SPACE-BASED POSITIONING
NAVIGATION & TIMING
NATIONAL ADVISORY BOARD

NATIONAL SPACE-BASED POSITIONING, NAVIGATION, AND TIMING ADVISORY BOARD

Twenty-Fifth Meeting

December 9-10, 2021

Sheraton Pentagon City

Arlington, VA

ADM (USCG, ret.) Thad Allen, *Chair*

Mr. James J. Miller, *Executive Director*

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Agenda

(https://www.gps.gov/governance/advisory/meetings/2021-12/)

THURSDAY, DECEMBER 9, 2021		
Livestream Recording: https://youtu.be/LqxHHlesxFQ?t=280		
8:30 - 8:35	**BOARD CONVENES** *Call to Order, Logistics, & Announcements*	Mr. James J. Miller, *Executive Director, National Space-Based PNT Advisory Board, NASA HQ*
8:35 - 8:55	Welcome Remarks	Hon. Pamela Melroy, *NASA Deputy Administrator*
8:55 - 9:25	Kick-Off of 25th PNTAB Meeting: *Roundtable & Brief Introduction of New Members, Remembrance of Brian Ramsay* ***VIEW PDF (443 KB)***	ADM Thad Allen, *Chair, PNTAB;* All Members
9:25 - 9:55	The Need to Protect, Toughen, & Augment GPS for All Users ***VIEW PDF (1 MB)***	Dr. Brad Parkinson, *1st Vice Chair, PNTAB*
9:55 - 10:25	GPS Program Update: *GPS III/IIIF Payloads & Capabilities* ***VIEW PDF (1 MB)***	Capt Jonathan Teer, *Lead Engineer, PNT Signals Management, Space Systems Command, U.S. Space Force*
10:25 - 10:55	National Security Council (NSC) Briefing: *Maintaining GPS as Critical Infrastructure*	Ms. Caitlin Durkovich, *NSC, Executive Office of the President*
10:55 - 11:10	**BREAK**	
11:10 - 11:40	DoD Perspectives and Priorities for the PNT Advisory Board	Mr. Fred Moorefield, *Deputy Chief Information Officer, Command, Control, and Communication (C3), DoD CIO, Co-Chair, PNT EXCOM Executive Steering Group*
11:40 - 12:10	U.S. / Russia Technology Resilience Gap	Mr. George Beebe, *VP and Director of Studies at Center for the National Interest*
12:10 - 12:30	Morning Session Wrap-Up: *Member Feedback on Areas for Further Discussion*	All Members
12:30 - 1:40	**LUNCH**	
1:40 - 2:05	Galileo High Accuracy Service (HAS) ***VIEW PDF (2 MB)***	Dr. Ignacio Fernandez-Hernandez, *Galileo Authentication & HAS Manager, European Commission*
2:05 - 2:30	Global Differential GPS (GDGPS) Task Force: *Preliminary Fact-Finding Report* ***VIEW PDF (601 KB)***	Dr. John Betz, *Chair, GDGPS Task Force*
2:30 - 2:55	A Resilient National Timing Architecture ***VIEW PDF (3 MB)***	Mr. Dana Goward, *RNT Foundation & PNTAB Member*
2:55 - 3:20	GPS & Galileo Civil Signal Authentication ***VIEW PDF (9 MB)***	Mr. Logan Scott, *President, Logan Scott Consulting*
3:20 - 3:45	Lunar GNSS Utilization: From Vision to Reality *A NASA PNT Update* ***VIEW PDF (4 MB)***	Mr. Joel J.K. Parker, *PNT Policy Lead, GSFC, NASA*
3:45 - 4:00	**BREAK**	
4:00 - 4:25	Digital Flight Rules Enabled by GPS: *Modernization of the National Airspace System* ***VIEW PDF (566 KB)***	Capt. William Cotton, *Founder & President, Cotton Aviation Enterprises, Inc.*
4:25 - 4:50	Using UAVs in GPS-Denied Environments ***VIEW PDF (4 MB)***	Mr. Pramod Raheja, *CEO, Airgility*
4:50 - 5:15	UAV Roadmap Follow-Up from 2015/2018 ***VIEW PDF (444 KB)***	Dr. Jim Farrell, *Owner, VIGIL,* & Mr. Bill Woodward, *PNT Committee Chair, SAE Int.*
5:15 - 5:40	FCC Spectrum Regulation: *Addressing Perceived Conflicts with Safety & National Security Systems* ***VIEW PDF (345 KB)***	Hon. Jeff Shane, *IATA Representative & PNTAB Member*
5:40 - 6:00	Recap of Presentation Highlights & Closing Thoughts: *Deliberation Preparation for Dec. 10*	All members, led by ADM Thad Allen
6:00	**ADJOURNMENT**	

