An Expurgated History of the GPS Revolution

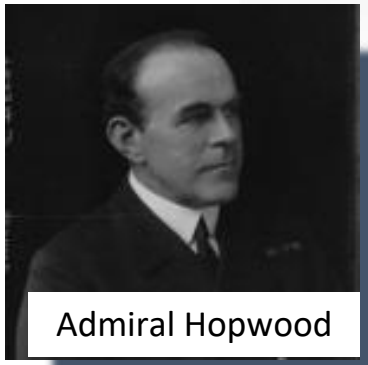
on the occasion of the **50th anniversary** of its initial approval in December of 1973

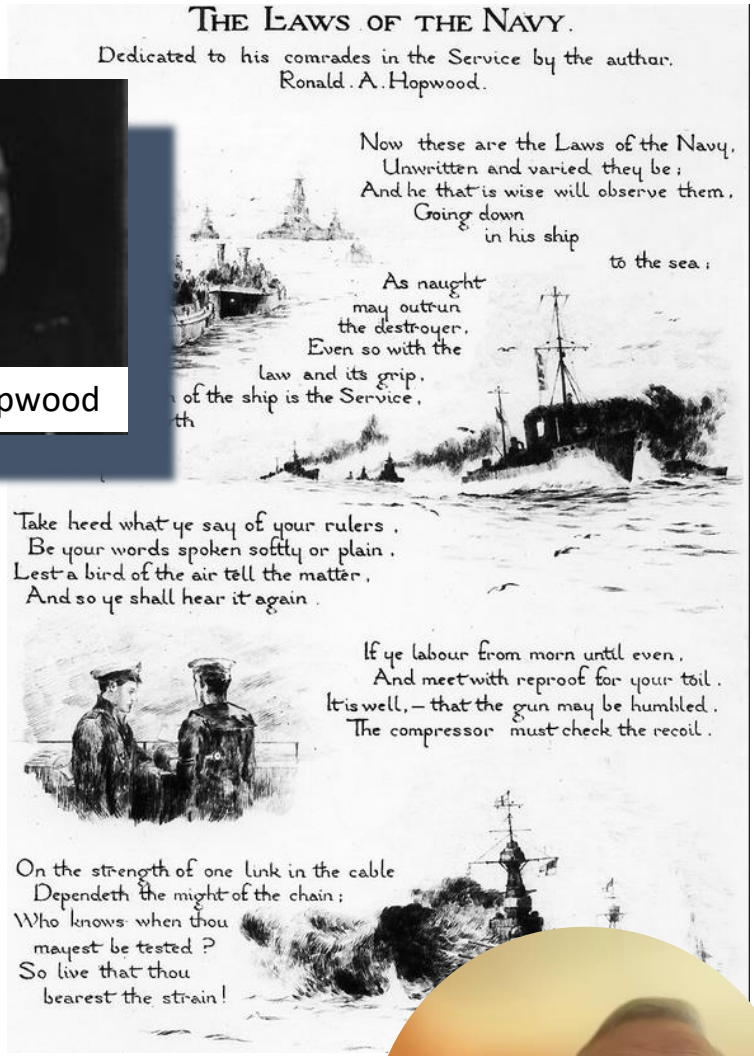
By Bradford Parkinson –
(There at the beginning…)

Plebe "Knowledge" at US Naval Academy in 1953

"1898 - Laws of the Navy" -

Law 5:


Admiral Hopwood


THE LAWS OF THE NAVY.

Dedicated to his comrades in the Service by the author.
Ronald. A. Hopwood.

Now these are the Laws of the Navy,
Unwritten and varied they be;
And he that is wise will observe them,
Going down
in his ship
to the sea;

As naught
may outrun
the destroyer,
Even so with the
law and its grip,
of the ship is the Service,
th

Take heed what ye say of your rulers,
Be your words spoken softly or plain,
Lest a bird of the air tell the matter,
And so ye shall hear it again.

If ye labour from morn until even,
And meet with reproof for your toil,
It is well, — that the gun may be humbled,
The compressor must check the recoil.

On the strength of one link in the cable
Dependeth the might of the chain;
Who knows when thou
mayest be tested?
So live that thou
bearest the strain!

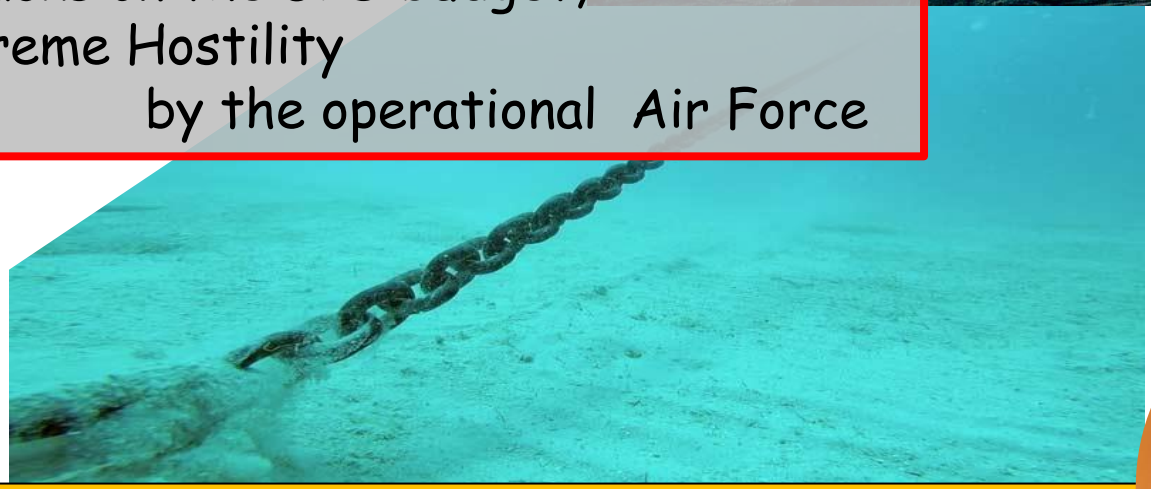
On the strength of *one link* in the cable dependeth the might of the chain;

Who knoweth when thou may be tested? So live that thou bearest the strain.

