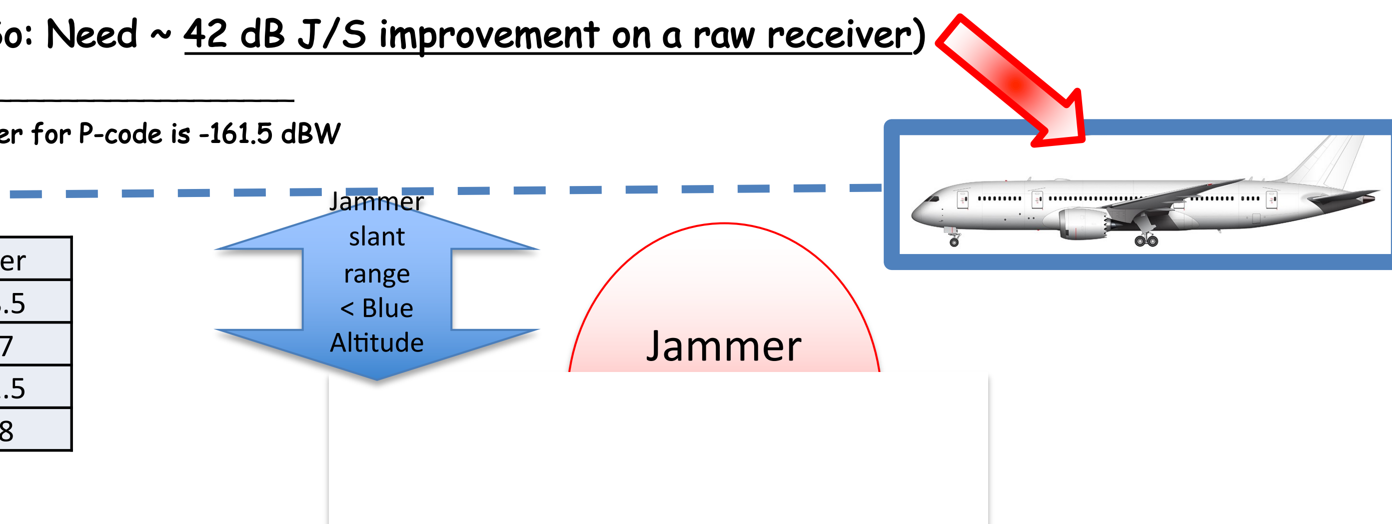
(Illustration only – ***My assumptions do not necessarily*** reflect current capability)

- "Raw Receiver"- nominal signal Track J/S = 58 dB
- Nominal Satellite Earth Coverage power = -160 dBW*
  - Can be boosted with GPS Satellite directional antenna - "Regional GPS Power" for circular area 600 Km radius results in about a 20 dB improvement
- **Consider Commercial Aircraft at 15,000 feet ~ 4.5 Km**
  - **Can "Operate Through" when slant operating range of Jammer is 4.5 Km or less; This is when effective J/S_0 is about ~ 100 dB.**

(So: Need ~ 42 dB J/S improvement on a raw receiver)

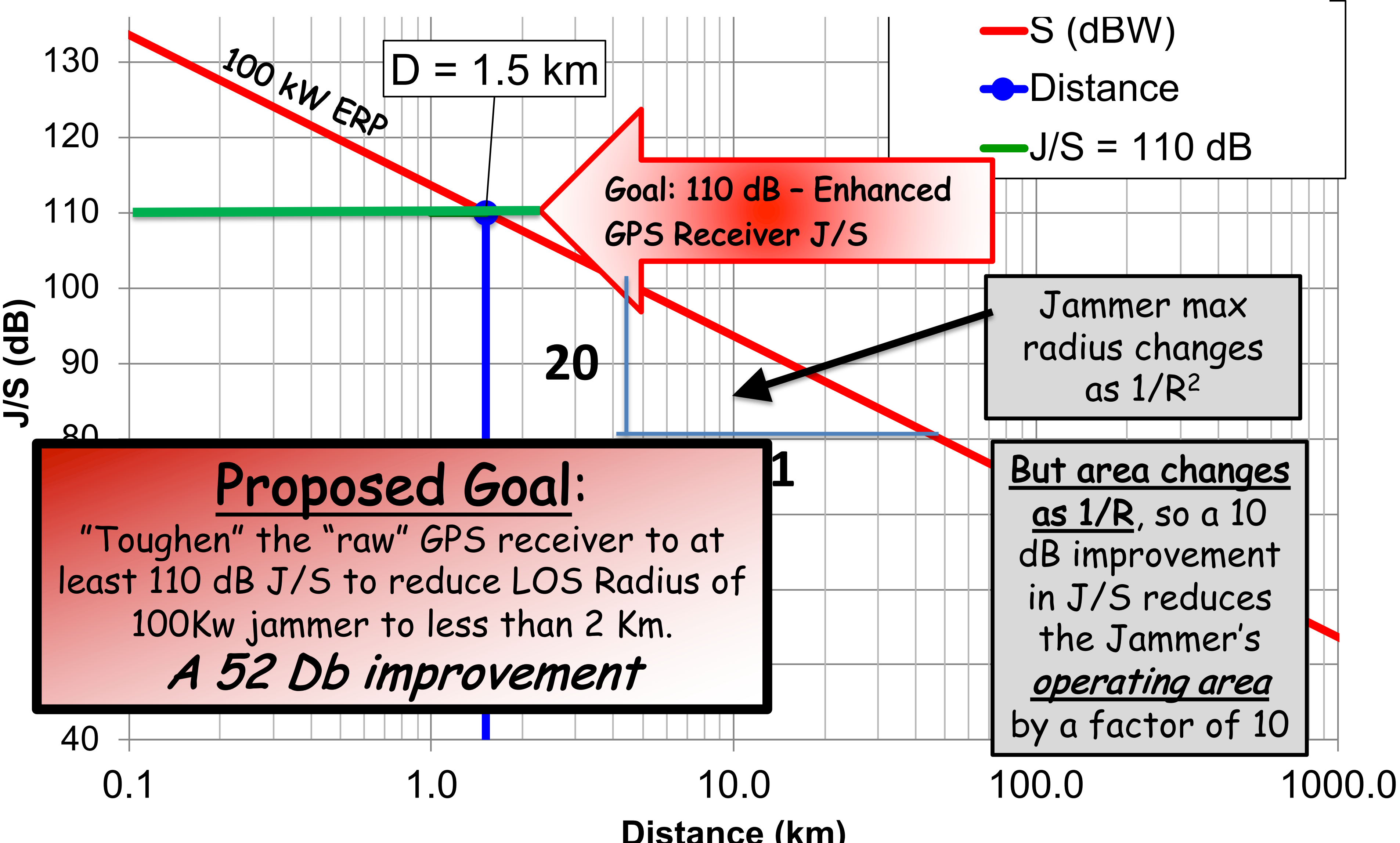
*. Spec power for P-code is -161.5 dBW

Signal	Power
l1 C/A	-158.5
L1C	-157
L2	-161.5
L5	-158



Well known Translation from J/S to Maximum Jammer distance - GPS in Track Mode

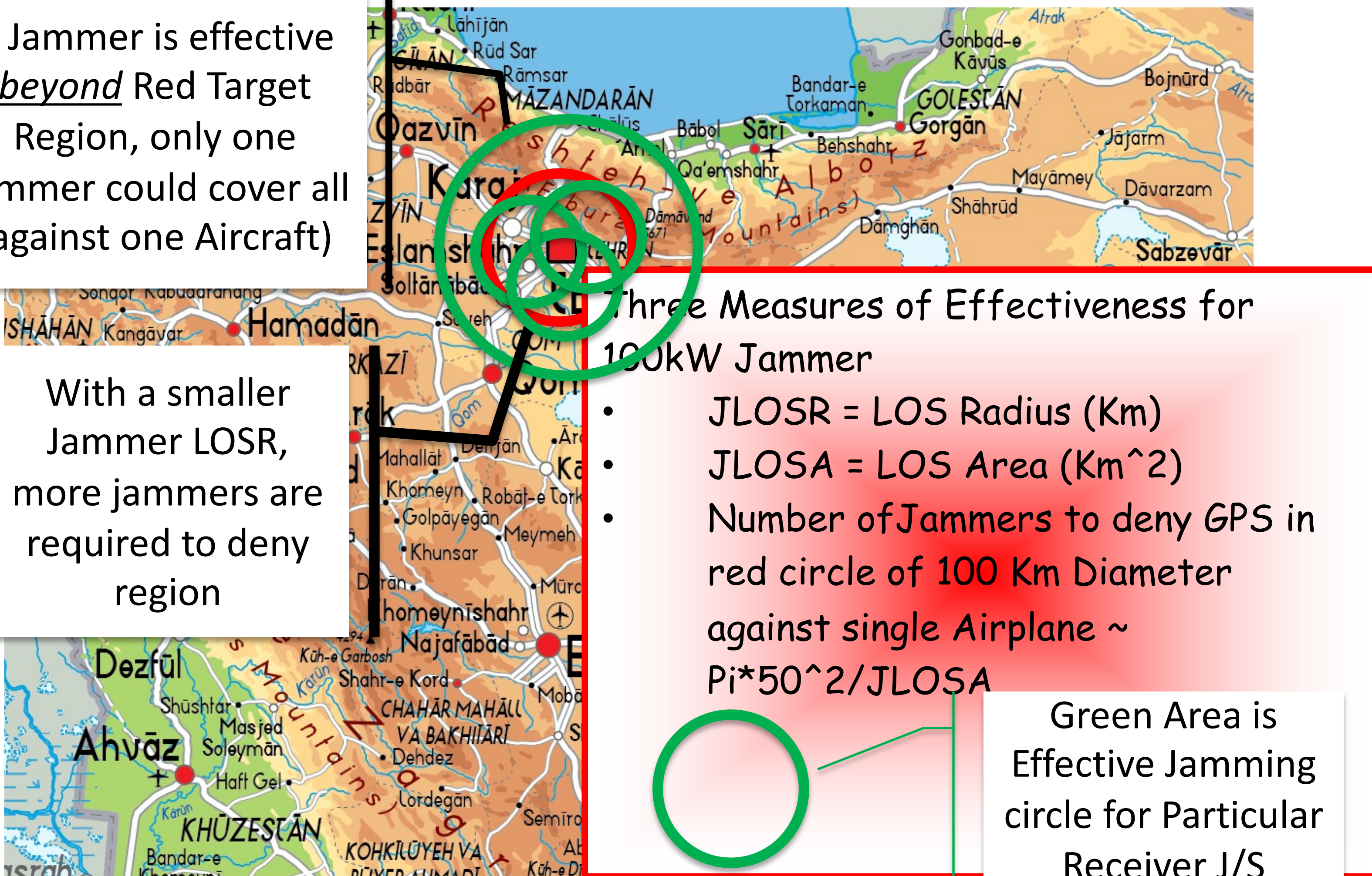
(assumes GPS P-Signal is -160 dBW - L1C and L5 very similar)



Scenario: How many 100 kW Jammers needed to cover area with 100 Km Diameter for various "Nibbles" to improve Aircraft Jamming to Signal (J/S) above nominal 58 dB?

If Jammer is effective *beyond* Red Target Region, only one Jammer could cover all (against one Aircraft)

With a smaller Jammer LOSR, more jammers are required to deny region



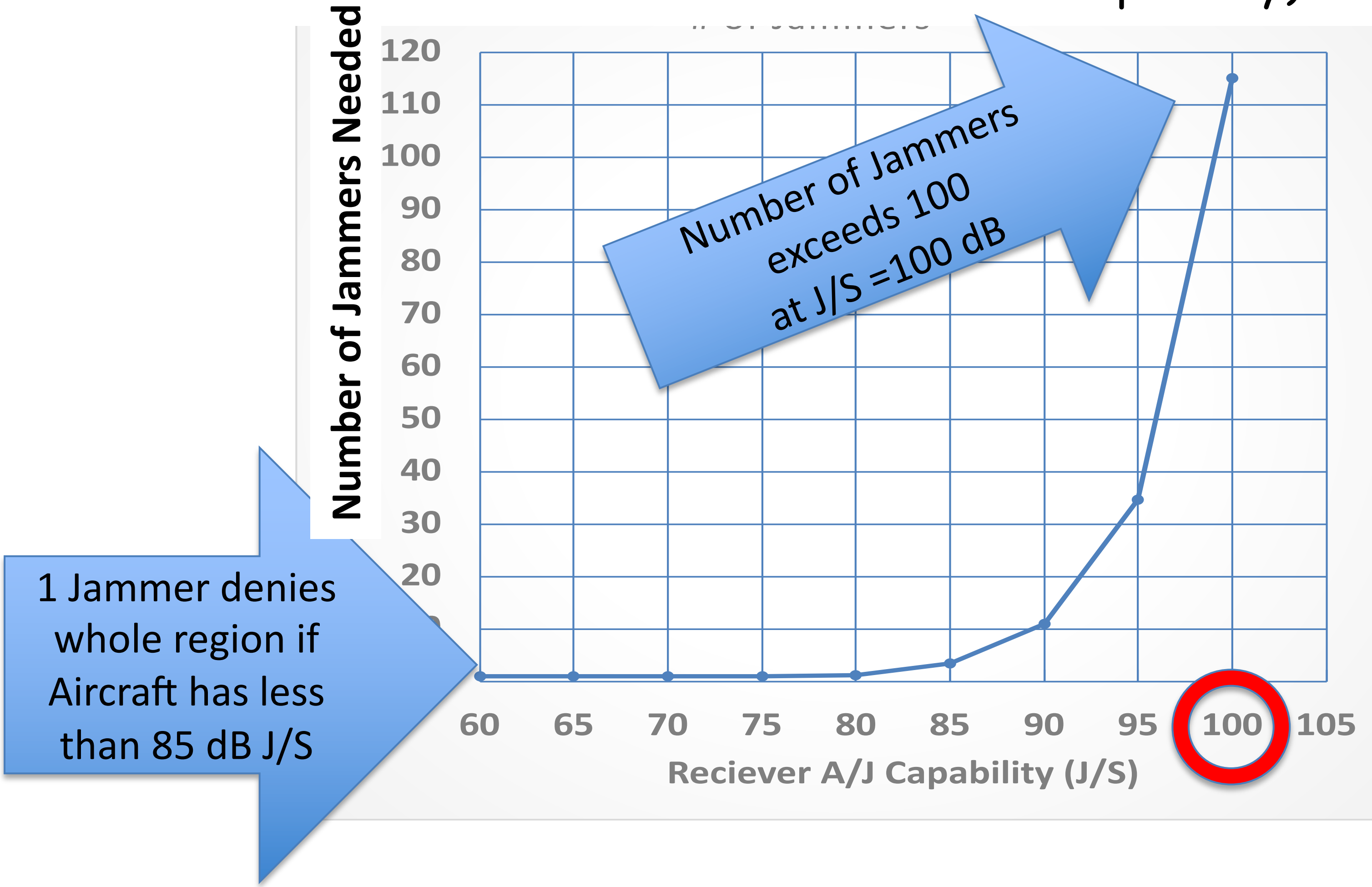
Three Measures of Effectiveness for 100kW Jammer