FRIDAY, DECEMBER 10, 2021		
Livestream Recording: https://youtu.be/lDcdUO1OGNE		
8:30 - 8:35	**BOARD CONVENES** *Call to Order*	Mr. James J. Miller, *Executive Director, National Space-Based PNT Advisory Board, NASA HQ*
8:35 - 9:05	**PNTAB Leadership Observations from Day 1:** ▪ Prioritization of Opportunities and Risks ▪ Protect, Toughen, Augment Focus Areas ▪ Establish Subcommittees to Develop Recommendations	ADM Thad Allen, *Chair, PNTAB;* Dr. Bradford Parkinson, *1st Vice Chair, PNTAB;* Gov. Jim Geringer, *2nd Vice Chair, PNTAB*
9:05 - 10:30	**Concise Observations from New Members:** ▪ Lt Gen Michael Hamel (USAF, ret.) ▪ Dr. Jade Morton ▪ Dr. Gregory Winfree ▪ Ms. Eileen Reilly ▪ Dr. Tom Powell ▪ Dr. Sonia Alves-Costa ▪ Dr. Vahid Madani ▪ Dr. Renato Filjar ***VIEW PDF (424 KB)*** ▪ Mr. David Grossman	New members, led by Chairs; All member observations are welcome
10:30 - 10:45	**BREAK**	
10:45 - 11:45	**Roundtable Discussion -- Recommendation Formulation:** ▪ Organization of Work for 2021-2023 (Subcommittees, Task Forces, etc.) ▪ Developing Findings & Recommendations	All members, led by Chairs
11:45 - 12:00	**Wrap-Up:** ▪ Workplan Priorities, Schedule, & Timeline for Deliverables ▪ Recognition of Subject Matter Expert Contributions to PNTAB: ○ Dr. Scott Pace & Mr. Logan Scott ▪ Closing Remarks	ADM Thad Allen, *Chair, PNTAB;* Dr. Bradford Parkinson, *1st Vice Chair, PNTAB;* Gov. Jim Geringer, *2nd Vice Chair, PNTAB*
12:00 - 1:00	**LUNCH** — *Working as needed*	
1:00	**ADJOURNMENT**	

Table of Contents

Executive Summary

The 25th Federal Advisory Committee Act (FACA) session of the National Space-Based Positioning, Navigation, and Timing Advisory Board (PNTAB) was held December 9-10, 2021 in Arlington, Virginia.

The session included a two-hour deliberation of tasks, objectives, and priorities for the board in the 2021-2023 term, including the potential recommendations to the PNT Executive Committee (EXCOM).

This document summarizes the key briefing points and deliberations during this meeting. Snapshots of some of the briefing slides are included in the minutes for clarity.

Links to the briefings and live-stream recordings are embedded in the meeting agenda (pp 3-4). They can also be accessed through the Global Positioning System (GPS) Portal (https://www.gps.gov/) of the National Coordination Office for Space-Based PNT (NCO).