GPS weathering *Protracted Storm*
(1972 to 1978)

The Anchor and the chain links had to hold in spite of:

- Reluctance to approve Demo System
- Multiple Technical Challenges,
- Complexity of Interface Management
  (My Office was acting as Integration Managers
- Attacks on the GPS budget,
- Extreme Hostility by the operational Air Force



"On the strength of one link in the cable dependeth the might of the chain; "

Setting the Scene :
A NavSat System study was completed in 1966:
An Ancient Era

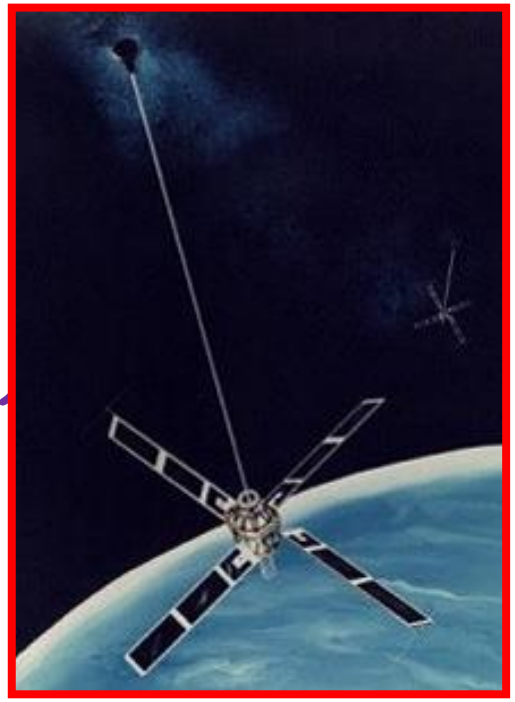
- There were no:
  - PCs
  - CDs and DVDs
  - Cell Ph
  - Facebook
  - eMail
  - iPODS
  - HDTV

- And there was no GNSS. **but** There **was** an existing Satellite-based Navigation System- **US Navy's Transit**

Navy's Transit – NNSS

(Doppler determined Range)

Two elements of heritage for GPS



- ***150 and 400 MHz (Iono Correction)***
- ***Orbit determination and prediction***

But:

- *2-D Fix available every few hours*
- 10 to 16 minutes for a fix
  - 0.1 to 0.25 Mile accuracy/ *2D (altitude had to be "known"*
  - Velocity Correction: 1 knot = 0.2 n. mi.

By 1964, Some felt a much improved
Satellite Navigation System
could be Developed (24/7, 3-D, Worldwide system

Original "GPS" System Study- USAF 621B

The Woodford/Nakamura Secret System Study

Preliminary 1964 – Final Classified Report in 1966

Woodford and Nakamura Option # 12 Was the ***First*** of three great innovations that were the foundation of GPS and other

Four Simultaneous Ranging measurer

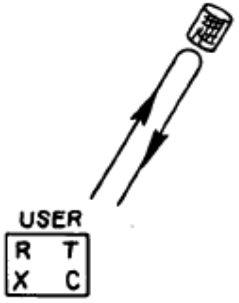
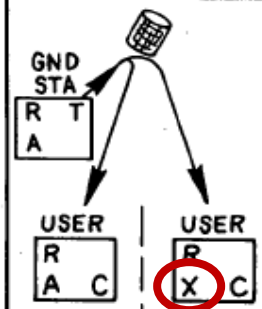
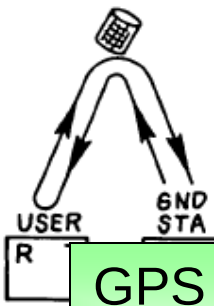
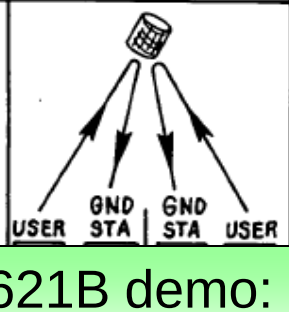
to find ***4-Dimensional Position***

First Essential Link in the Concept Chain - The GPS System Concept

USAF/621B Woodford Study – Alt. Passive Ranging Techniques

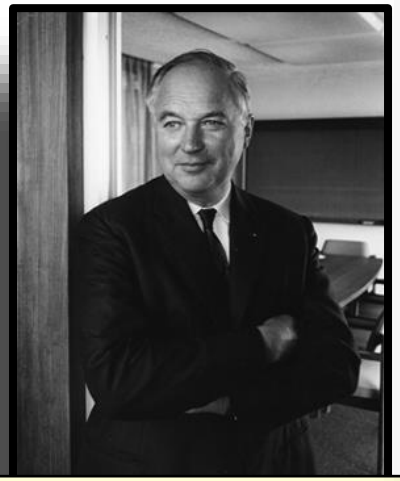
1

RANGE AND RANGE DIFFERENCE SYSTEMS

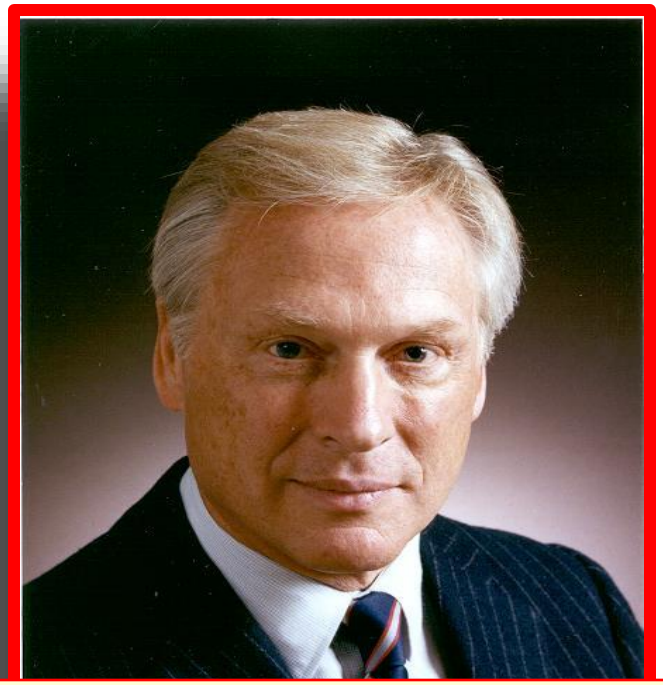
LOCATION OF COMPUTATION	COMPUTATION PERFORMED BY USER		COMPUTATION PERFORMED BY GROUND STATION	
NAVIGATION RADIO LINK	2 WAY	1 WAY	2 WAY	1 WAY
USER EQUIPMENT R = RECEIVER T = TRANSMITTER X = CRYSTAL CLOCK A = ATOMIC CLOCK C = COMPUTER				
APPLICABLE MEASUREMENTS 2 SATS ppḣ 3 SATS ppp 3 SATS ΔPΔḣ 4 SATS ΔPΔPΔP	✓ (ALTIMETER) ✓	✓(ALTIMETER) ✓ ✓(ALTIMETER) ✓	✓(ALTIMETER) ✓	✓(ALTIMETER) ✓
	USER ACTIVE	USER PASSIVE	USER ACTIVE	USER

GPS (621B demo: 1971/73)

Essential Links - Support
for the GPS Revolution -



The GPS Soothsayer
Dr. Ivan Getting
President and CEO
Aerospace Corporation



The GPS "Godfather"
Dr. Mal Currie
Undersecretary of Research and Engineering for the Office of Defense

The GPS
Air Force Sponsor
Lt.Gen
C

"Black Thursday"

Failure

50 years ago, August 1973

Recovery from Failure - Early Links in the Chain

-***Defining GPS*** -

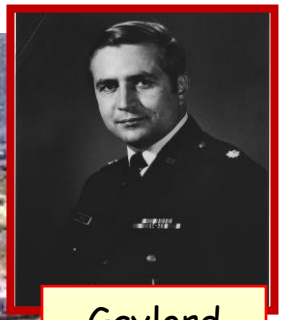
The ***Lonely Halls*** Meeting –GPS "Architected" –

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

Brad Parkinson
USAF

Frank
Butterfield
Aerospace Corp.