- JLOSR = LOS Radius (Km)
- JLOSA = LOS Area (Km^2)
- Number of Jammers to deny GPS in red circle of 100 Km Diameter against single Airplane ~ Pi*50^2/JLOSA

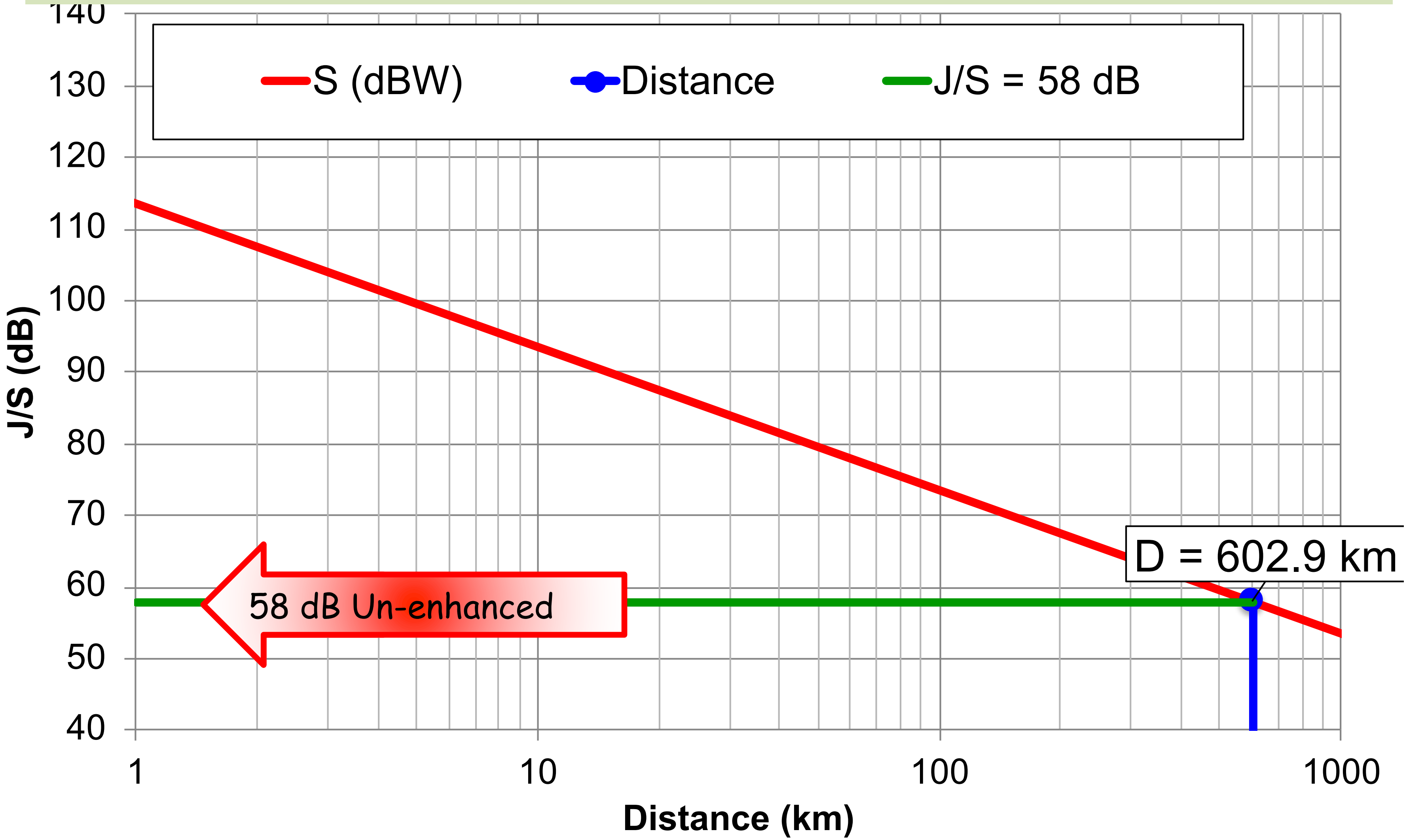
Green Area is Effective Jamming circle for Particular Receiver J/S

Approximate number of 100KW Jammers to deny PNT for 100 Km Diameter Region for an Aircraft at 15,000 feet

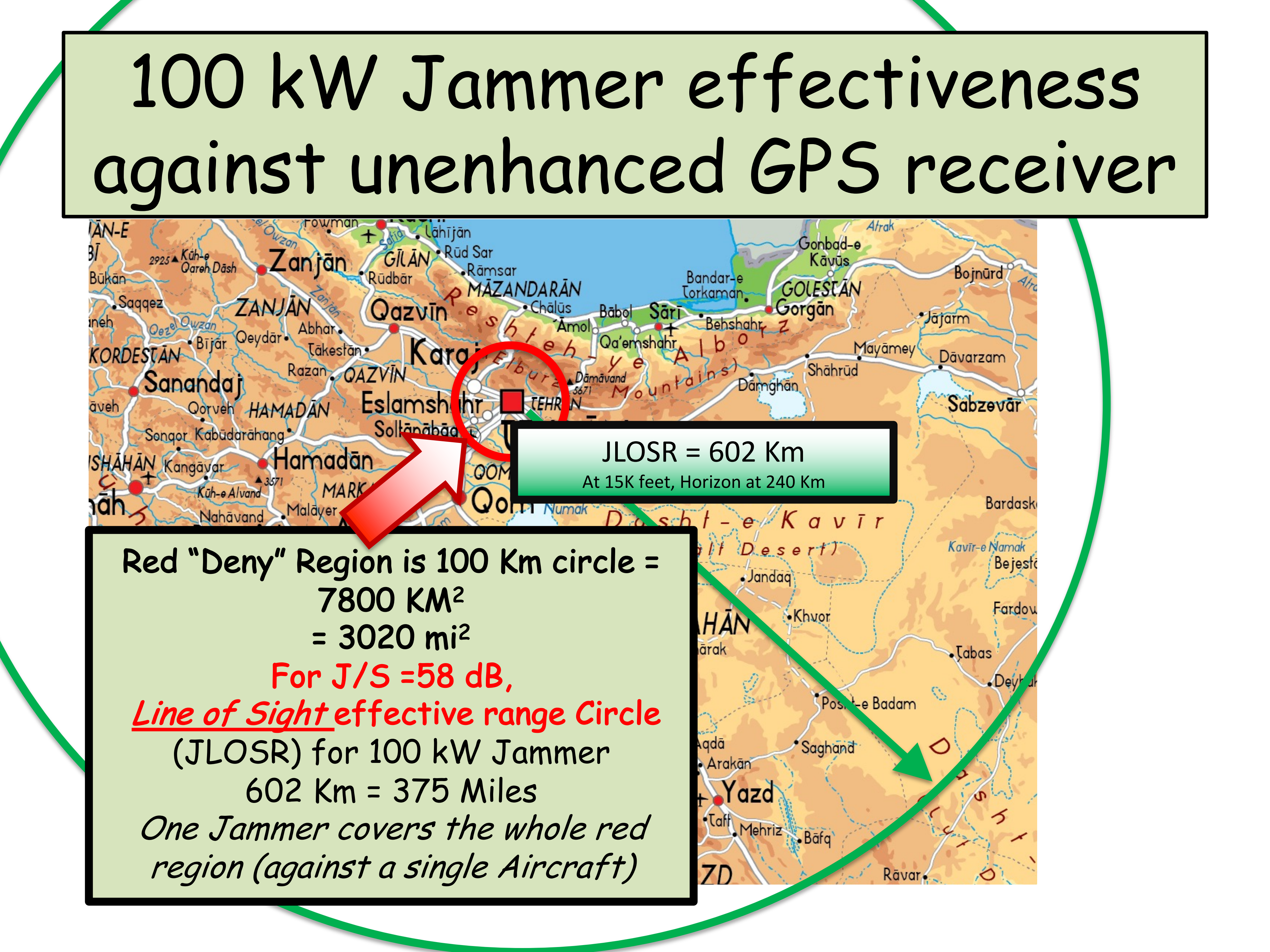
(as a function of Receiver A/J capability)



100 KW Jammer Maximum effective Line of Sight Radius against unenhanced GPS Receiver



100 kW Jammer effectiveness against unenhanced GPS receiver



Red "Deny" Region is 100 Km circle =
7800 KM²
= 3020 mi²
For J/S =58 dB,
***Line of Sight* effective range Circle**
(JLOSR) for 100 kW Jammer
602 Km = 375 Miles
One Jammer covers the whole red region (against a single Aircraft)

Current and Potential "Toughening" - nibbles and upgrades:

Category 1. *Signals and Processing*

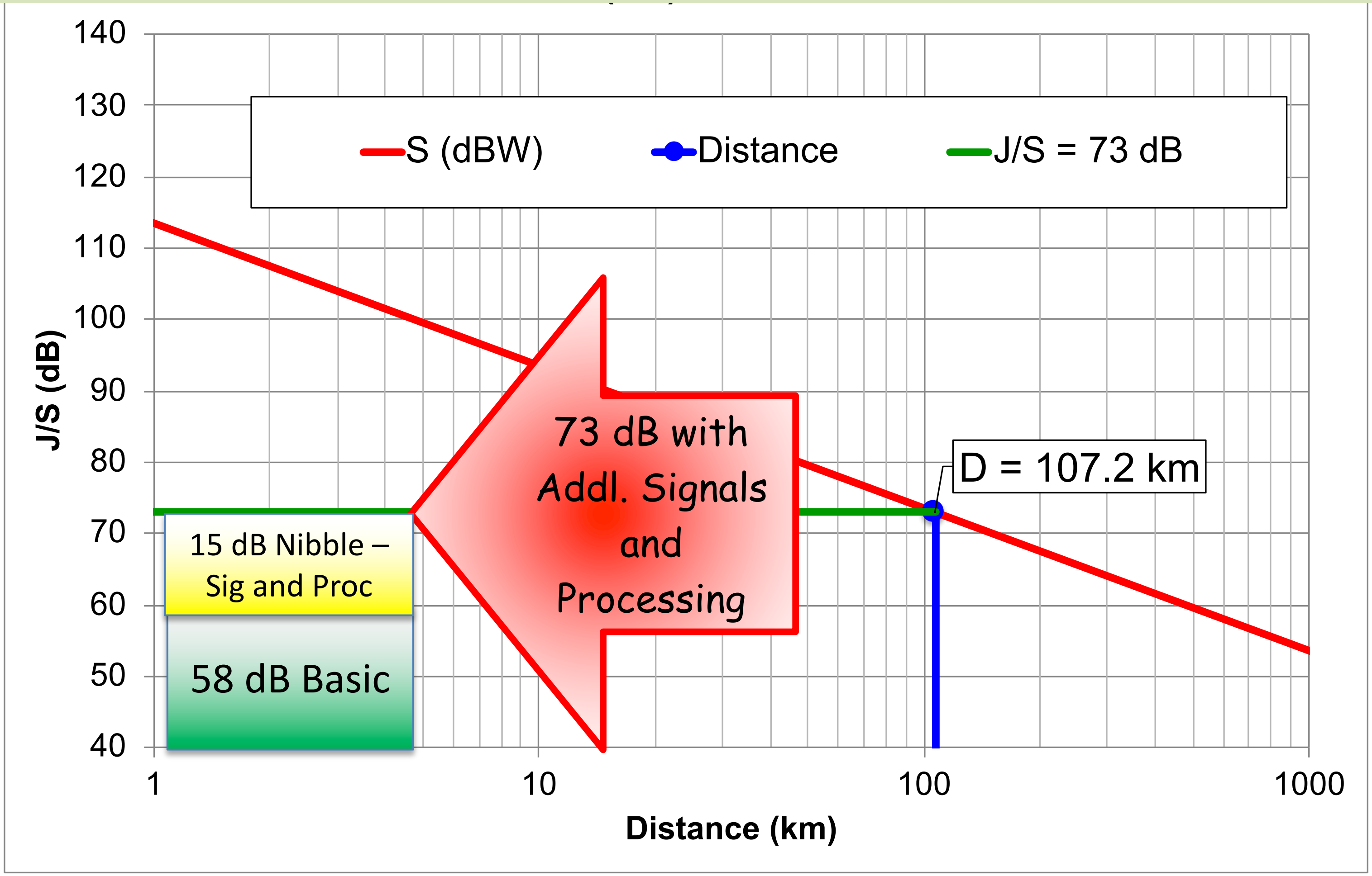
	Technique	Range of improvement			Estimated Time to Field
		Low	High	Example	
Receiver Techniques	Wider Spreading Sig. (e.g. L1C/Lm +L2/L5)	4 dB	7 dB	6 Db	Now to a few Years
	Aircraft Shading	2 dB	4 dB	3 Db	Now
	Vector Receiver	4 dB	7 dB	6 Db	Now to 5 yrs
	Totals – Signals and Processing	10 dB	18 dB	15 dB	Now to 5 years

