Prof. Dan deBra
1930 to 2021
Memorial Resolution

Daniel B. DeBra, the Edward C. Wells Professor (Emeritus) passed away peacefully, on Dec. 3, 2021, at home with family, at the age of 91.

Dan was known as a consummate engineer, and his work was essential to the development of the drag-free satellite, a system that enabled the relativity-confirming gyroscope used in Stanford’s Gravity Probe-B test of General Relativity. He was also a very valuable mentor and advisor to many students during his time at Stanford and famous for his numerous outdoor activities.
He made crucial contributions to many Programs, in addition to Gravity Probe B. These included the Navy’s Transit Navigation System, the European Space Agency’s GOCE spacecraft missions, and the Laser Interferometer Gravitational Wave Observatory (LIGO). All of them demanded instrumentation of exquisite precision and accuracy. This was Dan’s forte. His nested, isolation platform, built for LIGO, was said to be so stable it varied no more than an atom’s width relative to the surface of Earth.

The Gravity Probe B satellite was launched in 2004 and confirmed two predictions derived from Einstein’s general theory of relativity concerning the motion of the axes of orbiting gyroscopes. If gravity did not alter space and time, GP-B’s gyros would essentially point in the same direction forever.
But, in confirmation of Einstein’s theories, the gyros experienced measurable, minute changes in the direction of their spin due to orbiting the earth and earth’s rotation. This result is having a long-term impact on the work of theoretical physicists. Again, Dan’s contributions were key enablers.

Daniel Brown DeBra was born June 30, 1930, in the East Bronx section of New York City. He earned a Bachelor of Engineering in mechanical engineering at Yale University in 1952; a Master of Science, also in mechanical engineering, in 1953 from MIT; and his doctorate in engineering mechanics from Stanford in 1962. From 1956 to 1964, partially while still a graduate student, Dan worked in dynamics and control at Lockheed Missile and Space Company in Sunnyvale, California. In 1964, he became a Research Associate at Stanford, and later joined the Stanford faculty, where he served until his retirement in 1991.
Dan won the Industrial Research Award 100 for his work on drag-free satellites in 1973 and the Thurlow Award from the Institute of Navigation in 1983. He also received a Lifetime Achievement Award from the American Society for Precision Engineering (ASPE). In 1981, he was elected to the National Academy of Engineering.

Dan was a genial, consistently physically- active man who enjoyed life. Always positive, he willingly jumped in to help anyone with a need. At the same time, he was very self-effacing and instinctively gave credit to his many students and colleagues for engineering accomplishments, while he was content to remain in the background. He ran track as an undergrad at Yale and continued running for many years. He was a legendary bicyclist and a downhill skier (serving on the National Ski Patrol), scuba diver, mountain climber, backpacker and hiker.
Ever the design engineer, he also enjoyed actually building his designs. The family garage, it was said, was a “creative forge” of do-it-yourself bikes, cars, jets, hand-built furniture, and more.

Dan is survived by his wife, Teri Crosby DeBra, six children and 10 grandchildren.
A Historic Milestone

• Next month, November is the 50th anniversary of Brad Parkinson being abruptly reassigned to a floundering research program called 621B that became GPS.

• Upon transfer, his first significant management step was to hire the best engineering officers in the USAF
  • And his first request was for a bright young engineer from his past. He reached back to a young Masters candidate who arrived with him when he went to Stanford for a PhD in 1964.
    • He placed this man in the essential position as the manager of the development of the first-of-a-kind GPS Phase 1 Satellite
    • Due to this persons technical and managerial skills it was successfully launched in 44 months.
    • The first batch of Phase 1 satellites had an average life of over 9 years (design life 3 years).
  • **GPS is due to many people, none was more essential than this Great Engineer!**
Gaylord Green
USAFA and Stanford

• First GPS Satellite Manager 44 months to launch
• Later head of whole GPS Program
• Program Manger of Gravity Probe-B
Assuring PNT:

Some Issues and Observations

SCPNT
October 2022
Brad Parkinson*

*Conclusions and recommendations that have not been made previously by PNTAB are my own.
Primary Advisory Board Objective:

Assured PNT for all Users
and
to encourage/exploit system improvements and new techniques to advance PNT for all applications

• Our Strategy is the **PTA Program:**

  - **Protect** the **radio spectrum** + identify + shut down interferers
  - **Toughen** GPS receivers against natural and human interference (Jamming and Spoofing)
  - **Augment** with additional GNSS/PNT sources and Techniques
Bottom Line Up Front

*P, T, and A are complementary and are all needed*

- In spite of efforts to *Protect* there will always be situations where interferers break the rules. Sources must be quickly located and removed. More urgent government action is needed to do this. Toughen and Augment fill in during those situations.