Key Agreements & Action Items:

- The PNTAB Global Differential GPS (GDGPS) Task Force Chair, Dr. John Betz, presented its findings following 14 months of fact-finding meetings. The Task Force was established in October 2020, following deliberations at the PNTAB-24B virtual interim FACA meeting held on July 1, 2020. Its objective was to provide a Global Navigation Satellite System (GNSS) user perspective to the National Aeronautics and Space Administration (NASA) Working Group that was assessing GDGPS and developing options for its future organization and funding. Following deliberations at the PNTAB-25 meeting, a vote was held, and two recommendations were approved, which will be forwarded to the NASA Administrator.
- The PNTAB will set up subcommittees to study various topics over the 2021-2023 term. Findings will be reported to the board at subsequent FACA meetings for deliberation.
- A GPS High Accuracy Service (HAS) Task Force will be set up to study the development of a service to provide users with GPS satellite clock and orbit corrections, and ionospheric corrections over the internet with authentication through public key encryption. The Task Force findings will be presented for deliberation at a subsequent PNTAB FACA meeting.
- Other topics for study in the subcommittees include.
    - Enhancements to the energy sector (integrated electric grid)
    - Export control barriers
    - Proposal for improved PNT governance
    - Information reinforcement for GNSS resilience (to be included as part of the GPS HAS Task Force)
    - Spectrum legislation to protect critical systems
    - Endorsement and recommendation of a resilient national timing architecture within the United States (US)
    - Develop a formal partnership between GPS and Galileo
    - Taskings from the PNT EXCOM

Other Action Items:

- The next FACA meeting to be held early in May in the broader National Capital Area, to include briefings on:
    - Multi-GNSS in Positive Train Control (PTC)
    - North American Electric Reliability Corporation (NERC) GridEx Exercise

Session of Thursday, December 9, 2021

Board Convenes
Call to Order, Logistic, & Announcements
Mr. James J. Miller, *Executive Director, National Space-Based Positioning, Navigation, and Timing (PNT) Advisory Board*

Mr. Miller called to order the 25th meeting of the National Spaced-Based PNT Advisory Board. He noted a quorum was present and thanked all in attendance, particularly those who traveled internationally. He began by honoring the life and contributions of Mr. Brian Ramsay, a long-time Subject Matter Expert (SME) on the board and noted that the meeting would be held in his memory. He gave special recognition to the following persons attending this meeting: NASA Deputy Administrator Pam Melroy and Mr. Badri Younes (Deputy Associate Administrator for Space Communications and Navigation [SCaN], NASA). Mr. Miller also noted the Advisory Board was established per presidential policy, now Space Policy Directive 7 (SPD-7) for space-based PNT, to provide independent counsel to the PNT EXCOM, which consists of the deputy secretaries of thirteen federal agencies. The meeting takes place under the rules of the Federal Advisory Committee Act of 1973. He noted that formal minutes will be taken. All briefings were posted in advance of the meeting on the GPS.gov website. Members classified as Special Government Employees (SGEs) need to be mindful of any potential conflicts of interest. If they see a conflict then they must recuse themselves from discussion of that issue, with the recusal noted in the minutes. He noted the availability of meeting booklets for in-person attendees and asked all attendees for their patience with the challenges of a hybrid in-person/virtual meeting environment. With that, he turned the meeting over to ADM Thad Allen, Chair.

ADM Allen thanked the members for their attendance and turned the meeting over to Deputy Melroy, expressing his appreciation for the ongoing support from NASA.

* * *

Welcome Remarks
Hon. Pamela Melroy, *NASA Deputy Administrator*

Dep. Melroy thanked ADM Allen and Dr. Parkinson for their leadership. She mentioned that it was a great pleasure to be at the 25th PNTAB meeting, noting her personal knowledge of incorporating GPS into the cockpit of airplanes and the Space Shuttle during her career. GPS has enabled enormous changes and amazing capabilities to those systems. She officially welcomed the audience, noting that twenty-five sessions to-date indicate the long-standing worth and value of the board. On behalf of NASA Administrator Bill Nelson, she gave special welcome and greetings to the new members of the board who were recently appointed. As a unique group of experts, the new membership reflects the many diverse sectors of the GPS user community. Personally, she looked forward to supporting the efforts of this advisory board.