Takeaway

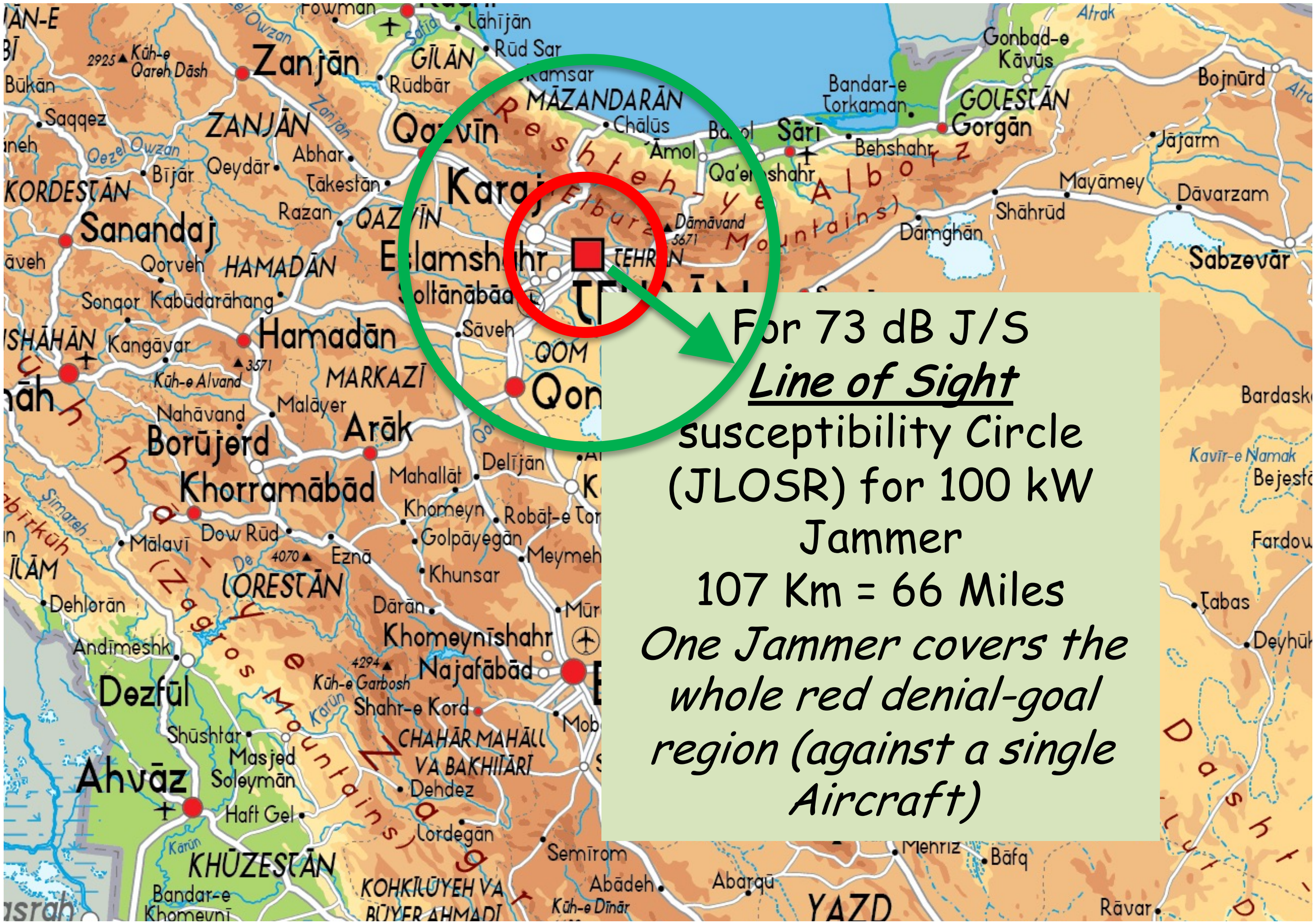
These nibbles can produce a useful 10 to 18 dB of improvements against the Goal of > 52 dB

Example will assume this "nibble" Category is 15 dB

100 KW Jammer Maximum effective Line of Sight Radius against GPS P-code Receiver with Category 1 J/S Enhancements: New Signals & Processing



100 kW Jammer effectiveness against GPS receiver with Signals and Processing Improvements of 15 dB



For 73 dB J/S

Line of Sight

susceptibility Circle (JLOSR) for 100 kW Jammer

107 Km = 66 Miles

One Jammer covers the whole red denial-goal region (against a single Aircraft)

Category 2 *Nibbles: Inertial Synergies –*

Well-Known Benefits

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

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)

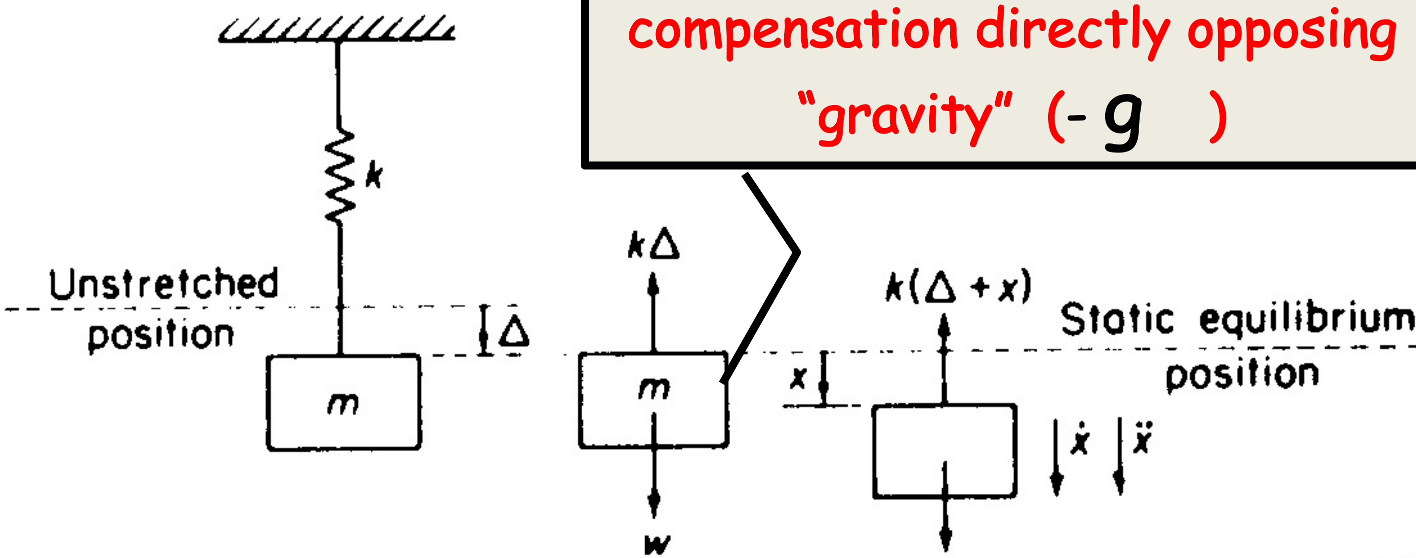
$$\vec{\boldsymbol{P}} = \int\int \vec{\boldsymbol{a}}\ d^2t$$

- 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)



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

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

The user has to know the Initial Position and Velocity

- So we have:

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

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

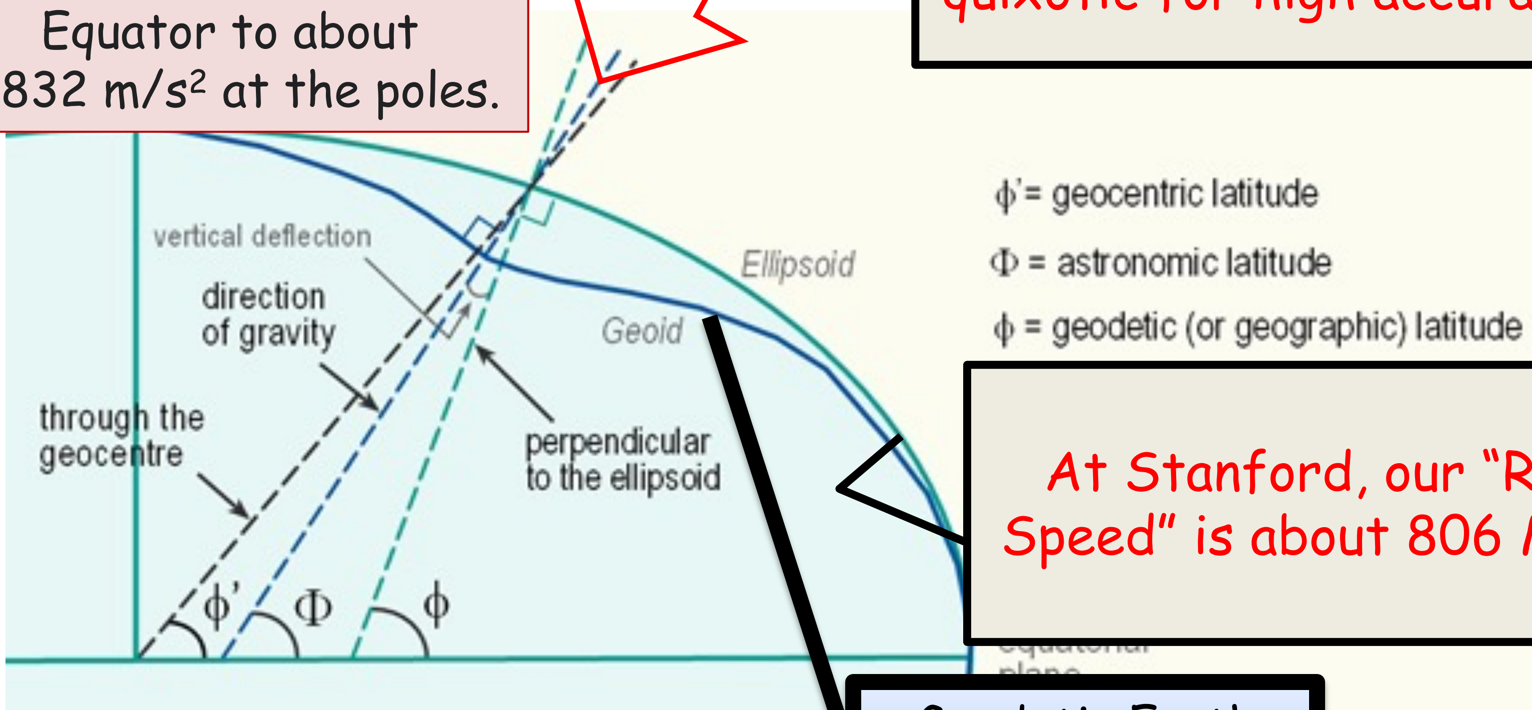
Where does an Inertial Measurement Unit find initial position?

(Hint: Frequently GPS!)

The gravity vector – "Down" is only Local

The force of gravity varies with latitude and increases from about 9.780 m/s^2 at the Equator to about 9.832 m/s^2 at the poles.

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



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

Geodetic Earth Surface

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)

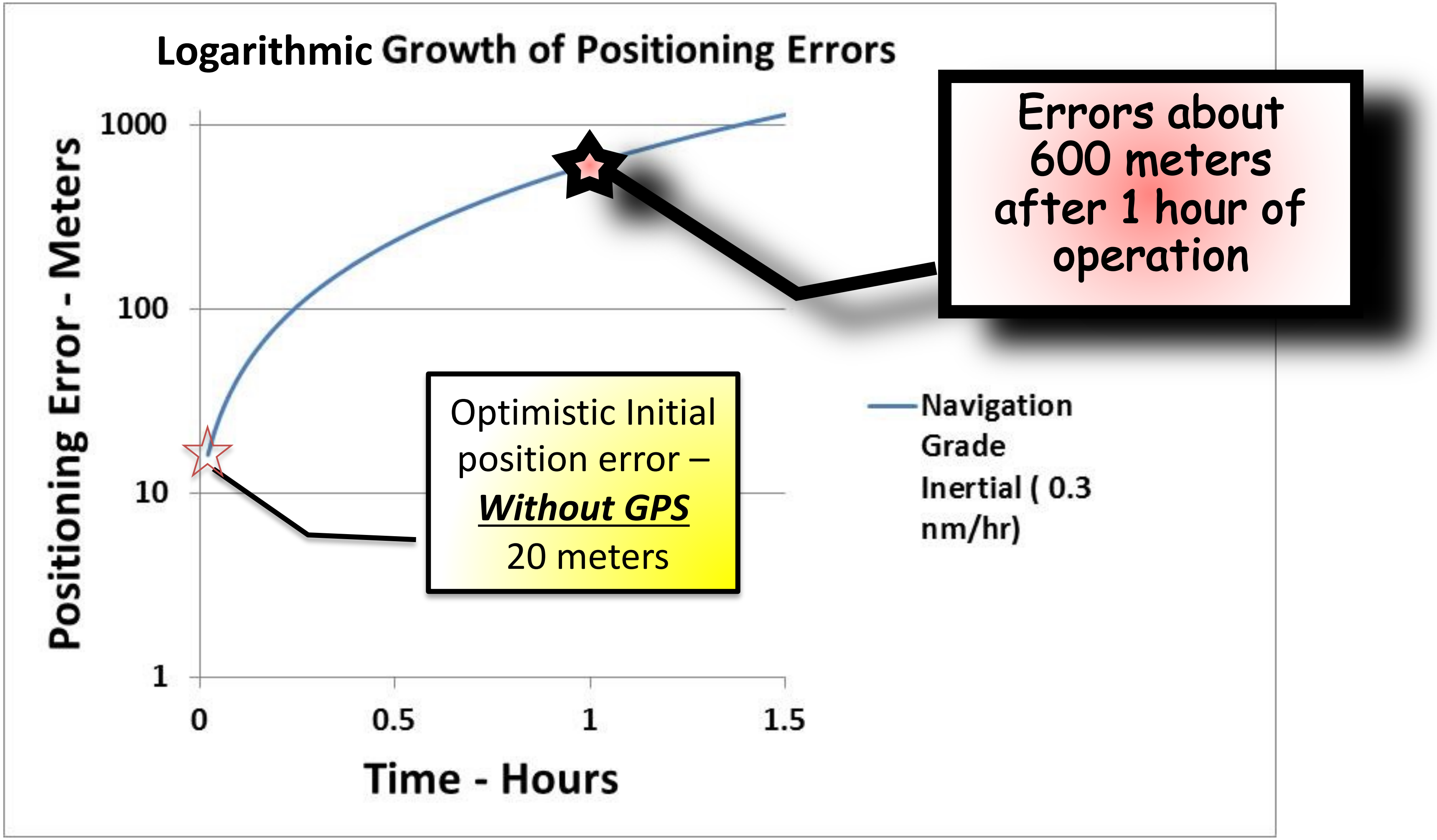
Wrap-up: Even Perfect "Accelerometers" can only be perfect *non-field force* sensors: They sense $\vec{f} = \vec{a} - \vec{g}$ not $\vec{a}$