- *Toughening* makes GPS thousands of times more resistant to challenges, but there are government restrictions to attaining full toughening potential. These restrictions should be immediately removed.

- In spite of Protecting and Toughening GPS, relying on a single source of PNT can be unwise. That's the role of *Augmentation*. But there is no known Augmentation, except for foreign satnav, that provides the GPS-like capability.

Augment alone cannot be the answer for the users with challenging needs. So called “signals-of-opportunity” (like undedicated LEOs) have severe flaws, when compared to need. Dedicated LEOs with long term viability can overcome some of these faults.
**Strategy 1: Protect** the radio-spectrum + identify & prosecute interferers

**Observations:**

- Ligado Problem is *not* resolved—Particularly for the installed base of Precision Applications
- Identifying and Prosecuting Interferers does not seem to be an active priority of the FCC or USG but effort is slowly increasing
- Promising crowd sourcing (J911) is slowly being recognized
  - Use AGC or C/No estimates Analogous to routing software assessing traffic speed.
  - Should be nationally gathered and generally available
  - Propose Coast Guard Center as official central location
Traffic Density - A similar GPS crowd-sourced interference map (from J911 data) could be made based on **cellphone and cell towers** as sensors (AGC or C/No estimates)

- Must protect privacy (just a is done for traffic)
- US AI to determine most probable location
- National and accessible real-time database at Coast Guard Center

- We have admired this solution long enough
- It is time for extensive prototyping and iterations and rapid deployment
- Scott Logan and perhaps Google pursuing
Ligado Adjacent band interference concern

“Upper” band is apparently off the table. Is this forever?

“Lower” band Power reduced to 10 Watts. FCC order specified minimum spacing of 433 meters. To meet broadband requirements it could be much less - Micro or Femtocells call for 100 to 200 meters.

11/3/22
Maximum allowable Ligado Power to protect **90% of Area** for High Performance Receivers (HPRs)
(i.e. Degradation limited to 10% of Transmitter Region)

<table>
<thead>
<tr>
<th>% of High-Performance Receivers Degraded</th>
<th>400m Tower Spacing</th>
<th>Maximum Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>400m Tower</td>
<td>0.004W</td>
</tr>
<tr>
<td>10%</td>
<td>400m Tower</td>
<td>0.031W</td>
</tr>
</tbody>
</table>

If the 1 dB criteria is relaxed to 4 dB, it does not change the overwhelming conclusion of incompatibility.

Based on quantitative data taken from 40 Different HPRs, tested by DOT for Adjacent Band Compatibility.

Ligado want 10 Watts to support marketable data rates.

PNT Issues 2022
It may be worse - not included in analysis...

- Multiple towers contribute additive noise
- Reflections from ground and buildings can increase normal $1/R^2$ models by factors of over 10 (Factors of 15 measured in Las Vegas tests)
- The newer GNSS signals have wider RF bandwidths for greater accuracy and A/J, but the receivers also may have greater sensitivity to the adjacent band power. In ABC tests, the Galileo E1 signal was more sensitive for HPRs.
- The new military signal deliberately pushes energy away from the center frequency, closer to Ligado power.

But it may also slowly be getting Better...

- Manufacturers fielding more resistant receivers
  - Does not quickly solve the fielded-equipment problem
The Protect Strategy - Ligado, the take away

- A reasonable compromise is to protect 90% of the Installed High-Performance receivers in 90% of the area. With 1 dB criterion, this would require either:
  - A maximum of 31 milli watts of Ligado power at original tower spacing of 400 meters
  Or:
  - A minimum of 7000 meters spacing between Ligado towers at the “new” power level of 10 watts.

However, Ligado seems to be planning a typical mini-tower spacing of 400 to 1000 meters. In that case I propose a PNTAB recommendation for the EXCOM and FCC:

Either swap the Ligado spectrum to another portion of the spectrum or Just say no.
Looking at **Sources of PNT** - The **Ten Attributes** of PNT Systems - **Applies to all GNSS as well as Augmentations**

- Propose (notionally) considering basic measures of Capabilities/requirements:
  1. Accuracy (Centimeters to hundreds of meters)
  2. Integrity - Probability that PNT measurement “out of Protection Limits”
  3. Signal Availability (Open sky, temporal or day to day - unjammed)
  4. Resistance to interference (A/J)