The PNTAB is comprised of members nominated by the PNT EXCOM departments and agencies and are appointed by the NASA Administrator. Members are nominated because they are recognized as world-class experts in PNT services and both GPS and GNSS capabilities and applications. Technical contributions and leadership in this area improve space operations and science for everyone, including civil, commercial, and military. Space is growing in every area, from commercialization capabilities around Earth, to exploring out into the solar system, to the moon and beyond to Mars. NASA's exploration plans are at the cusp of returning to the moon with the Artemis I mission. NASA's science missions are deeply enmeshed with international partners and capture the world's imagination through missions like the Perseverance rover and Ingenuity helicopter currently on Mars. Breakthroughs in space and aviation technology are happening at an incredible rate, not just in the US, but globally. GPS is a critical enabler for many sectors that already serve everyone where these and many other missions unfold. NASA looks forward to receiving expert recommendations from PNTAB on how to work together to make it operate even better in the future to serve all humankind.

Dep. Melroy then turned to look from the NASA viewpoint to emphasize what an enabler GPS has been for the agency, naming it as a force multiplier that enriches NASA science and enables more precise and safe autonomous operations in space. From space geodesy to weather forecasting, to measuring ice melt and sea level heights, to earthquake monitoring and tsunami warnings, to enabling spacecraft to fly precision formations halfway to the moon, GPS is a creation from which we continue to benefit with seemingly infinite number of potential advances for the future. Dep. Melroy emphasized that she is also fully aware of the military and economic impacts of GPS worldwide. Space is increasingly becoming deeply interlinked. The space sector has been used to thinking that areas such as national security, civil, and commercial space are separate silos, and some policy has reflected that. In Dep. Melroy's view, GPS and this advisory board are a model for how to think in the future about an integrated approach. Sometimes there is tension between all those areas, but it is necessary find a way to make the best recommendations. GPS is not only valuable in that respect, but also critical to the leadership of the US and key partners, some of whom are represented as board members.

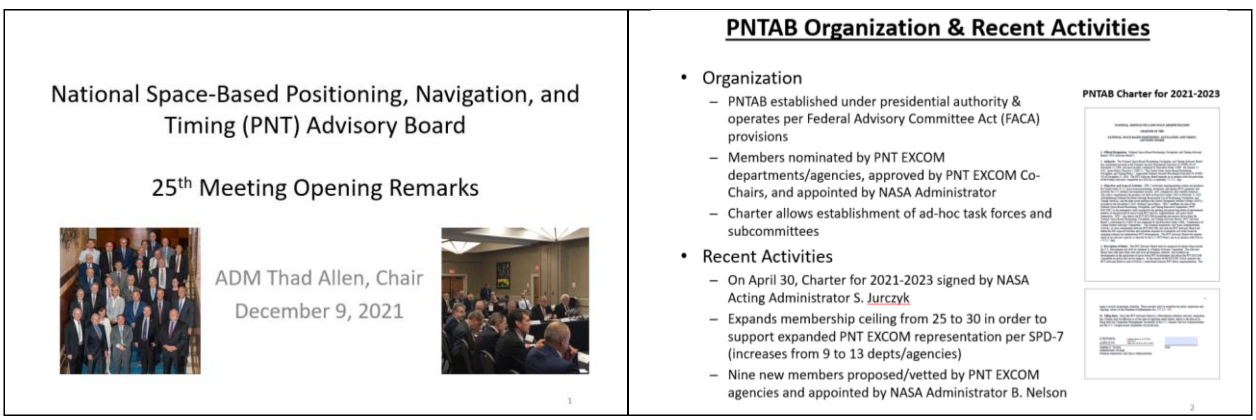
NASA sponsorship of the PNTAB is its contribution as an agency to PNT policy, which complements the technical contributions to GPS to improve service, performance, and availability. Dep. Melroy expressed gratitude for partnership with the US Air Force (USAF), US Space Force (USSF), as well as the Department of Transportation (DOT) for their advocacy on behalf of the civil user community. NASA looks forward to building on what has been achieved thus far, bringing industry, government, and academia together under one umbrella. This allows for rich conversations with other GNSS service providers. She added that this work is championed through the United Nations (UN) at the International Committee on GNSS (ICG). This partnership does not only extend to the US community, but also has significant international contributions.