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

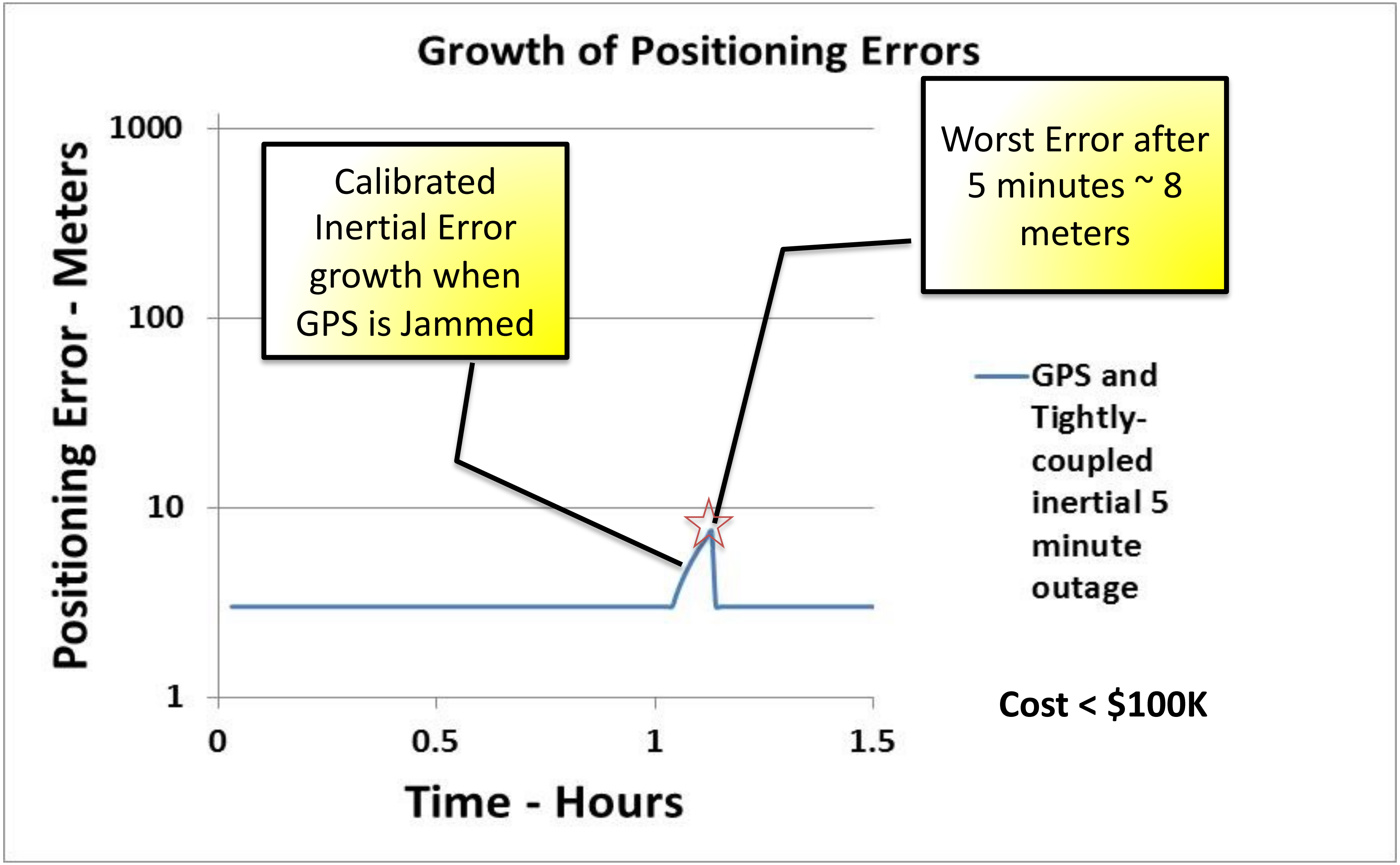
- So PNT system has to accurately know both $\vec{f}$ *and* $\vec{g}$.
- Initial Alignment errors within "local" coordinate frame propagates errors
- Inertials are unstable sensors of *altitude* – i.e. 2 Dimensional only

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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Summary: Current and Potential "Toughening" – nibbles and upgrades –

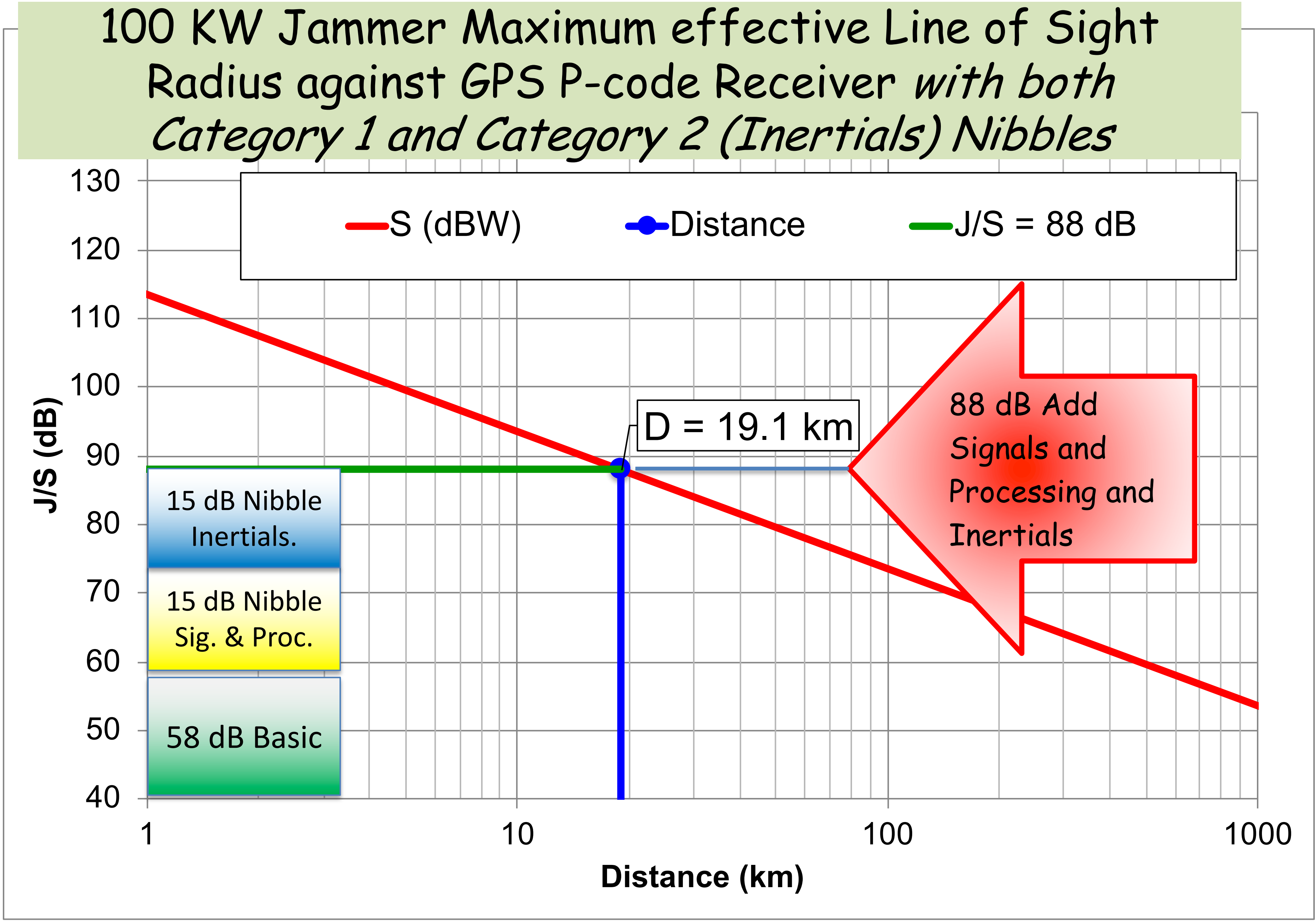
Category 2 *Inertial Synergies*

	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 this could be as high as 20 dB.

Will use 15 dB in our example

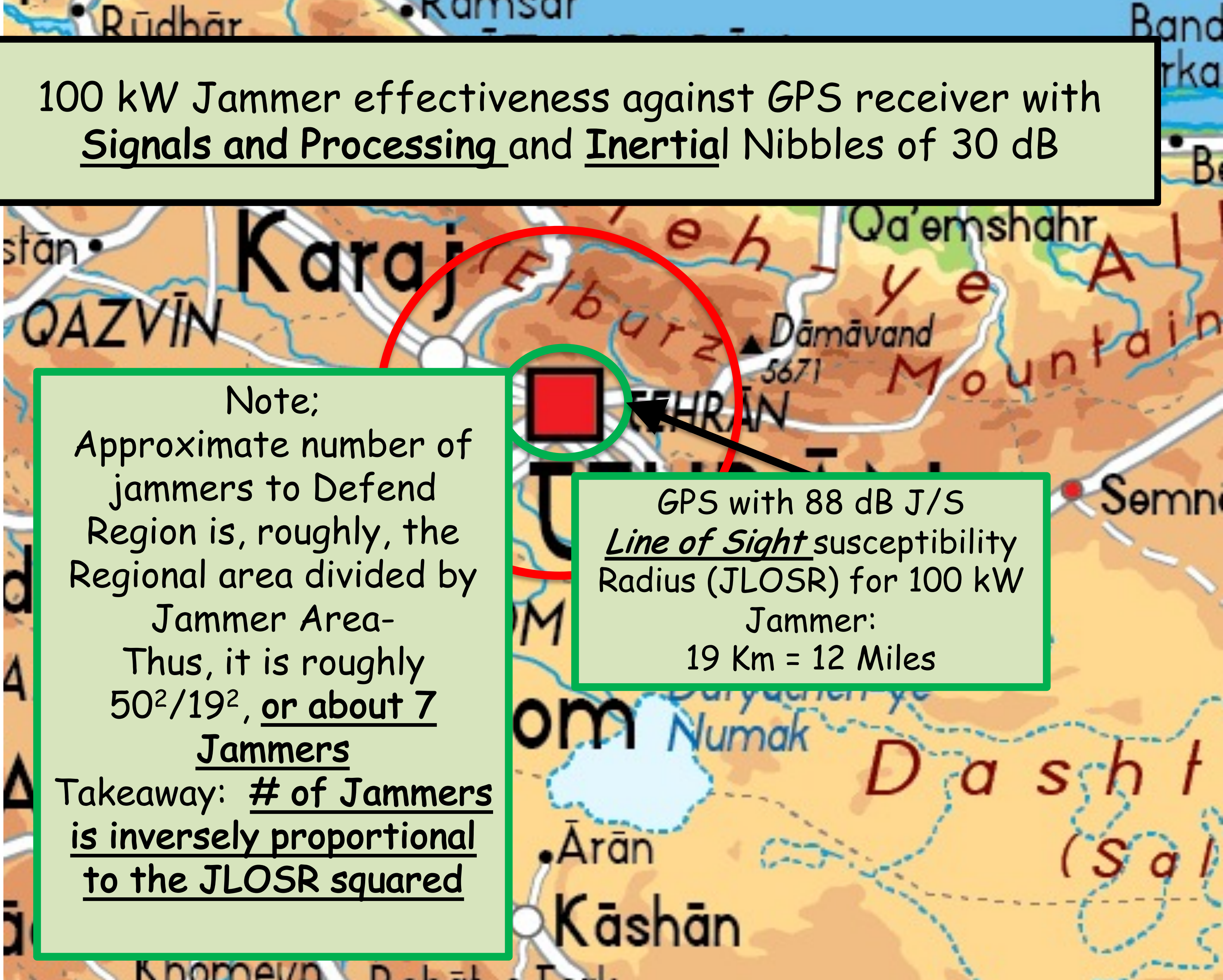

100 KW Jammer Maximum effective Line of Sight Radius against GPS P-code Receiver *with both Category 1 and Category 2 (Inertials) Nibbles*
S (dBW)
Distance
J/S = 88 dB
D = 19.1 km
88 dB Add Signals and Processing and Inertials
15 dB Nibble Inertials.
15 dB Nibble Sig. & Proc.
58 dB Basic
J/S (dB)
130
120
110
100
90
80
70
60
50
40
1
10
100
1000
Distance (km)

100 kW Jammer effectiveness against GPS receiver with <u>Signals and Processing</u> and <u>Inertial</u> Nibbles of 30 dB