Bill Huston
USN



Gaylord
Green
USAF

Steve
Gilbert
USAF

The Pentagon "Lonely Halls" System Design Meeting

Program Office/Aerospace in Attendance (~12 attendees)

Design: Confirmation of Fundamental 621B concept (4 Sats in view)

- Selection of USAF/621B CDMA Signal structure
- But direct to Space-hardened Atomic Clocks (Advocated by 621B and Timation – actively attempted by Timation/NRL)
- 24 Space Vehicles Constellation- Orbits modified to Inclined 11H 58.03M - Sidereal Semi -Synchronous (stable test area – Yuma)

Machiavelli on Innovation

(1513 The Prince-Ch. VI)

"and it ought to be remembered that there is nothing more difficult to take in hand, more perilous in its success, than to take the lead in the introduction of a new order of things.

Because the innovator has for enemies all those who have done well under the old conditions, and lukewarm defenders in those who may do well under the new.

This coolness arises partly from fear of the opponents..., and partly from the incredulity of [people], who do not readily beli things until they have had long e with them."

Reversal! 50 Years Ago, Approval Success:

Phase-One Demonstration *Approved* December 1973

- Budget about $150M (1973$ - 1.03 B$ 2023), and included:
  - 4 Initial Satellites (Later 6)
  - 4 Launch Vehicles and operations
  - Ground Master Control and 6 worldwide monitors
  - 7 Kinds of User Equipment
  - Extensive, 18 month Test Program, mostly at Yuma Proving Ground
- ~ 4 Year Development + 1 year of Testing –
- ***Civil use offered, but at risk***

I testified before congress that we were offering the Receiver Signal Spec to the public from the First civil set locked up on GPS within 24 hours broadcast (students at Leeds - 1978) But the signal was *not* guaranteed!

Selecting the System Design and Signal ***Type*** not enough…

Additional *Engineering Challenges*

*(Critical Development Links That **had** to work)*

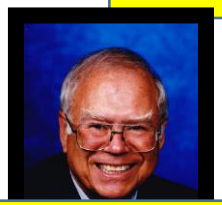
1. Developing **all interfaces** between the three major segments: *Space, Ground Control, and User Equipment*
2. **Near real-time Orbit prediction** - a few meters (URE) in ***90,000 miles of travel***
3. **Spacecraft lifetimes** approaching ten years (GPS affordability)
4. A complete family of **User equipment** that co… eventually be miniaturized and produced at …
5. Evolutionary test concept based on 621B (… Range")

More Links in a Chain that would not break

Don Henderson
Deputy Program Director

Ed Lassiter
Led Aerospace Support

Brock Strom
Chief Engineer for Program Office

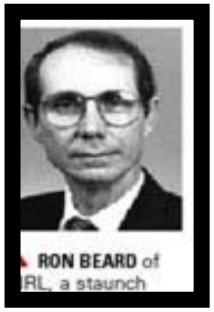


Walt Melton
Led Development of Ground Control and User Equipment General Dynamics

Sherm Francisco
Control Software
IBM

Dr. Bob Cooper

Dr. Bob Rennard



Ed Martin

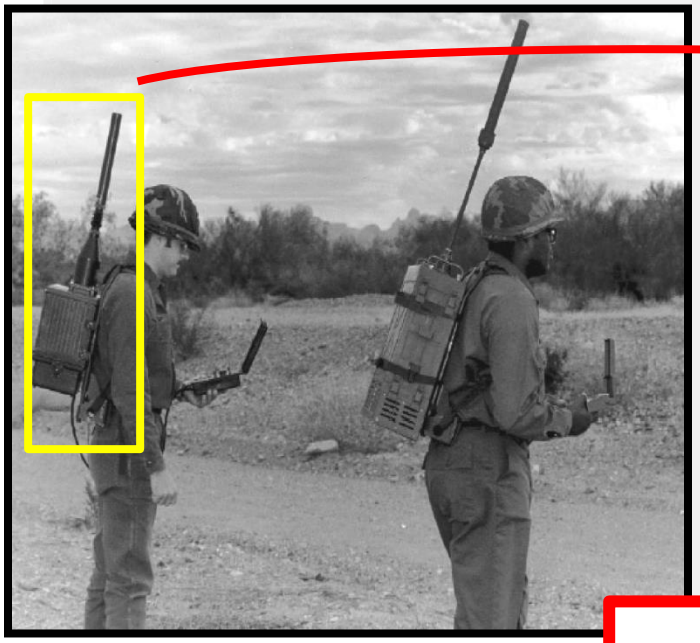
Then What?

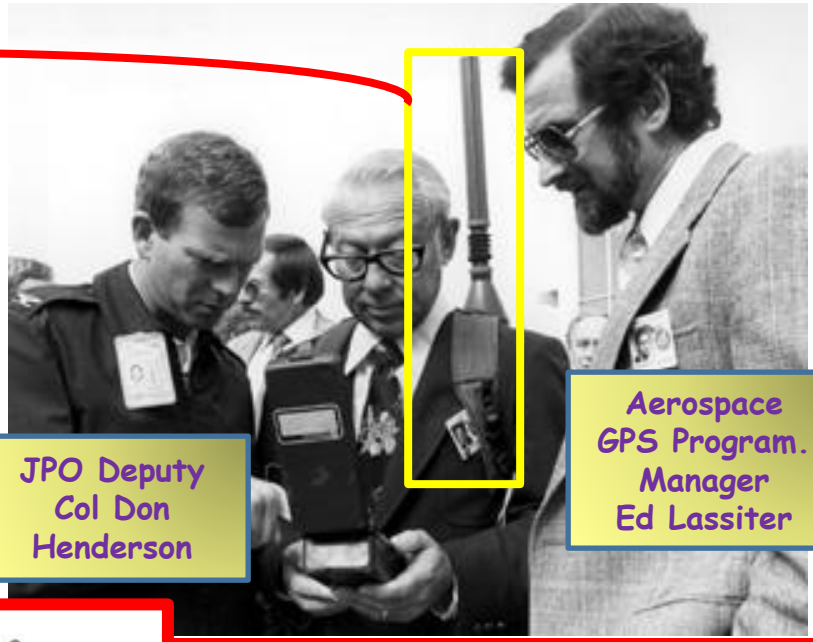
- First launch of GPS February 1978 -
  44 months after contract award.
- Extensive testing by 1979 confirmed all capability promises made in 1973…
- In 1979, US Air Force still tried to cancel development, but Civilian leadership in the Pentagon over-ruled the attempt!
- Full Operational Capability (FOC) as of April

  (23 years after initial approval – could have been 15 year

And an Allied Affordabilty-Enabling Development:

The Integrated Circuit - not widespread until late 1970s





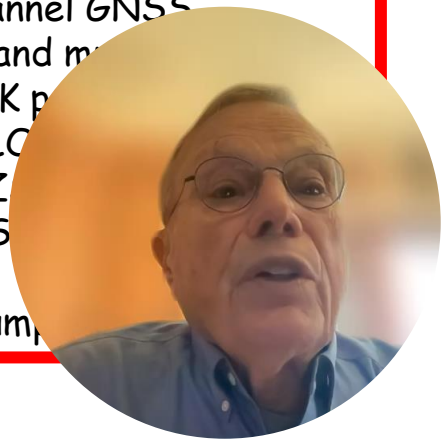
1978 "Manpack"

- "Discrete Transistors
- About 40#
- One Channel/frequency
- Batteries lasted about 6 hou
- About 10 m accuracy

A Modern Chip >100 channels

About $3 each

- Support 135-channel GNSS
- Dual-frequency and m
  constellation RTK p
- Support GPS, GLO
  BEIDOU and QZ
- Capable of SBAS
  MSAS, GAGAN)
- Low power consum

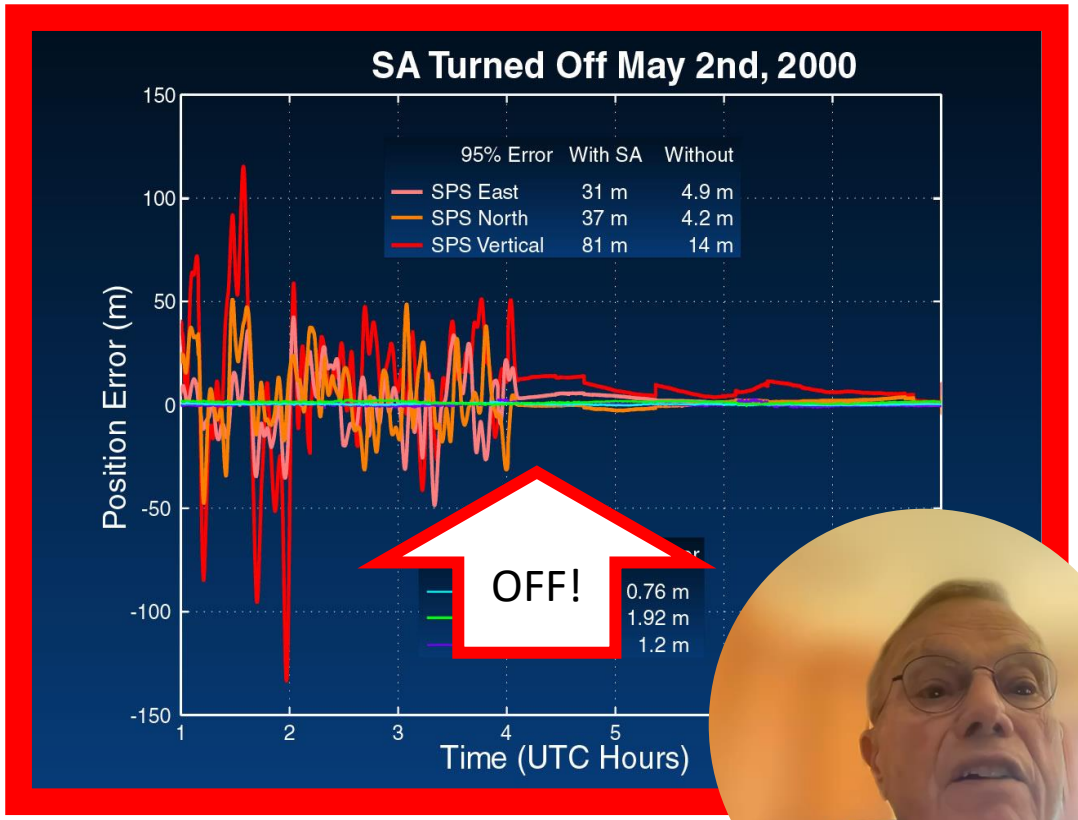


Two Defining Events

(Insured Availability of an accurate, worldwide system)

- **Pres. Reagan** Commits GPS to the World (1983)

- **Pres. Bill Clinton** orders ***Deliberate Errors (SA) turned off*** at midnight May 1, 2000 (UTC).

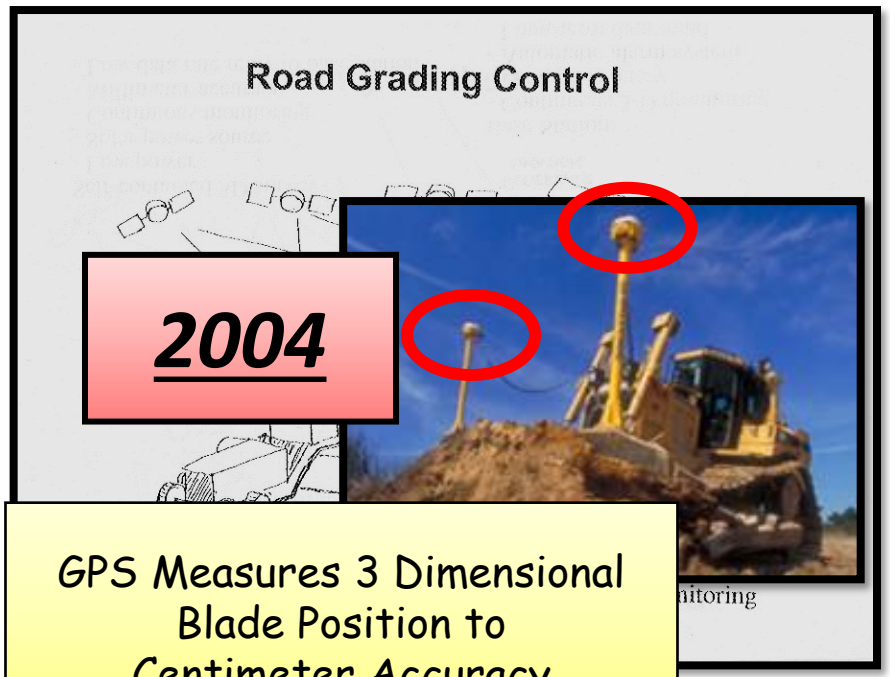


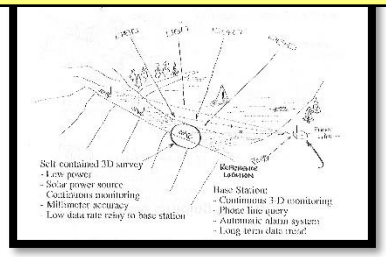
GPS Applications have Proliferated

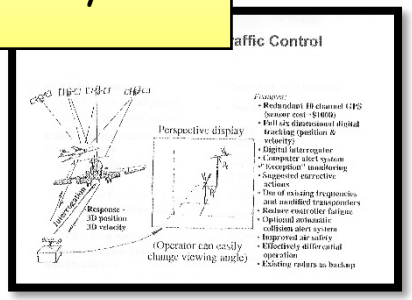
- Civil
  - Transportation
    - Aviation
    - Automobile
    - Maritime
    - Rail Control
  - Public Services
  - Timing & Frequency
  - Surveying
  - Surveillance
  - Other
- Military

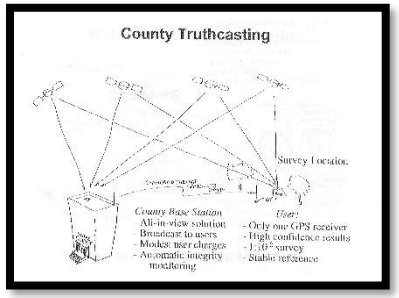
BP 1978 Hand drawn Applications

(Some just *slightly* ahead of their time - over 20 years!)