- Of course, other attributes are also important, such as:
  5. Long-Term Guarantees of Availability
  6. User Costs (recurring/non-recurring)
  7. Geographic coverage (local/regional/oceans/polar)
  8. Indoors Coverage
  9. System Level Vulnerability
  10. Time to full Operational Capability (now up to ten years)

- And Ultimately:
  - Applications served or not served
1. GPS System Capabilities General Receiver

- Accuracy: cm
- Time to full capability: 5
- System Level Vulnerability: 4
- Indoors Coverage: 3
- Geographic Coverage: 5
- User Costs: 5
- Signal Availability: 5
- Interference Resistance: 4
- Long Term Guarantees: 5

GPS - General Receiver
2. GPS Capabilities General Purpose versus High Performance

- GPS Capabilities for HPR
- GPS - General Receiver

- Accuracy
- Integrity
- Signal Availability
- Interference Resistance
- Long Term Guarantees
- User Costs
- Indoor Coverage
- Geographic Coverage
- System Level Vulnerability
- Time to full capability

Accuracy: 5 cm
Integrity: 5 dm
Signal Availability: 5 m
Interference Resistance: 200 m
Long Term Guarantees: 5
User Costs: 5
Indoors Coverage: 3
Geographic Coverage: 5
System Level Vulnerability: 5
Time to full capability: 5
3. GPS System Capabilities with WAAS

- GPS General Capabilities
- GPS with WAAS

Accuracy: 5 cm

Time to full capability: 4 dm

System Level Vulnerability: 3 m

Indoors Coverage: 3

Geographic Coverage: 4

User Costs: 5

Signal Availability: 5

Interference Resistance: 3

Long Term Guarantees: 5
5. GPS with WAAS and Aircraft Landing Requirements

Red is within Blue
- GPS with WAAS/LAAS meets Landing (Regional) requirements -

Except for a preferred increase in Jamming Resistance
**Strategy 2: Toughen** GPS receivers against natural and human interference

- Techniques for making GPS *receivers* virtually Jam and Spoofing immune (“Toughening”) have been known and demonstrated for the last 40 years - were first tested in 1978.
  - Major Techniques: 1. New signals and signal processing. 2. Deep integration with inertial sensors, 3. use of multiple element Digital Beam steering antennas (CRPAs)
- This is a largely underemphasized strategy - although being pursued by some manufacturers
- Reasons for neglect:
  - Perceptions of excessive cost - particularly retrofit for Aircraft
  - Conformal (flat) Antennas would benefit from a 1 meter diameter
  - New L5 signal not yet operational
  - Federal regulations (ITAR) have precluded use of more than three element’s in beam-steering antennas

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But Receiver Toughening is clearly the quickest solution to threats of J&S
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**Example**: Phased array technology is well known and has been deployed for at least 44 years

- Pave-paws Radar
- 2677 elements
- UHF, Solid State
- Operational 1978
Phased-array technology AN/TPS -59/77

L-band pencil beam search radar with solid-state transmitters. The AESA principle uses active transmitters in each individual antenna in the 44-by-32 antenna array.
4. GPS HPR and high A/J Capabilities

Green shows A./J improvement with Inertial plus Digital, multi-element antenna.
Denial Radius of 1Kw Jammer (Kilometers)

Three GPS signals: L1 C/A, L1C, and L5

Left side: No Receiver Augmentation,
Right Side: CRPA and Inertial Augmentation

1 Kw Jammer Denial Radius - Kilometers

State

L1 C/A

Without Receiver A/J Augmentation

With Inertial and CRPA Augmentation
A 16 element phased array antenna
6-10 weeks to release the product
(Ahmet Erdem)

8 element phased array antenna
“over 2500 sold” (this and other 8 element products)

The world’s smallest
Anti-Jamming solution for
civilian applications

8 element phased array antenna

GNSS signals.

The system eliminates interference by applying novel beamforming techniques. With an 8-array CRPA antenna, the system can assure the normal operation of GNSS receiver in presence of interference from jamming sources.

GNSS CRPA System can be employed using various configurations and military GPS receivers for the land, sea, air platforms (including drones) and fixed installations. The product has an embedded GNSS receiver that supports all satellite constellations. Wide bandwidth of the system also enables the SBAS signals to GNSS receiver.
Turkish company CEO claims they have sold over 2500 of these 8 element antennas. Intend to release 16 element this year. Mostly in the middle east, many. For use on Iranian RPVs.