Note;
Approximate number of jammers to Defend Region is, roughly, the Regional area divided by Jammer Area-
Thus, it is roughly $50^2/19^2$, **<u>or about 7 Jammers</u>**

Takeaway: **<u># of Jammers is inversely proportional to the JLOSR squared</u>**

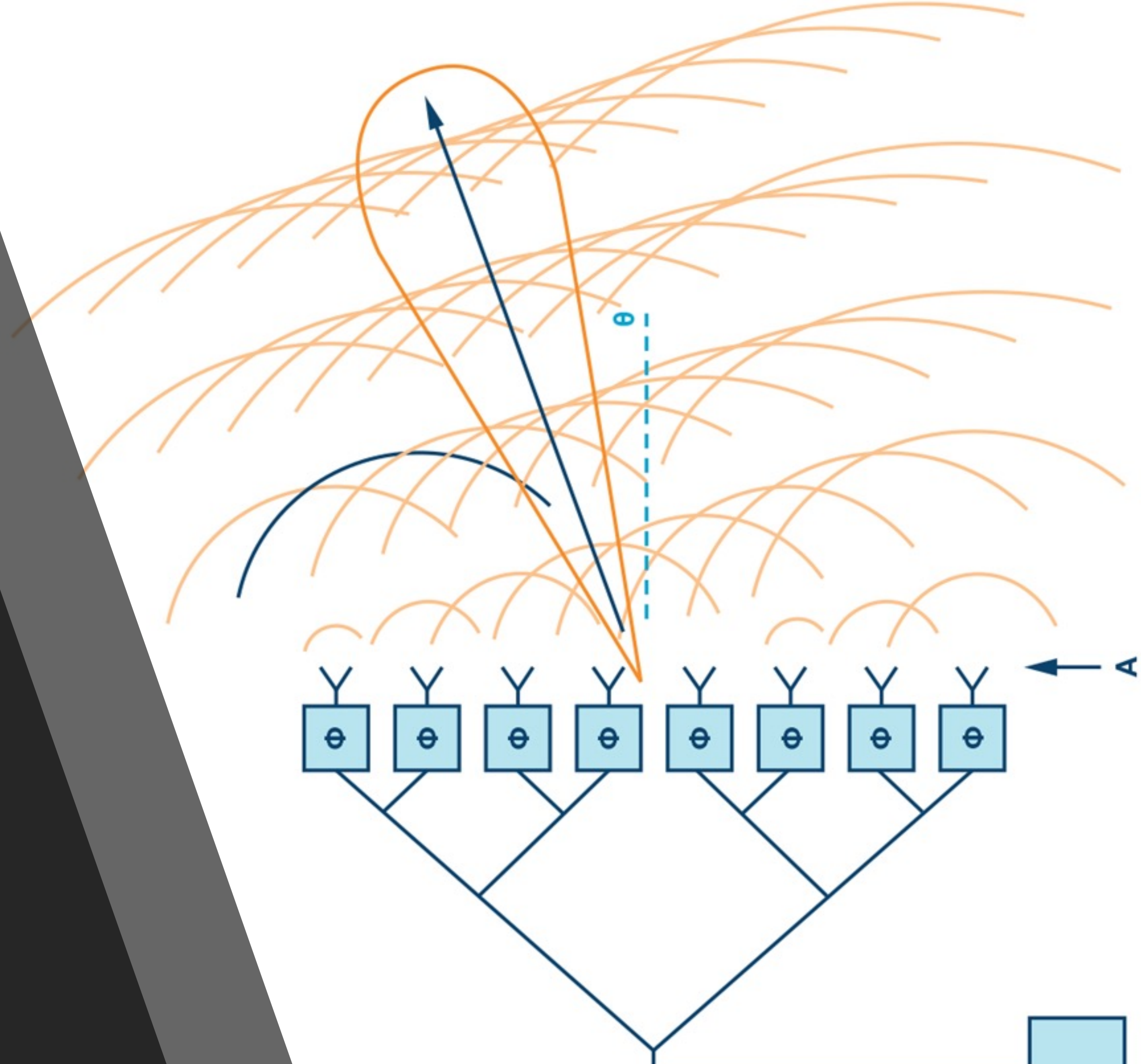
GPS with 88 dB J/S
<u>Line of Sight</u> susceptibility Radius (JLOSR) for 100 kW Jammer:
19 Km = 12 Miles



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
- Military has neglected and delayed deployment of CRPAs
- Cost should greatly decrease with continuing advances in digital electronics, and large-scale use,
  and with equipage when vehicle is manufactured

Basic Concept of Phased Array



Digital Antenna results from Bartone and Stansell public paper

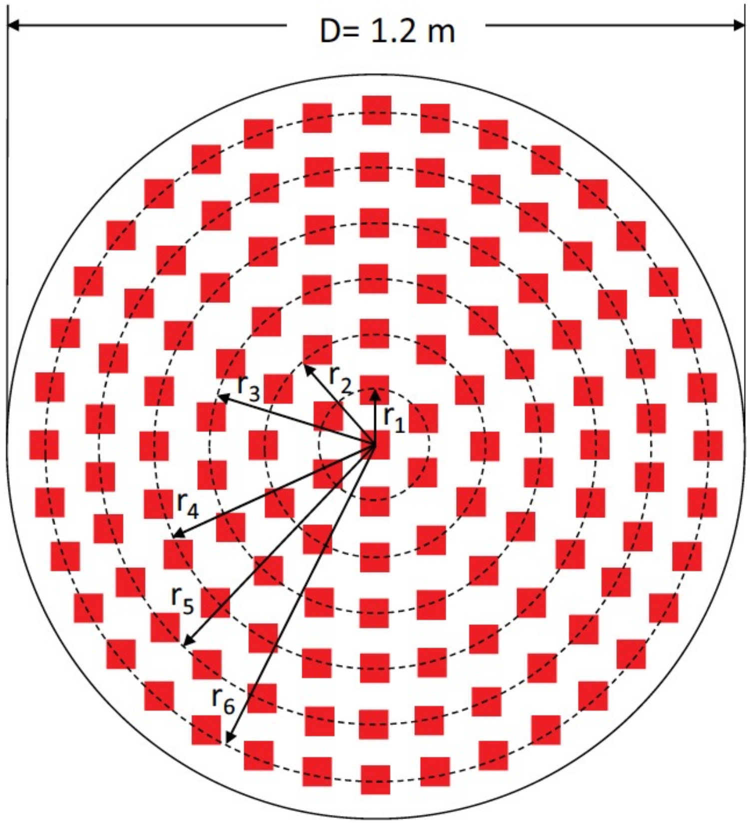


Figure 1: 127-element L=Band CRPA Configuration

- Authors studied many configurations - up to 127 inexpensive antennas
- Analyzed the # versus performance tradeoff
- Most large vehicles should have an available footprint and power for assured PNT
- When pursued, the efficiencies of large scale production should help reduce cost
- *Currently prohibited by ITAR for greater than 4 elements for civil use*

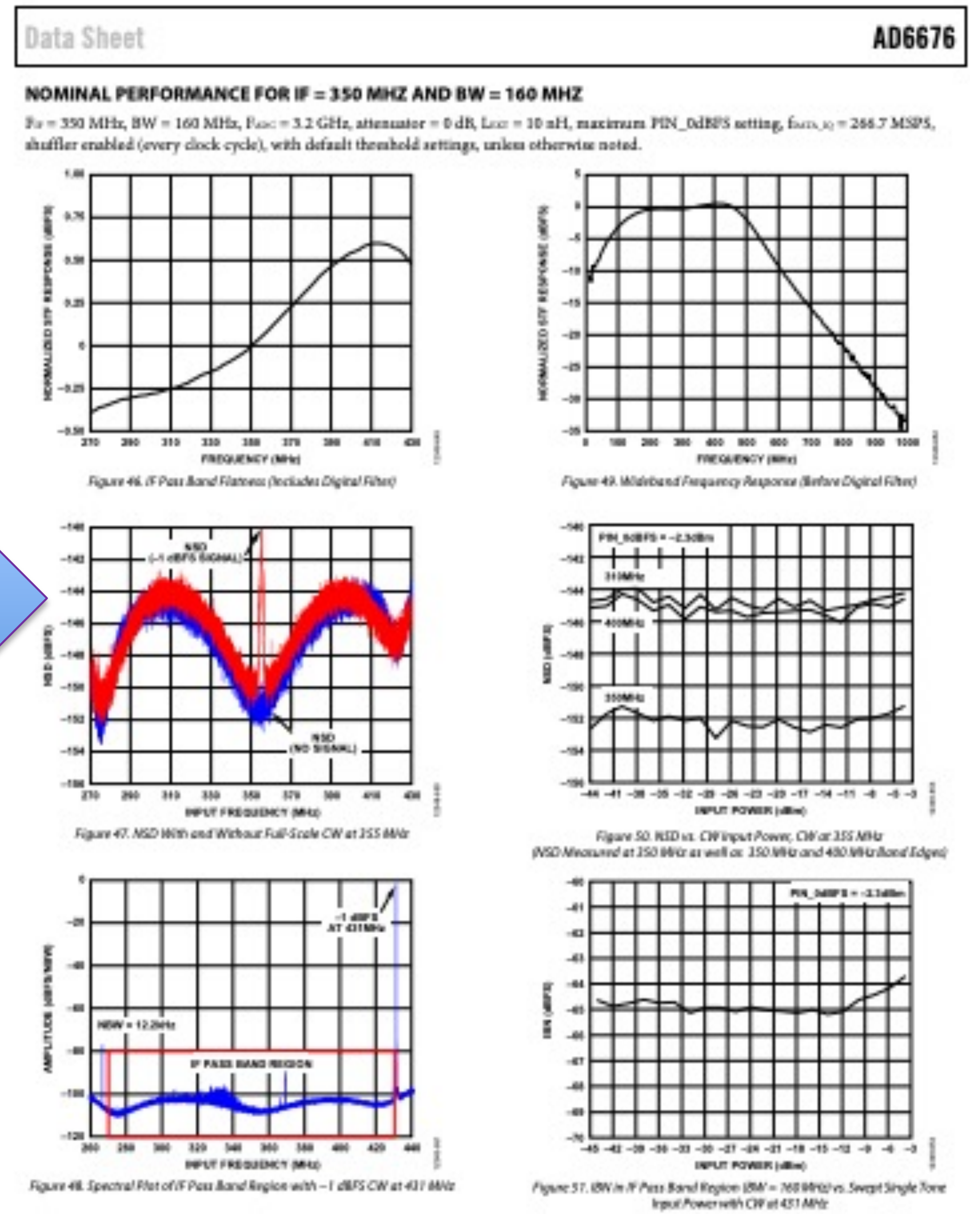
CRPA Configurations with Approximate Dimensions

		Number of Elements in Each Ring								r_i base on 1_L1/2 [m]	Mounting Ring Allocation [m]	Diameter (D)	
Rings	CE	1	2	3	4	5	6	Total # Elements	Directivity, max [dB]			D [m]	D [in]
0	1							1	2.0	0.000	0.095	0.10	3.75
1	1	6						7	[illegible]	0.095	0.170	0.36	[illegible]
2	1	6	12					19	19.0	0.190	0.170	0.55	21.69
3	1	6	12	18				37	21.9	0.286	0.170	0.74	29.18
4	1	6	12	18	24			61	24.0	0.381	0.170	0.93	36.68
5	1	6	12	18	24	30		91	[illegible]	0.476	0.170	1.12	[illegible]
6	1	6	12	18	24	30	37	128	27.3	0.571	0.170	1.31	51.68

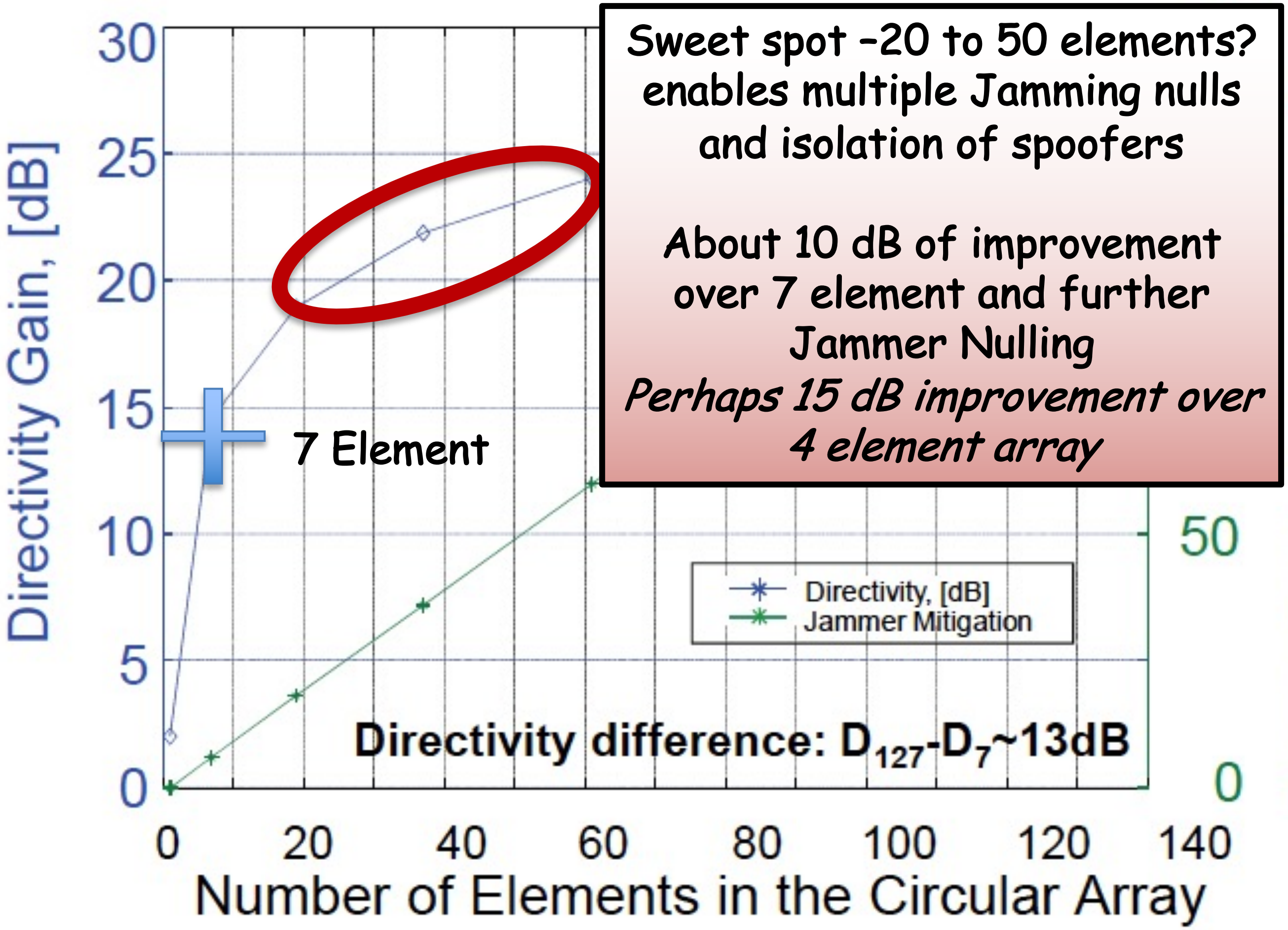
Feasibility:

"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



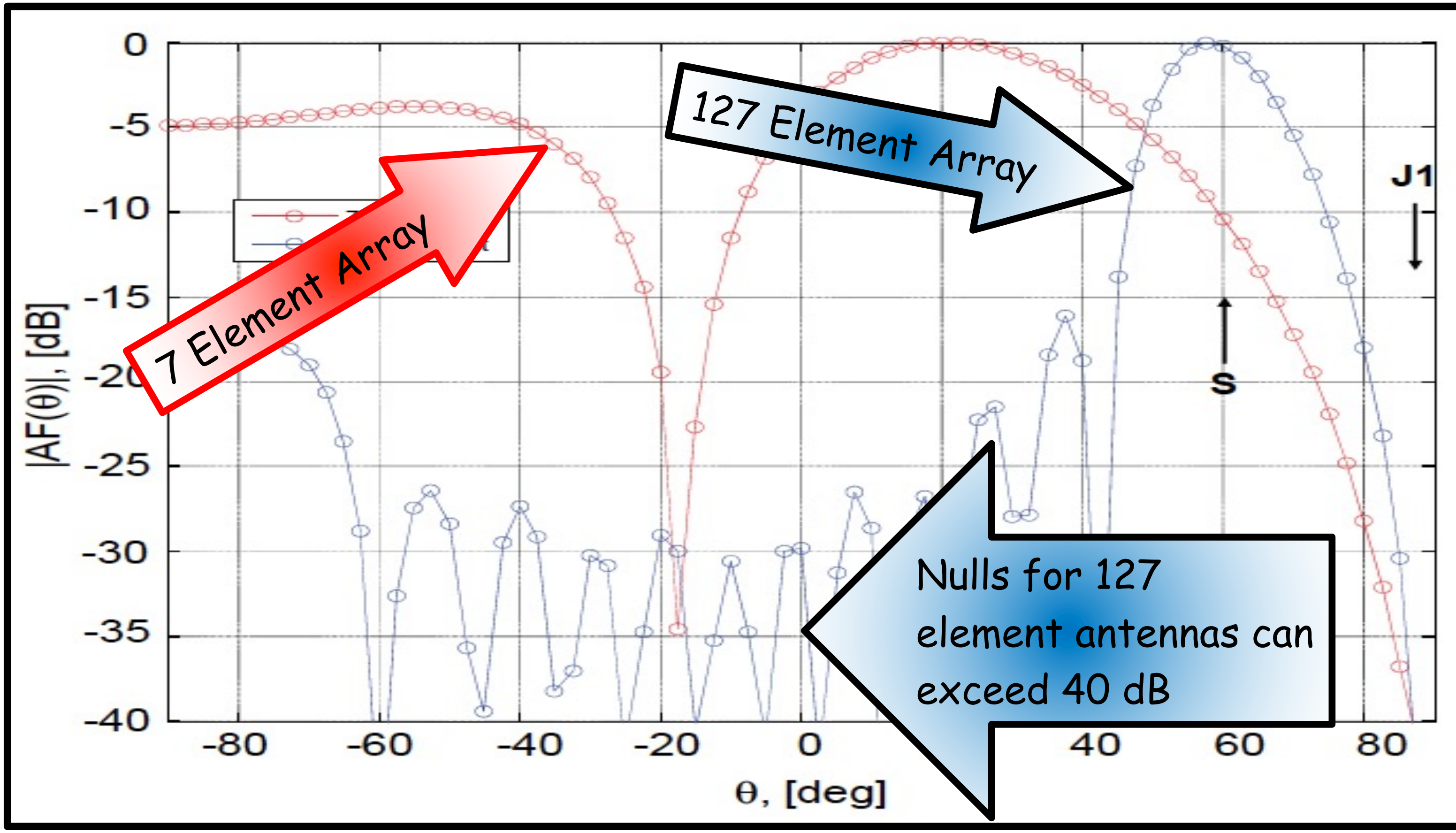
Price: about $150 each



Additional Digital Elements Have high payoff and have become relatively cheap

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

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



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

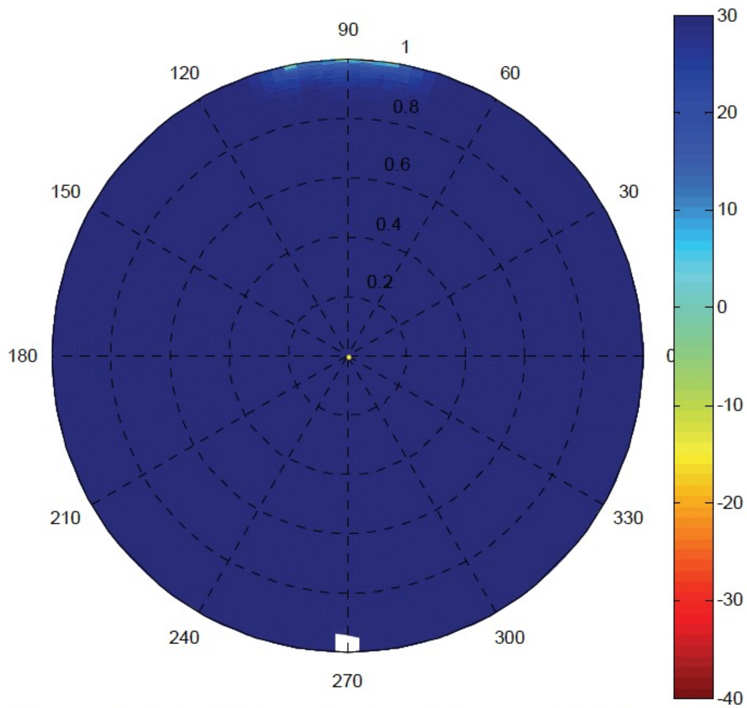


Figure 12: SINR Values for the 127-element CRPA with 5 Interference/Jammer Sources

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

Current and Potential "Toughening" – nibbles and upgrades –

Category 3 *Digital Beam Forming and Null steering*

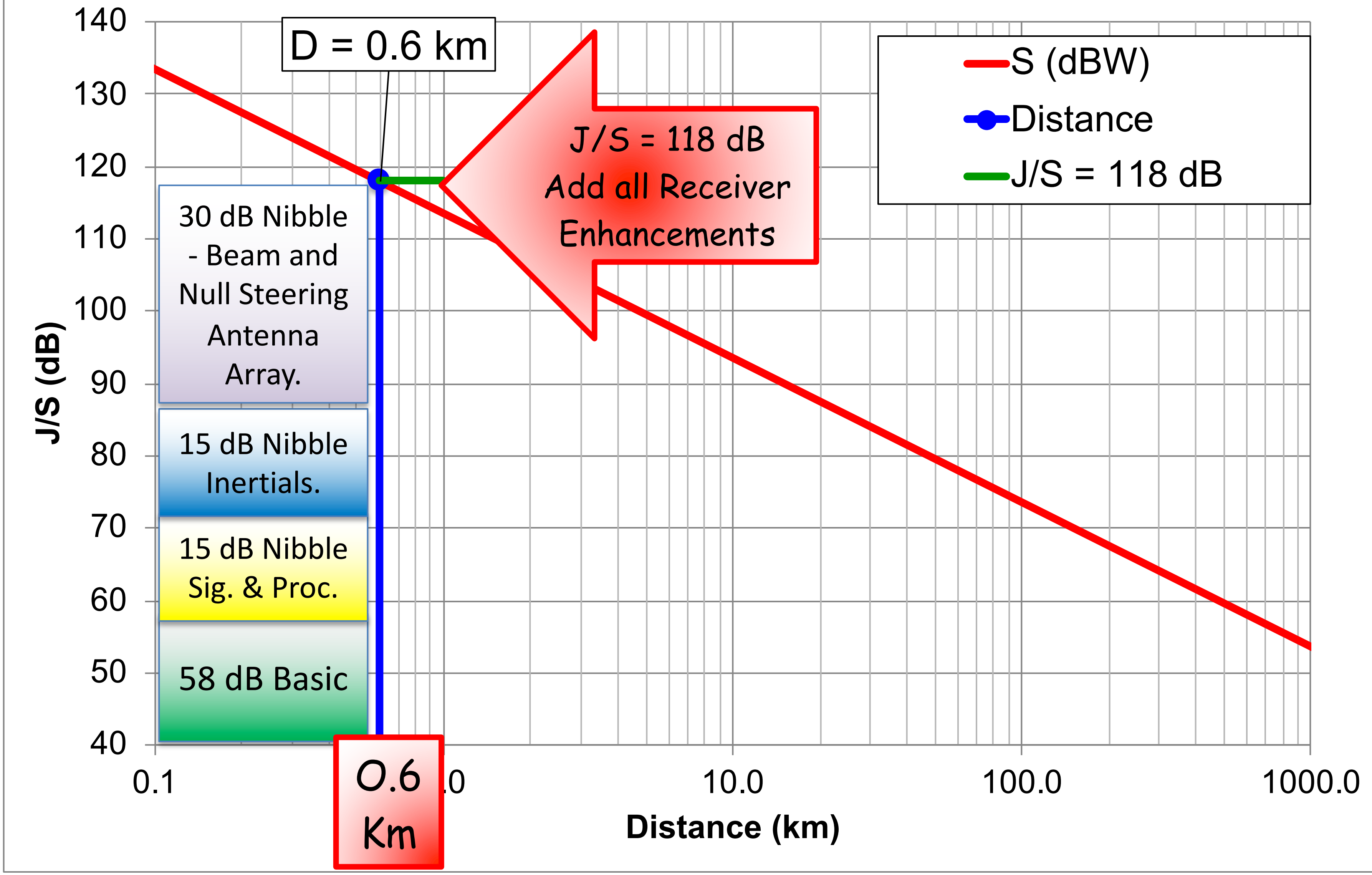
	Technique	Range of improvement			Estimated Time to Field
		Low	High	Example	
	Digital Beam Forming and Nulling Antenna	20 dB	45 dB	30 dB	Now to 5 Yrs

Takeaways:

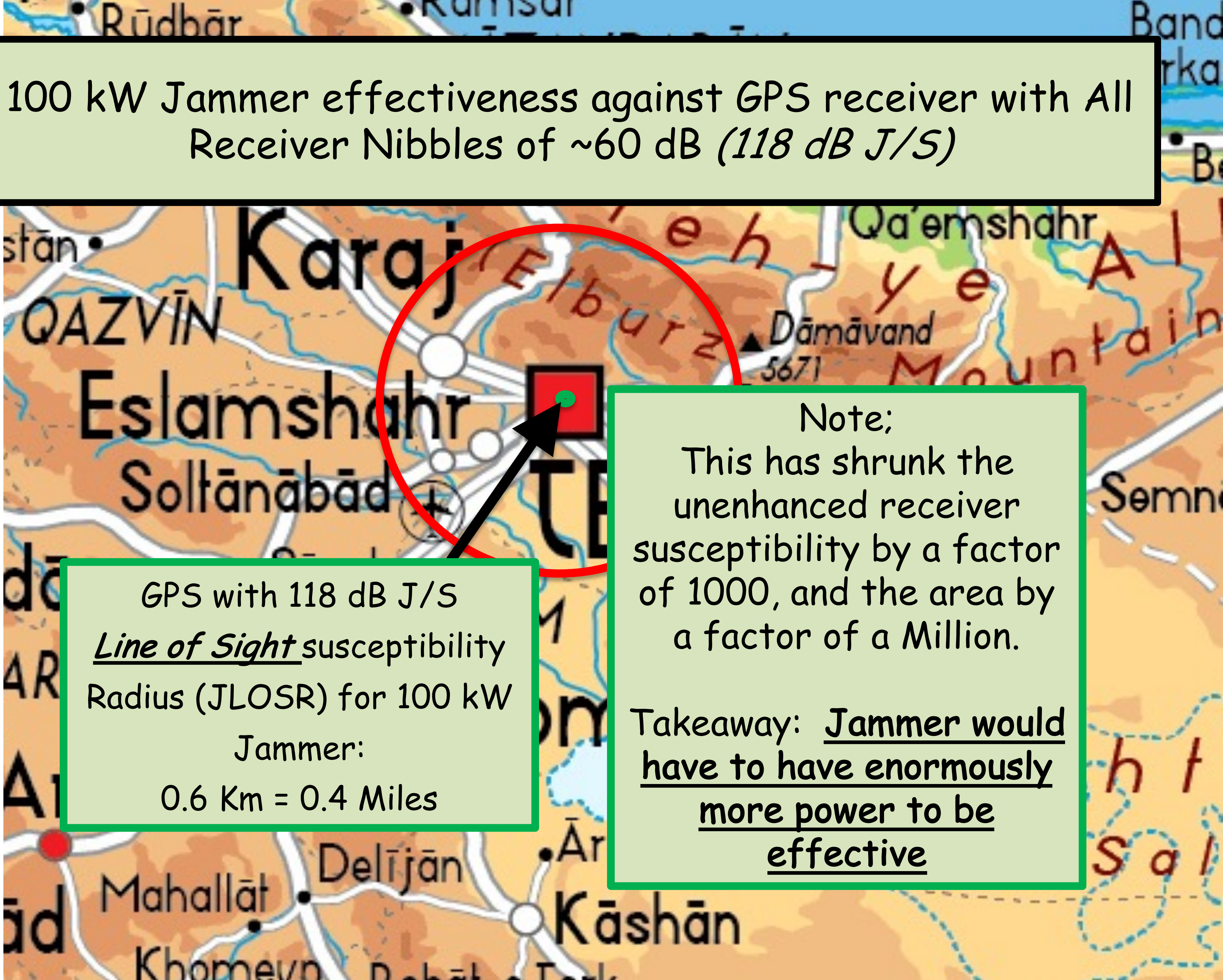
- At least 30 dB of improved J/S_0 has been verified with hardware
- For good results, need about a 1-meter diameter Footprint
- Payoff exceeds penalty of finding space for certain users
- Also should enable enhanced situational awareness re: Jammers
- **At a median 30 dB improvement,**

  this "nibble" alone can drive # of 100 kW Jammers to 7

Combining Example: Receiver-side Nibbles



100 kW Jammer effectiveness against GPS receiver with All Receiver Nibbles of ~60 dB *(118 dB J/S)*



GPS with 118 dB J/S
__Line of Sight__ susceptibility Radius (JLOSR) for 100 kW Jammer:
0.6 Km = 0.4 Miles

Note;
This has shrunk the unenhanced receiver susceptibility by a factor of 1000, and the area by a factor of a Million.