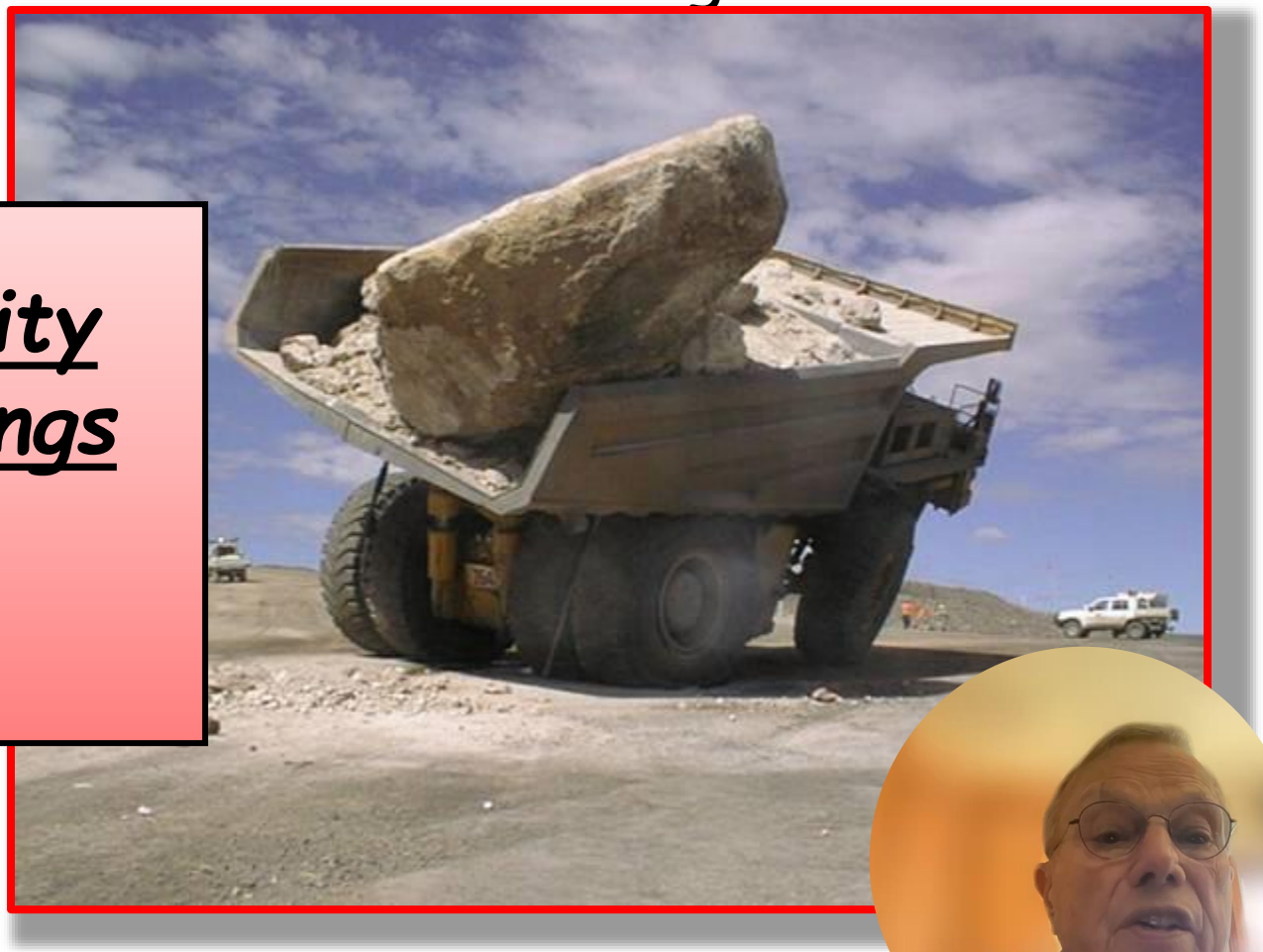








GNSS Robotically Guided Off-highway Trucks
- Wheels 3 meters high

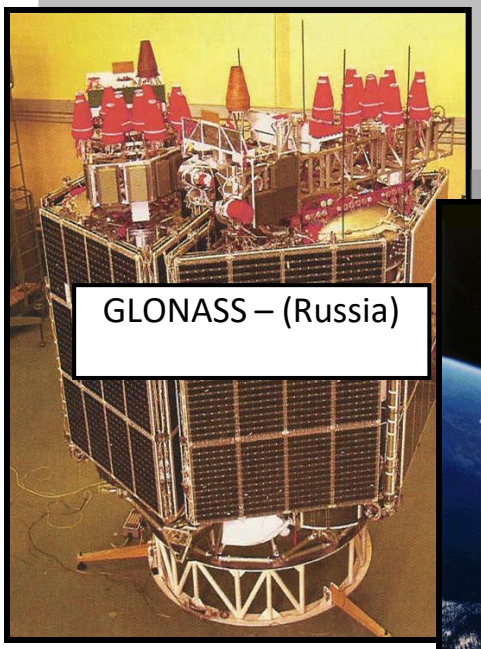


Productivity Savings

But…

A Reminder: GNSS can guide, but don't select the wrong path…

There are now 4 GNSS – all use CDMA



GLONASS – (Russia)

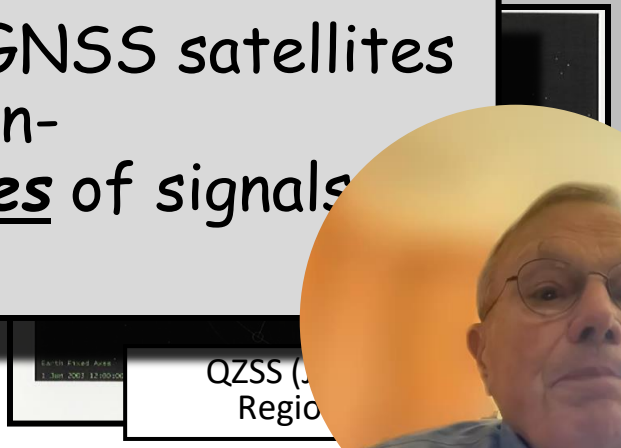
GP(t)S
(USA)

- First Operational Civil Signal

Galileo
(European)

Typically between 40 and 60 GNSS satellites above the horizon-
and over 20 ***different types*** of signals available

Compass
(Beidou China*)*



QZSS (J
Regio

Worldwide GNSS Signals – ***200 to 300 Signals*** simultaneously in view anywhere in the world!