Dep. Melroy highlighted some of NASA's key contributions to GPS, including developing protection standards specifically for cyber, supporting GPS modernization by furnishing laser retro-reflector payloads for GPS III, developing a Medium Earth Orbit (MEO) Search and Rescue (SAR) capability integrating GPS, and working with USSF to refine the Space Service Volume (SSV) to support users operating in cislunar space. There is almost limitless potential for the things that GPS can do. Dep. Melroy emphasized that the goal of the PNTAB is to protect and enhance the worldwide utility of GPS even as new GNSS constellations come online. GPS services such as precision timing are so deeply interwoven into the fabric of civil, national security, and commercial applications, as well as the global economy. The PNTAB has pursued a Protect, Toughen, Augment (PTA) program, on which ADM Allen and Dr. Parkinson previously briefed Dep. Melroy and the Administrator, to ensure that GPS and GNSS services will continue to be available to a user community that is growing exponentially. Dep. Melroy fully supports the PTA framework. She acknowledges the challenge of the work, noting the tension between the different needs of a diversity of users. Dep. Melroy is impressed by the diversity of the advisory capability, not just technical but also in the areas of business and users. She encouraged the board to have a vibrant dialogue and to recognize that the work being done will have a huge impact for the time to come. She looks forward to hearing the board's recommendations. As a previous member of the National Space Council (NSpC) Users' Advisory Group (UAG), she is well aware of the significance of the recommendations, which are taken very seriously by the government. She assured that the board's recommendations are heard and welcomed. She wished the board best of luck with their work and welcomed them back as face-to-face meetings resume.

* * *

Kick-off of 25th PNTAB Meeting
Roundtable & Brief Introduction of New Members, Remembrance of Brian Ramsay
ADM Thad Allen, *Chair*

ADM Allen thanked Dep. Melroy for her remarks and service to the nation. This is the first meeting of the reconstituted version of the PNTAB since the change of administration and new membership appointments, which had been delayed due to COVID-19. This is the 25th Meeting of the PNTAB, organized under FACA (Slide 1). In the past year, there was a transition of administrations, the charter was renewed, and new members were appointed (Slide 2). The board has positioned itself to move forward as aggressively as possible with the PTA framework developed over several years.



Slides 1-2

ADM Allen congratulated the new members and invited them to raise their hands when recognized: Sonia Alves-Costa, Renato Filjar, David Grossman, Michael Hamel, Vahid Madani, Jade Morton, Tom Powell, Eileen Reilly, and Gregory Winfree (Slide 3). ADM Allen has been on the PNTAB for 10 years, and noted that this is the most cognitive, ethnically, and gender-diverse board since it first met in 2007. It was clear from the preparatory meetings yesterday during the exchange of ideas and comments that the new members are bringing a rich background and expertise regarding PNT and other GNSS. He looked forward to hearing more from the new members in the discussions on Friday. ADM Allen also thanked and acknowledged the work of departing board members, including Gerhard Beutler, Sergio Camacho-Lara, Ann Ciganer, and Refaat Rashad (Slide 4).

Welcome to New Members

- **Sonia M. Alves-Costa**, Head of Geodesy, Institute Of Geography and Statistics-IBGE, Brazil (*Nominated by DOS)*
- **Renato Filjar**, Honorary Professor of Electronics Engineering, University of Rijeka, Croatia *(Nominated by DOS)*
- **David J. Grossman**, Vice President of Regulatory Affairs, Consumer Technology Association *(Nominated by DOC)*
- **Michael A. Hamel**, Independent Consultant; Commander (ret.), Space & Missile Systems Center *(Nominated by DoD)*
- **Vahid Madani**, Executive Engineer, GridTology *(Nominated by DOE)*
- **Jade Morton**, Professor, University of Colorado Boulder *(Nominated by DOI / NASA)*
- **Tom Powell**, Principal Director, The Aerospace Corporation *(Nominated by NASA)*
- **Eileen Reilly**, Chief Executive Officer, Global Train Services, LLC *(Nominated by DOT)*
- **Gregory Winfree**, Agency Director, Texas A&M Transportation Institute *(Nominated by DOT)*