Takeaway: **__Jammer would have to have enormously more power to be effective__**

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

Improvement Group	Median Improvement
Signals and Processing	15 dB
Tightly coupled Inertial	15 dB
Digital Null and Beam Steering Antenna	30 dB
Total Receiver Enhancements	60 dB

Nominal Improvements results in 58+60, or:

J/S = 118

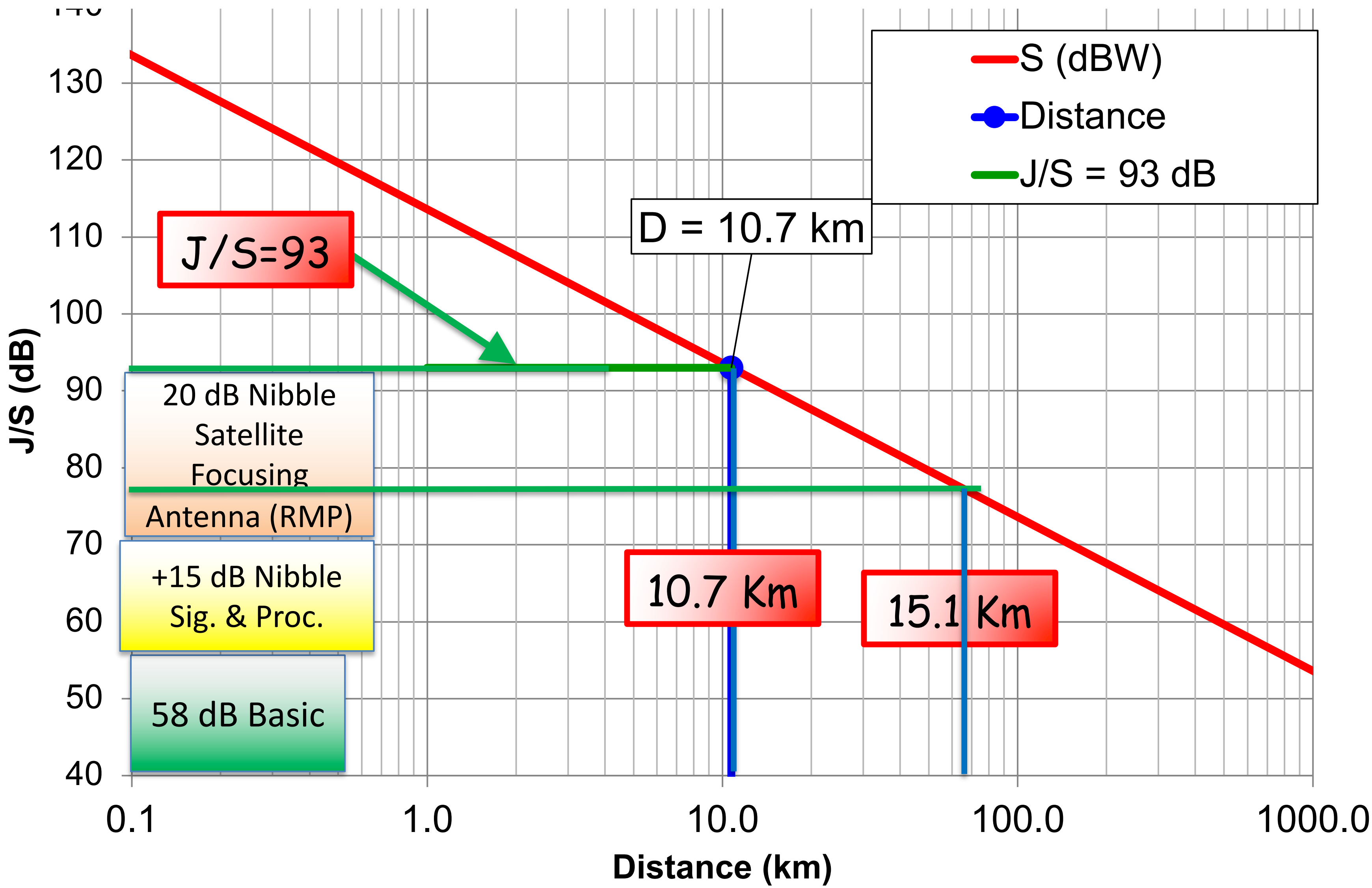
- A total of 60 dB improvement results in 118 dB of J/S
- **This has been roughly verified with real hardware**
- **All of these Nibbles should be achievable in available users sets within 5 years**
- Impact on defeating ***100KW jammer***:
  - Slant Range 0.6 Km (A/C Alt = 3 Km)
  - Area of Ground Jamming 1.14 square Km
  - To completely cover 100 Km diam. ground region would require:
    ~ 6900 Jammers of 100kW power

Category 4: Satellite signal power enhancement with focused antennas

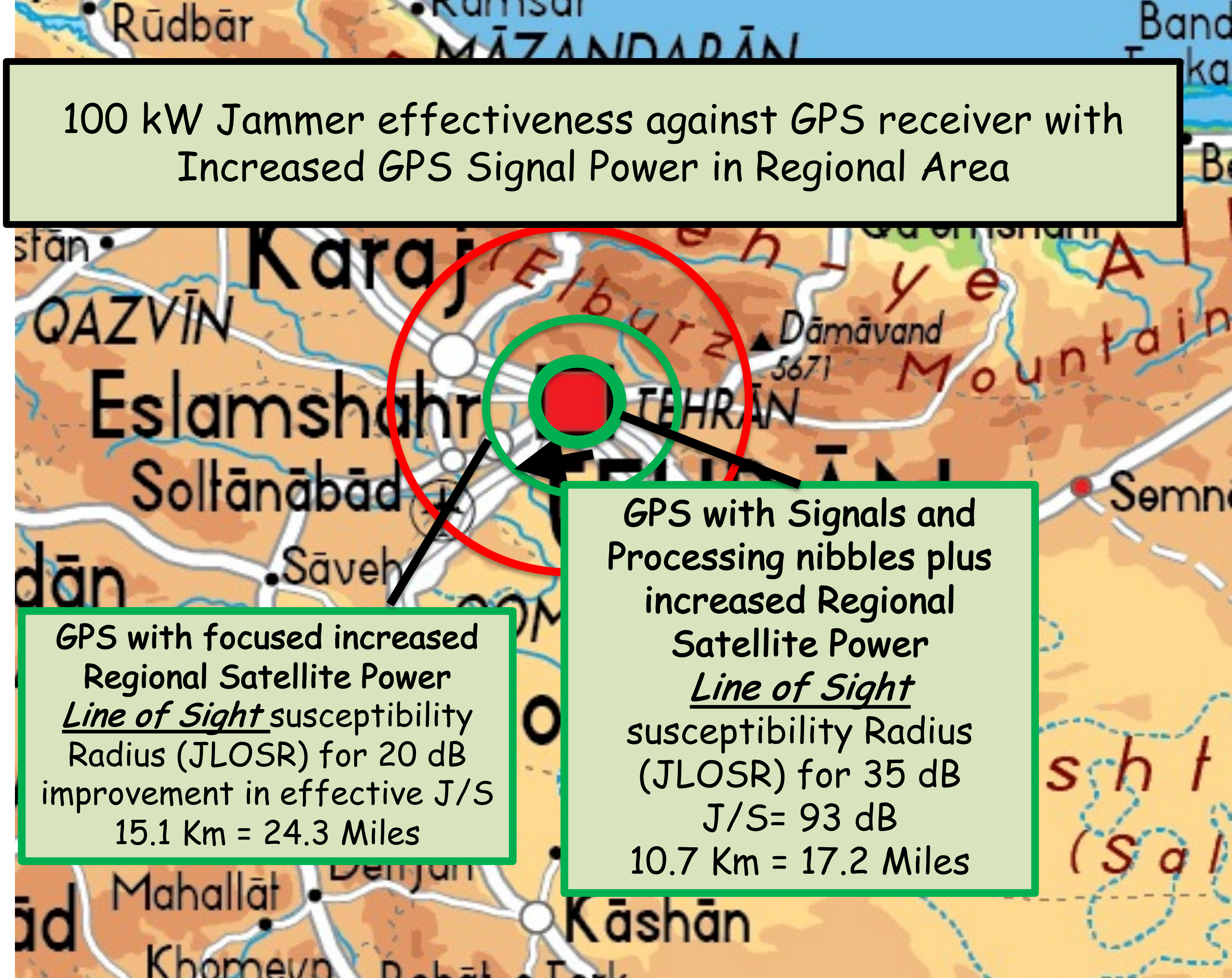
- **Concept:** Focus Military signal on a designated Earth Region – use beam steering to maintain at least 4 satellites in area
  - Called RMP – Regional Military Power. Currently planned for next block of GPS III Satellites
  - Here we will assume a 600 Km radius circle.
- Power enhancement would be about 20 dB
- With all receiver Nibbles except CRPA, RMP s would yield about 50 dB
- Current Plan is to complete 22 launches by 2034. Assume operational in 2035/6.
- Against this "nibble" alone, the 100 kW jammer would have an effective radius of 28.7 KM.

Satellite Nibble: Regionally focused Antenna (RMP)

(Without Cat 2 – Inertial and Cat 3 Receiver Beam-forming antenna)



100 kW Jammer effectiveness against GPS receiver with Increased GPS Signal Power in Regional Area



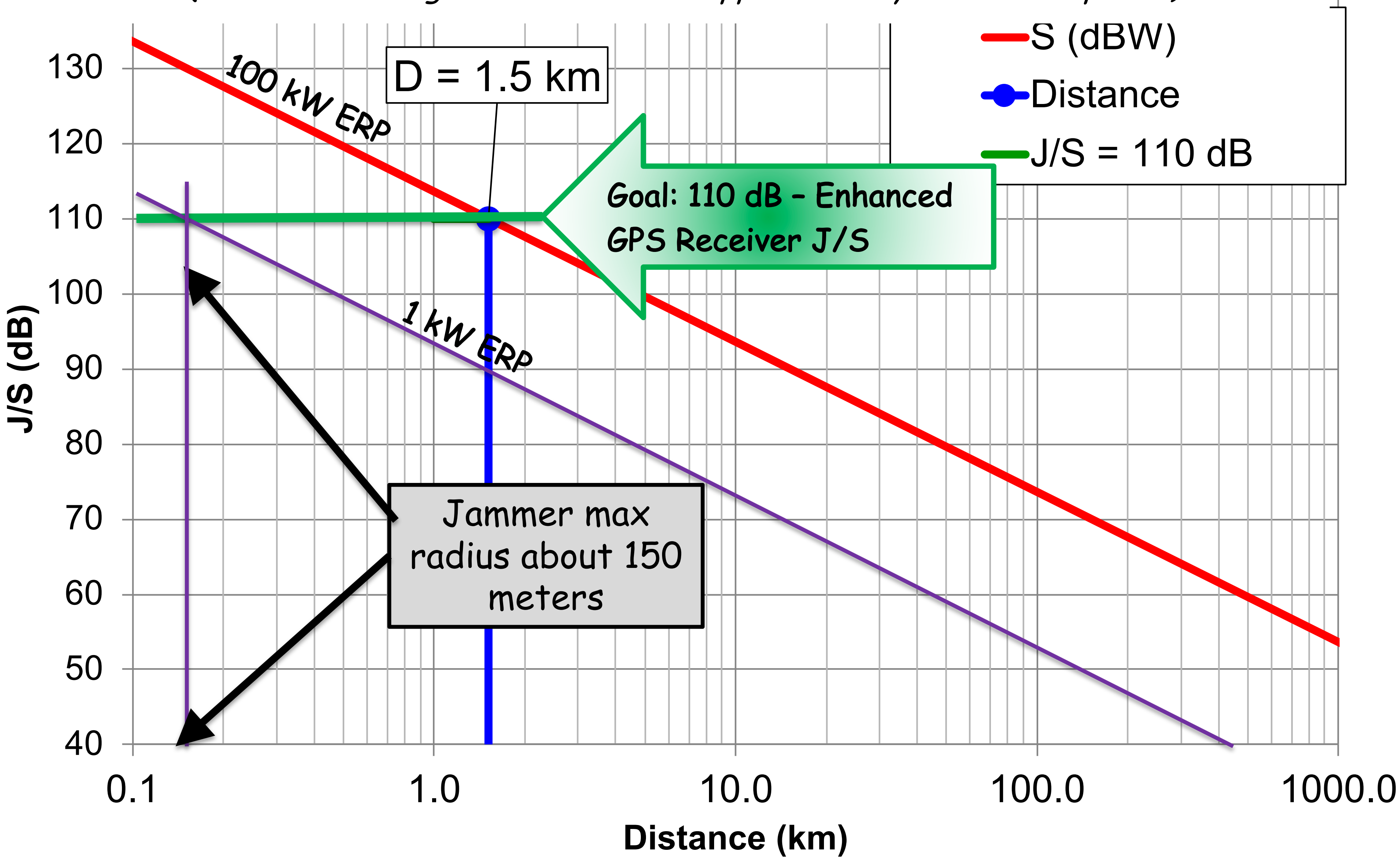
GPS with Signals and Processing nibbles plus increased Regional Satellite Power *__Line of Sight__* susceptibility Radius (JLOSR) for 35 dB J/S= 93 dB
10.7 Km = 17.2 Miles