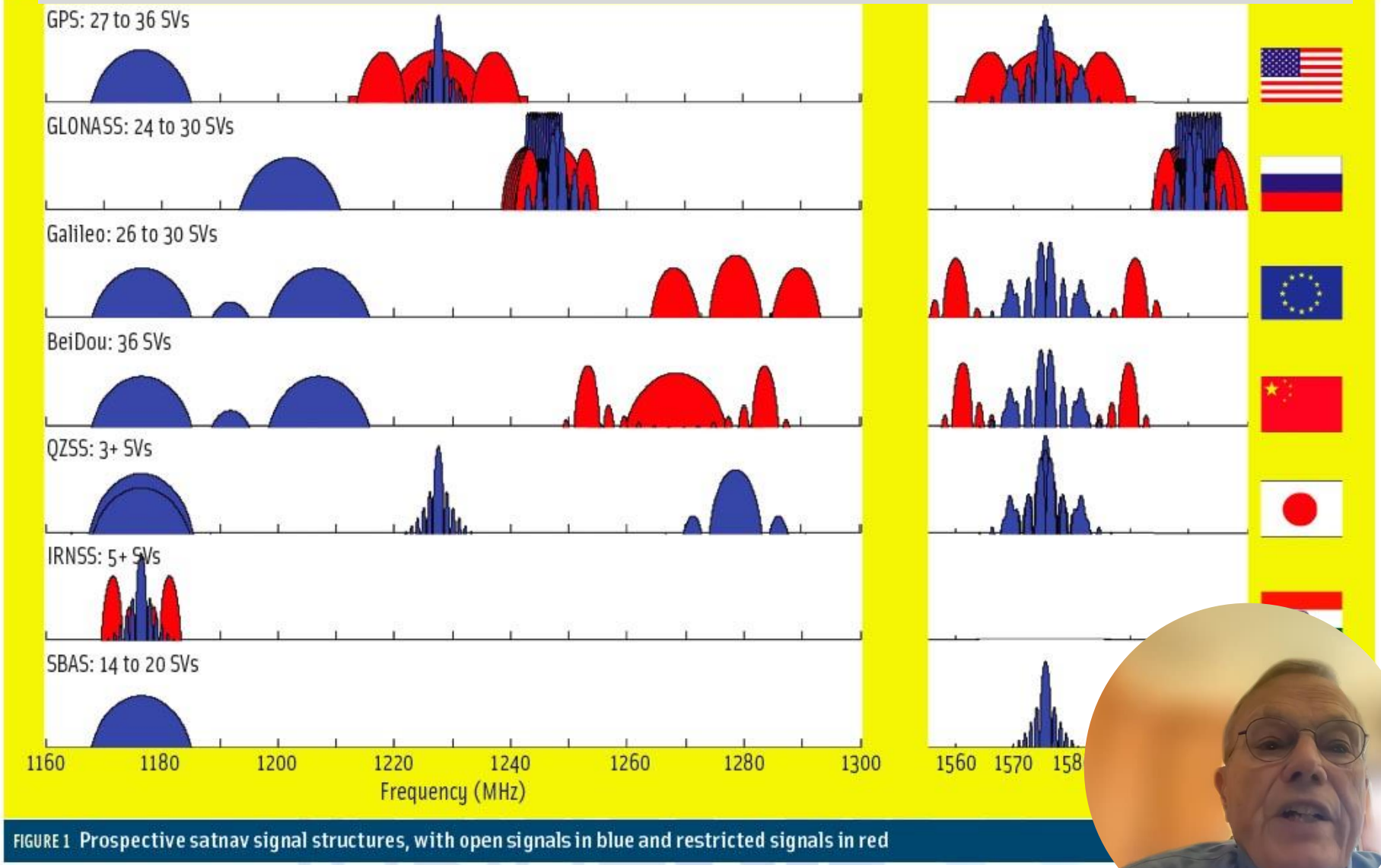
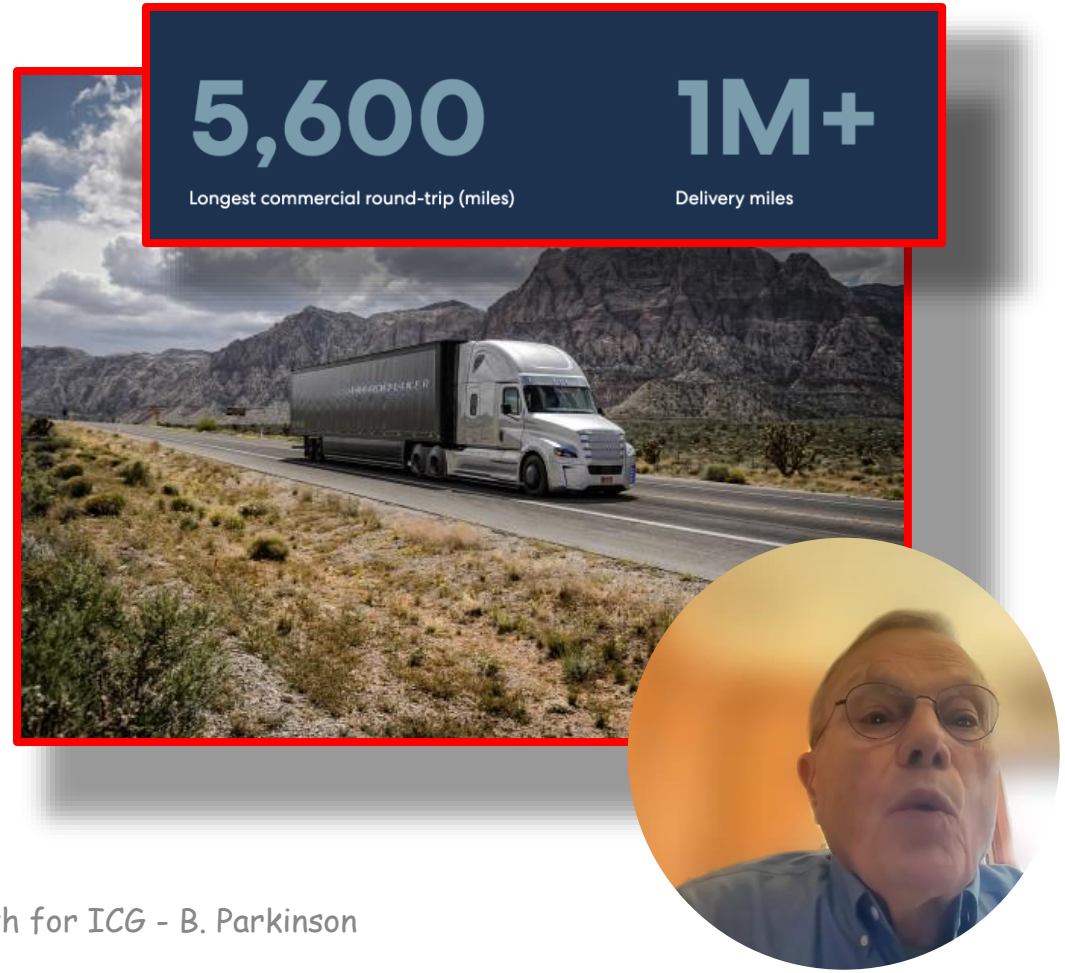


FIGURE 1 Prospective satnav signal structures, with open signals in blue and restricted signals in red

A glimpse of the Future?