- So apparently, UAVs, built in Iran, with 8-element GPS A/J antennas from Turkey, are flying for the Ukrainians.
- Jamming resistance is claimed to be 100,000 times that allowed by our government for commercial aircraft.
- If our commercial aircraft were so equipped, the US concerns of GPS interference would nearly vanish.
- Who in the US government is responsible for fixing this obviously ineffective restriction on technology?
Digital Phased arrays - the keys to near jamming and spoofing immunity

• Technology known and deployed for at least 45 years
• For GPS, provides increased Jamming resistance factors of 10,000 of more
• US Government denies access to this technology for civil use (ITAR: must be less than 4 elements)
Toughen - Conclusions

• The L5 signal is a significant improvement over the ubiquitous L1 C/A.

• With known (and demonstrated) toughening techniques, the high-powered Jammer threat can be reduced by factors of over 10,000*.  

• **ITAR has been a major impediment through restrictions that preclude the needed, beam-forming (and interference-rejecting) digital antennas. Needs USG action.**

• Small highly-capable digital devices have plummeted in cost - should accelerate market introduction that was slow due to toughened receiver cost

• **Manufacturers and Sensitive user groups should be encouraged to pursue Digital, steered-beam antennas - particularly commercial aviation, self-driving vehicles, and maritime.**

* 1kW jammer effective area reduced from about a million square km to about 2.5 square km.*
Strategy 3: **Augment** - with additional GNSS/PNT sources and Techniques

- Augmenting/replacing GPS is the current USG focus for resolving jamming and spoofing or system vulnerability issues
  - Examples: LEO/Comm Satellites, eLORAN, Inertial Navigators, fiber for timing
  - Other GNSS also can augment, both with or without assured integrity (WAAS look-alikes)
- Generally supported by the PNTAB - we feel that implementing augmentation is long overdue, “**we have admired the problem long enough**”
  But let us be clear: **“None Of The Known Augmentation Techniques Can “Replace GPS/GNSS” For Most High-Value/High-Precision Applications.**
- Objective assessment of Augmentation Systems should consider all **significant** System Attributes and compare to User Requirements
6. LEO signals of Opportunity

**Issues:**
1. Integrity
2. Long Term Guarantees
3. Time to full capability

**LEO signals of Opportunity**

- GPS with WAAS
- LEO of Opportunity

- Accuracy
- Integrity
- System Level Vulnerability
- Signal Availability
- Interference Resistance
- Indoons Coverage
- Geographic Coverage
- User Costs
- Long Term Guarantees
- Time to full capability
7. Dedicated LEO with Long-term Government Guarantees

**Improvements:**
1. Integrity
2. Time To Full Capability
3. Long Term Guarantees
LEO Augmentations

• LEOs can potentially supplement or fill in for most of the non-precision applications and can operate deeper indoors

• But there are major issues

• Government Backing is needed

• A dedicated, robust Navigation Signal would be very helpful – not simply a “signal of opportunity”
### Non-Precision GPS Applications

<table>
<thead>
<tr>
<th>Categories</th>
<th>Example applications</th>
</tr>
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<tbody>
<tr>
<td>Aviation</td>
<td>Area navigation</td>
</tr>
<tr>
<td>Agriculture</td>
<td>crop spraying</td>
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<tr>
<td>Automotive</td>
<td>Turn-by-turn guidance, OnStar</td>
</tr>
<tr>
<td>Emergency and Rescue Services</td>
<td>911, ambulance, fire, police, emergency beacons, airplane and ship locaters, OnStar</td>
</tr>
<tr>
<td>Intelligent Transportation</td>
<td></td>
</tr>
<tr>
<td>Military</td>
<td>Rescue, unit and individual location</td>
</tr>
<tr>
<td>Recreation</td>
<td>GeoCaching, control of models, hiking, outdoor activities</td>
</tr>
<tr>
<td>Robotics and Machine Control</td>
<td></td>
</tr>
<tr>
<td>Scientific</td>
<td>weather forecasting, climate modeling, tsunami warning, soil moisture, ocean roughness, wind velocity, snow, ice, and foliage coverage, ......</td>
</tr>
<tr>
<td>Survey and GIS</td>
<td>tagging disease outbreaks</td>
</tr>
<tr>
<td>Timing</td>
<td>Cell phone towers, banking, power grid</td>
</tr>
<tr>
<td>Tracking</td>
<td>Fleets, assets, equipment, shipments, children, Alzheimer’s patients, wildlife, animals, law enforcement, criminals, parolees, ......</td>
</tr>
</tbody>
</table>
### Categories