GPS with focused increased Regional Satellite Power *__Line of Sight__* susceptibility Radius (JLOSR) for 20 dB improvement in effective J/S
15.1 Km = 24.3 Miles

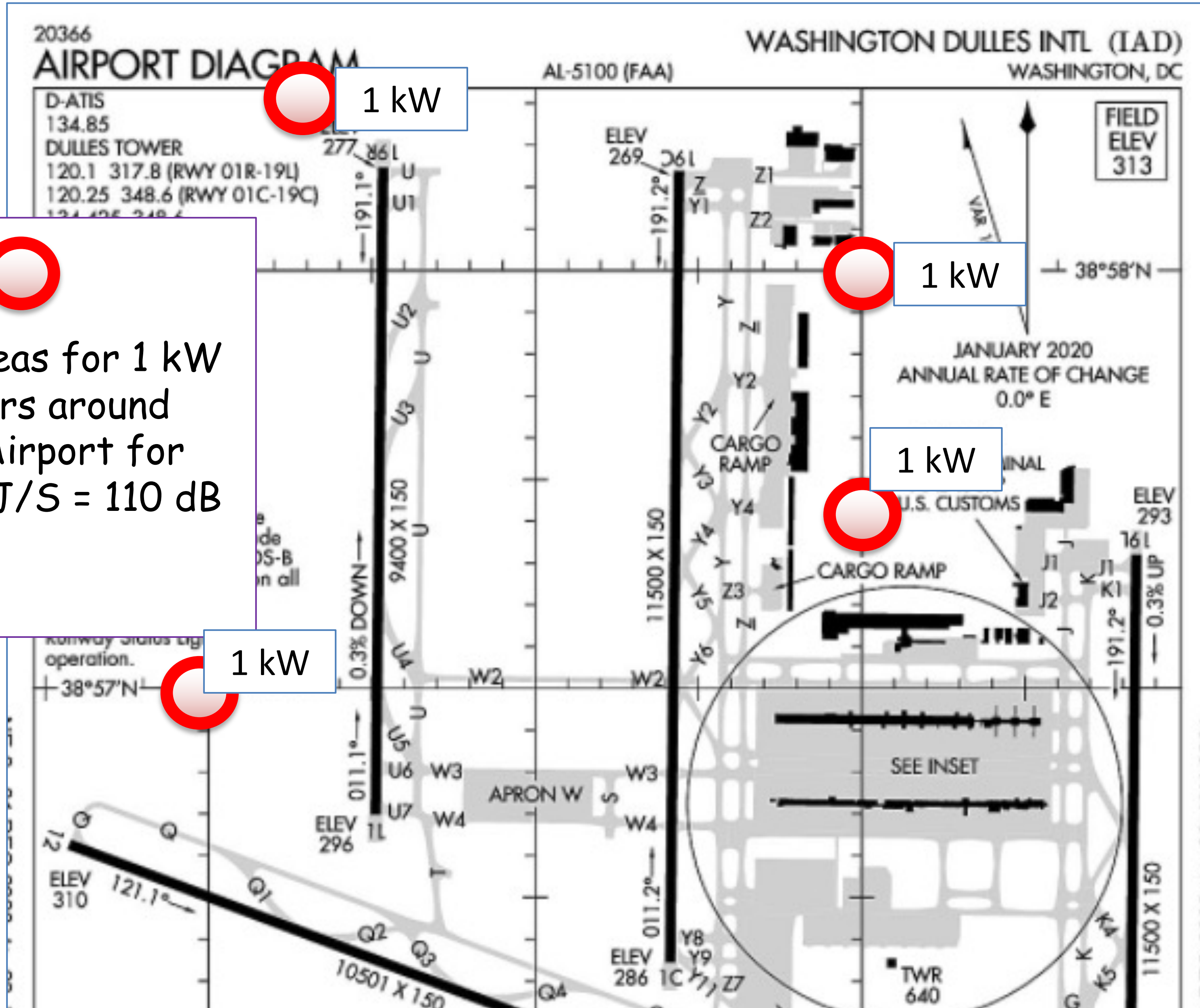
Consider a Commercial Aircraft and a "Domesticated", 1 kW Jammer

What would 110 dB of A/J do for a a 1 kW jammer (say a domestic Airport) ?

(assumes GPS Signal is -160 dBW – approximately L1C and L5 power)

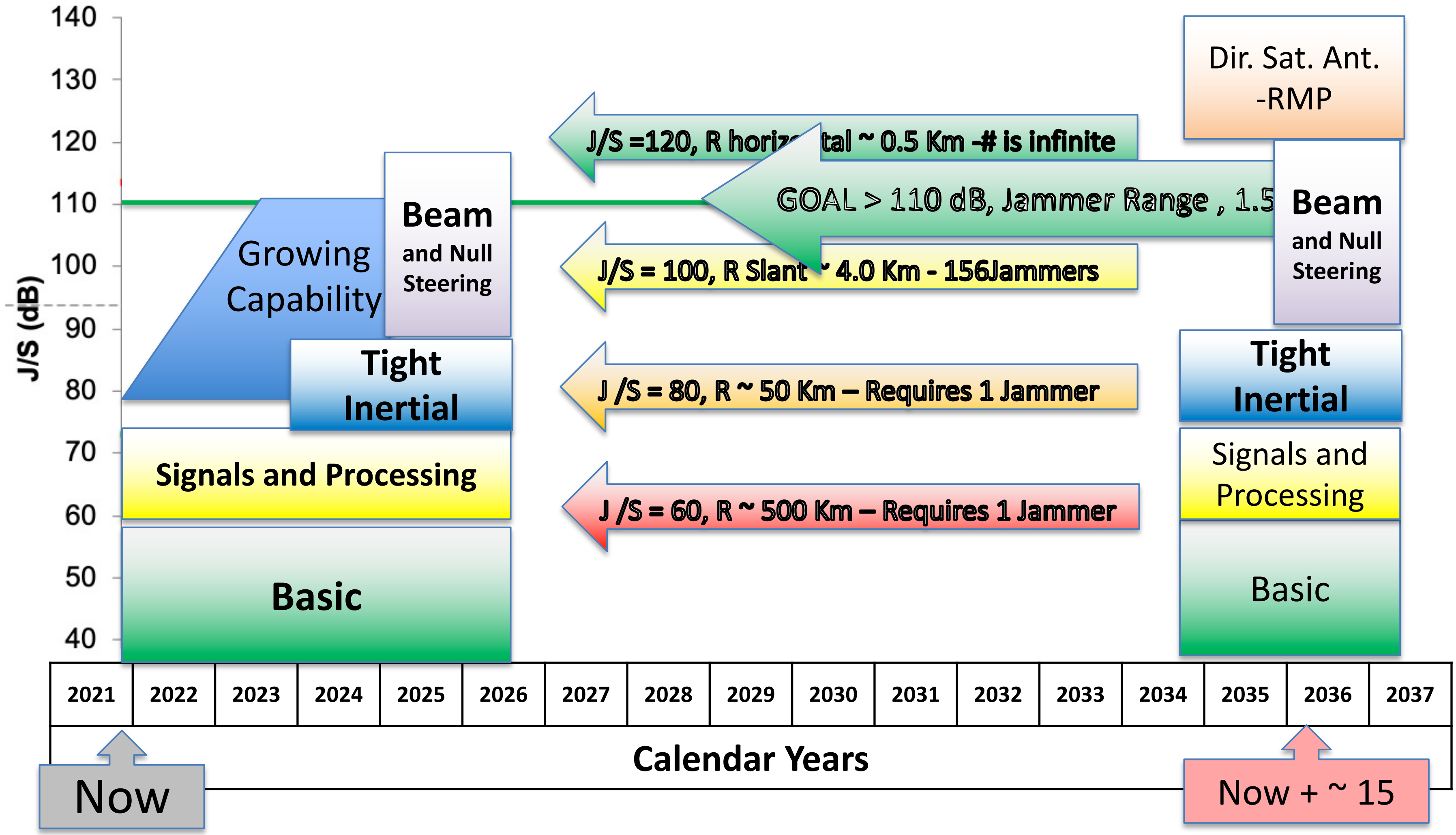


Denial Areas for 1 kW Jammers around Dulles Airport for Receiver J/S = 110 dB



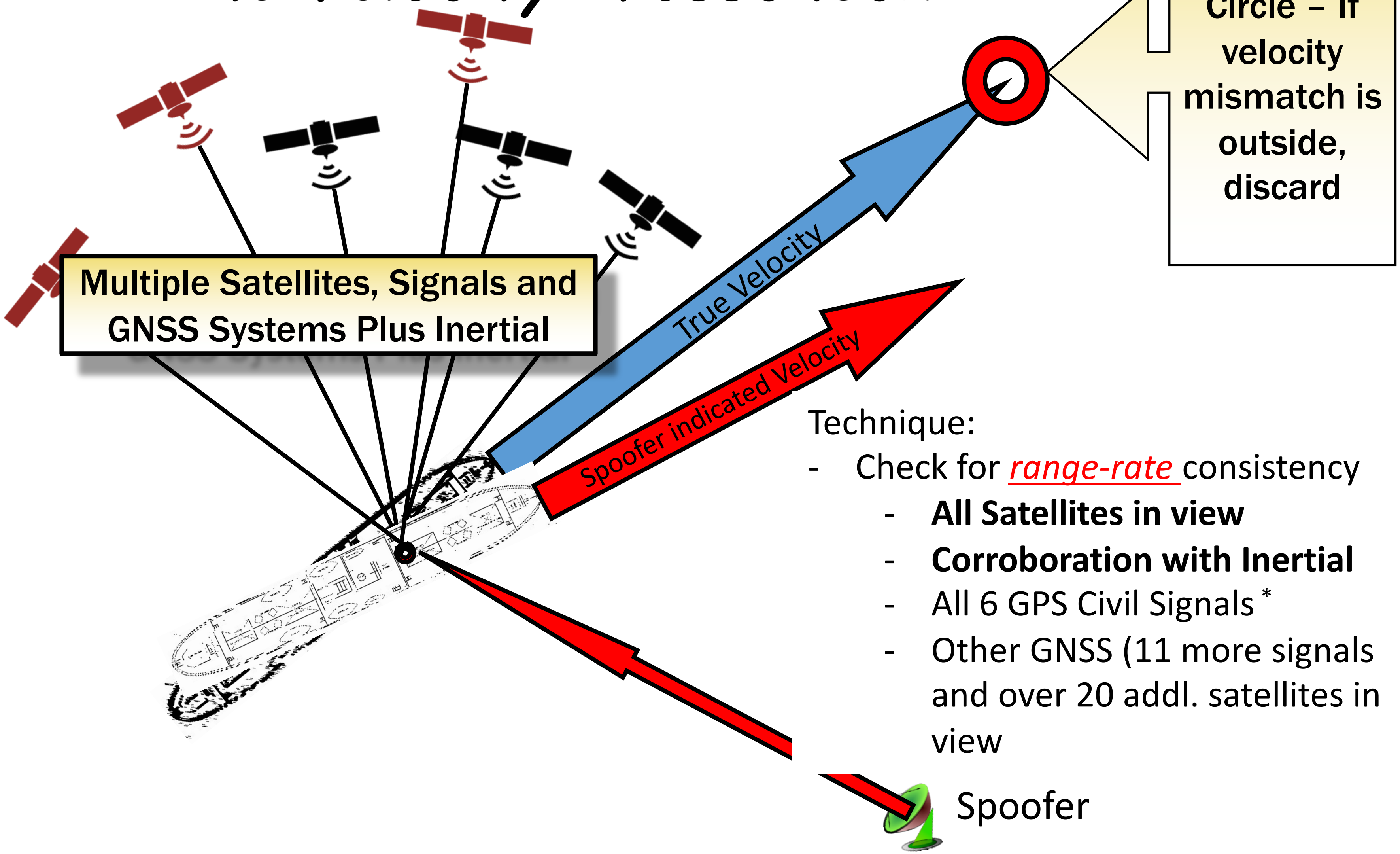
The 4th Dimension: *When* can the J/S nibbles be realized?

(Many are demonstrated or underway)



Spoofing

Spoof Detection Example:
The Velocity Crosscheck



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

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

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"

- 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
- FAA can help by beginning work on MOPS for ***Toughened*** GNSS Recievers
- While Inertial Systems can flywheel through GPS outages, they must be periodically reset because of unbounded error growth –*even with perfect "accelerometers"*
- The satellite power solution (RMA) is apt to take at least 15 years, be very expensive and operationally cumbersome. Alone, it would not defeat a 100 kW Jammer. It also requires CRPAs.

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.

Thank you