The World's First Self-Driving Semi-Truck Hits the Road (May 2015 - more demos since – look up Kodiak and Aurora)

- "The Freightliner"
- Daimler-Benz *Prototype*
- GPS *plus*
- Stereo Camera Reads Lanes
- Short and Long Range Radars



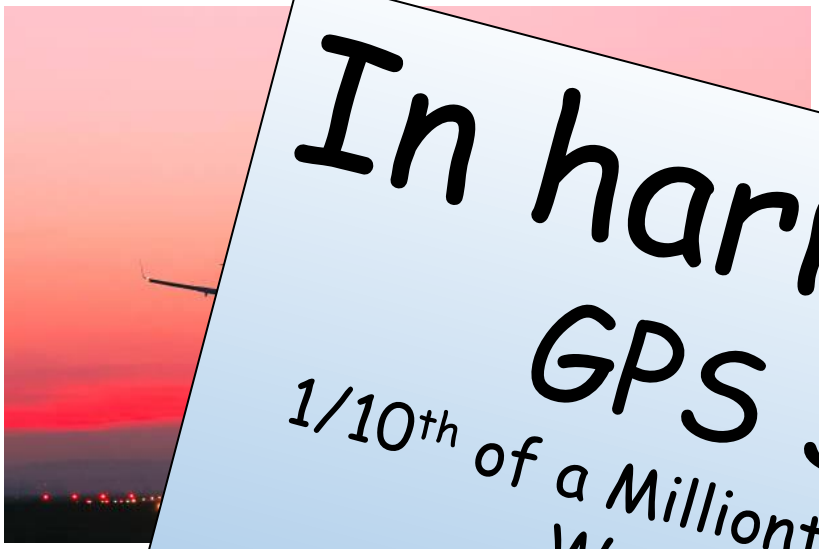
Challenges

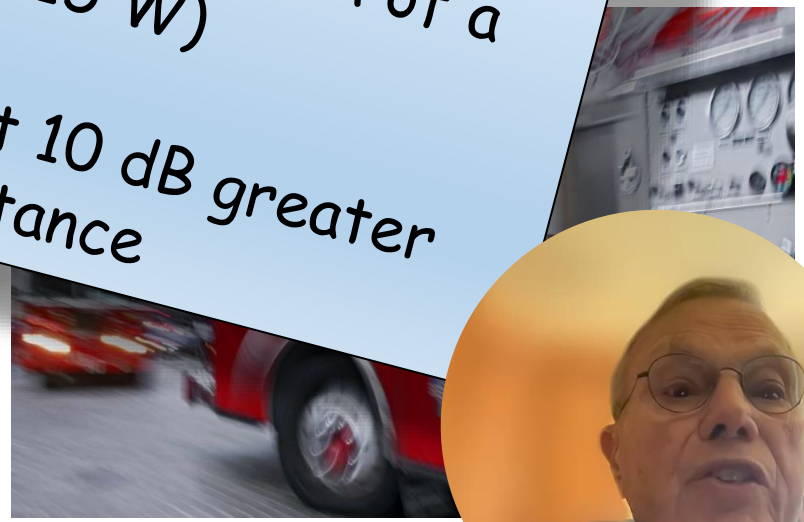
In harm's Way?

GPS Signal=

1/10th of a Millionth Of a Billionth of a Watt (0.1 e -15 W)

Note: L5 will give about 10 dB greater jamming resistance





Is the Illegal Interference Problem Significant?

"Portable GPS supplier says people who value their privacy need GNSS Jammers."