<table>
<thead>
<tr>
<th>Categories</th>
<th>Example applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aviation</td>
<td>Precision and non-Precision Landing To Cat III, Nextgen</td>
</tr>
<tr>
<td>Agriculture</td>
<td>Autofarming: Precision Cultivating, Yield Assessment</td>
</tr>
<tr>
<td>Automotive</td>
<td>Driverless Cars And Trucks</td>
</tr>
<tr>
<td>Emergency and Rescue Services</td>
<td>IFR Rescue Helicopters</td>
</tr>
<tr>
<td>Intelligent Transportation</td>
<td>Train Control And Management, Precision UAVs, Intelligent Highways</td>
</tr>
<tr>
<td>Military</td>
<td>Precision Weapon Delivery,</td>
</tr>
<tr>
<td>Recreation</td>
<td></td>
</tr>
<tr>
<td>Robotics and Machine Control</td>
<td>Bull Dozers, Earth Graders, Mining Trucks, Oil Drilling</td>
</tr>
<tr>
<td>Scientific</td>
<td>Earth Movement And Shape, Atmosphere, Ionosphere, Space Weather,</td>
</tr>
<tr>
<td>Survey and GIS</td>
<td>Mapping, Tectonic Motion Monitoring,</td>
</tr>
<tr>
<td>Timing</td>
<td>Require High Availability but do not press accuracy</td>
</tr>
<tr>
<td>Tracking</td>
<td></td>
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</table>
Augmentation SUMMARY

• None Of The Known Augmentation Techniques Can “Replace GPS/GNSS” For Most High-Value/High-Precision Applications.

• Augmentations have good promise for the non-precision applications such as shown earlier

• In comparisons, a pivotal issue is vulnerability to Jamming and Spoofing. GPS toughening can, largely, prevent harmful interference. This deserves higher priority in terms of funding and priority.
  • ITAR restrictions on number of beam-steering antenna elements should be completely removed. The techniques and inexpensive basic devices are widely understood and available
Summary of Recommendations

• **Protect** the spectrum and silence interference sources. Immediately prototype, rapidly evolve and deploy J911.

• **Toughen** our GPS satellite receivers through the known techniques, *unhampered by outdated government restrictions* (ITAR).
  
  • This is the only known way to meet the accuracy, availability, integrity and Jamming resistance requirements of the high precision applications which reap the greatest economic benefits.

• Select and field **augmentation** techniques (eLORAN, and LEOs with dedicated and supported signals), but recognize that they cannot be used for many of the precision and safety-of-life PNT applications (*the GPS economic benefit study showed these applications provide 10s of billions of $ of yearly economic benefits to US*)

• **Protect, Toughen, and Augment** are complementary. No one of these is adequate by itself.
Current PNTAB Assessment:

“No current or foreseeable alternative to GNSS (Primarily GPS) can deliver equivalent accuracy (to millimeters, 3D), integrity, and world wide 24/7 availability.”
Accuracy and Integrity of Positioning (Notional) - System Needs for Precision or Safety-of-Life Applications

Required Accuracy and Integrity
(Expect 1 case of misleading information per X Samples

Accuracy - Meters

ICAQ Requirement for LI Phases

Safety of Life Integrity, ?

PNT RTK/Survey/Carrier Differential

X - Number of samples per out of Protection Limits results

0.01 0.1 1 10 100 1000 10,000 100,000 1,000,000 10,000,000

PNT RTK/Survey/Carrier Differential

11/3/22

PNT Issues 2022
Accuracy and Integrity of Positioning - System Capability for Precision or Safety-of-Life Applications

Required Accuracy and Integrity
(Expect 1 case of misleading information per X Samples)

X - Number of times X case per out of Protection Limit results
Accuracy and Integrity of Positioning - System Capability and Application Requirements

Required Accuracy and Integrity
(Expect 1 case of non-synched data information per X Samples)

Accuracy - Meters

1000
100
10
1
0.1
0.01
0.001
10,000,000
1,000,000
100,000
10,000

GPS Capabilities - Including WAAS, RTK and Differential Carrier

Planned eLORAN

Planned LEO/COMM

X - Number of Samples per out of Protection Limit results

11/3/22

PNT Issues 2022
Accuracy and Integrity of Positioning - System Capability and Application Requirements

Required Accuracy and Integrity
(Expect 1 case of information per X Samples)

- Accuracy - Meters
- GPS Capabilities - Including WAAS, RTK and Differential Carrier

- Planned LEO/COMM
- Planned eLORAN

X - Number of Protection Limit results

11/3/22