Handheld GPS Jammer
GJ02

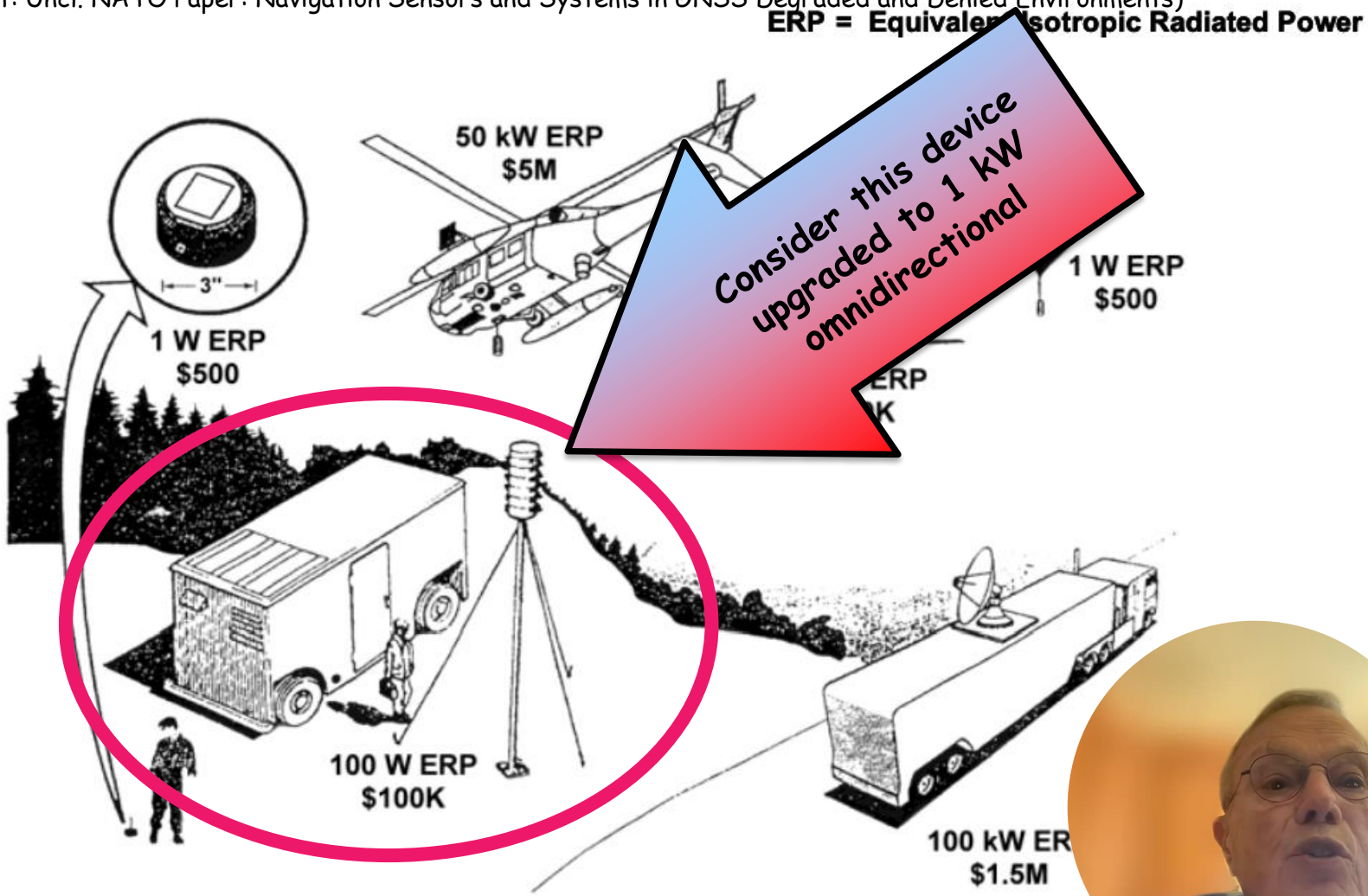
Unit Price: $33.00

GPS L1 - 1575.42MHz
Output power: 0.5 Watt

Similar Devices also jam all GNSS and Cell Phone Frequencies

Background: Deliberate Jammer Alternatives

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



Primary Advisory Board Objectives: **1. Assured *PNT* for all Users**

and

2. To encourage/exploit system improvements and new techniques to *advance PNT* for all applications

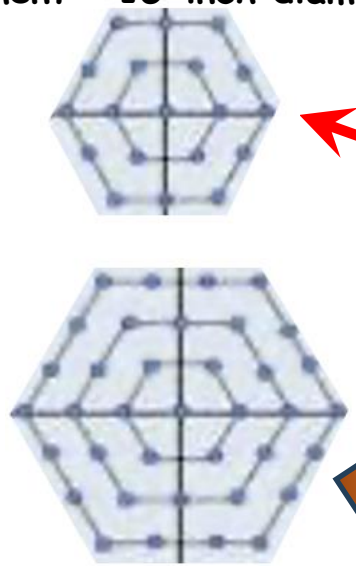
- Our Strategy has been the ***PTA Program:***

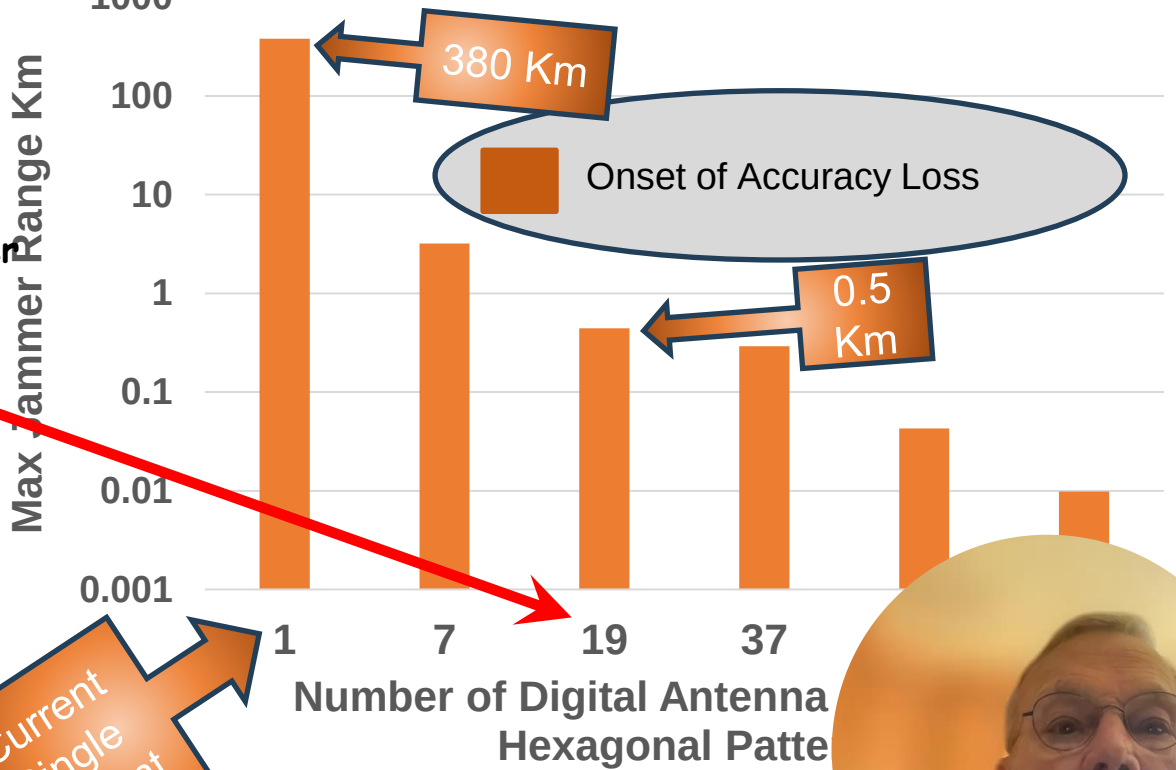
1. ***Protect*** the **radio spectrum** + identify + shut down interferers
2. ***Toughen*** GPS receivers against natural and human interference (Jamming and Spoofing) and to other system threats
3. ***Augment*** with additional GNSS/PNT sources and

Toughening GPS receivers using Digital Controlled Reception Pattern Antennas (CRPAs)

1 Element – FRPA

19 Element – 15-inch diameter





Current Single Element

Aside: Are civil sets currently available with full system A/J?

NO!

- *US ITAR* forbids more than 3 elements in US civil GPS antennas
  - Although this technology at L band has been known and used for over 60 years
  - Inexpensive A/D devices are off-the shelf
  - A Turkish company is advertising a GNSS antenna with 16 elements *(and claimed **100,000 times** imp*
    Jam resistance, but not yet verified with public dat

TUALAJ - 16300 D
16 Array
GPS L1 and L2, Galileo, BeiDou, GLONAS
G1 and G2

Moving to the Future

Many of these under active consideration/study by the ICG

- Allow multi-element Digital Antennas for Civilian Receivers
- Laser Retroreflectors
- High Accuracy Service
- Anti-spoof Authentication with signals
- Added signals
- Transmission in higher Bands

Future Summary: Two GNSS Challenges

1. **ITAR restrictions** on well- known, multi-element A/J enhancements.
   - Can enable integrated receivers to be virtually jamproof
   - First demonstrated 45 years ago
2. **Future - moving to field new capabilities**
   - E.g. laser cross links
   - Consider a more affordable, proliferated MEO designs: proliferation will reduce any pl vulnerability

So, about 50 years ago, GPS weathered the Protracted Storm (1972 to 1978)

The Anchor and the Chain Links hel

And GPS became a System f
Humanity

Thank you!