Special Thank You to Departing Members

- **Gerhard Beutler,** International Association of Geodesy (Switzerland)
- **Sergio Camacho-Lara**, UN Regional Education Center of Science & Space Technology (Mexico)
- **Ann Ciganer**, GPS Innovation Alliance (U.S)
- **Refaat M. Rashad**, Arab Institute of Navigation (Egypt)

Slides 3-4

ADM Allen then paused to reflect on the contributions of Mr. Brian K. Ramsay who passed away on November 21, 2021 (Slide 5). Brian Ramsay spent many years as subject matter expert to the PNTAB.

Mr. Badri Younes also spoke about Mr. Ramsay's passing, noting the deep impact it had on the entire community. Brian was a tremendous asset throughout his many years of service, from his early days in the USAF, providing support to Fred Moorefield at the Department of Defense (DoD), to coming to NASA to work for NASA's missions. His heart was always for the Air Force and he pivoted back to that community later in his career. Mr. Younes knew Mr. Ramsay for 25 years. He was a person of great caliber and technical excellence, and he will be missed tremendously. NASA prepared a small montage in recognition for his contributions to the PNT community at large, but also to NASA and USAF (Slide 6).

Mr. Miller presented the montage to the family of Brian Ramsay, watching online. He read the dedication on the montage, "With our deepest gratitude, the NASA community is thankful for your friendship and dedicated professional support over many years to protect the radio spectrum that Global Positioning System users worldwide have come to rely on. You have been and will always be in our hearts as part of the National PNT Advisory Board established to help serve millions of users around the world. You have made a positive difference to all you have touched, and we will remember." Mr. Miller added that Mr. Ramsay was not only a colleague, but a friend. Mr. Miller noted Mr. Younes' signature on the front and turned the montage to show signatures from PNTAB members on the back.

ADM Allen read the message he had shared with Brian's family following the news of his passing: "This is Admiral Thad Allen. I chair the PNT Advisory Board your Dad so ably supported. Our entire PNT 'Family' held your Dad in the highest regard and depended on his technical expertise, organizational insights, and a knowledge of federal regulatory law that distinguished him from his peers. I personally relied on his advice and knack of reducing complicated concepts to useful narratives that helped me make our case. He prepped me for Congressional testimony and was always there when I called or emailed, day or night. He will be sorely missed and was much admired. There are some people you can replace, but there are others that are irreplaceable. We are going to have to learn to live without your Dad and our lives are diminished. We will always strive to reflect his work ethic and values in our work ahead. With deepest sympathy and respect." Brian, we thank you.

In Memoriam

BRIAN K. RAMSAY

Subject Matter Expert, PNT Advisory Board

Brian K. Ramsay, 63, of Winchester, passed away on Sunday, November 21, 2021. He was a valued member of the PNT board community, and his absence will be felt deeply.

He served 4 years in the US Air Force where he found his professional calling. He spent the next 25+ years helping to guide domestic and international spectrum management policy and regulation while working at US State Department, NTIA, NASA, Iridium, Lockheed Martin, MITRE, Booz Allen Hamilton, and Arinc Research, and served as a US delegate to numerous World Radio Conferences (WRC-95, 97, 2000, 07, 12, 15).

Brian enjoyed hunting, fishing and relaxing at his property in WV. After retirement he took up golf and enjoyed playing often. Brian loved being with his family and friends. He is survived by his wife Holley Winborne Ramsay of Winchester; his mother, Carolyn H. Ramsay of Strasburg, VA; two daughters, Erin Ramsay of Winchester and Caitlyn Ramsay of Martinsburg, WV.

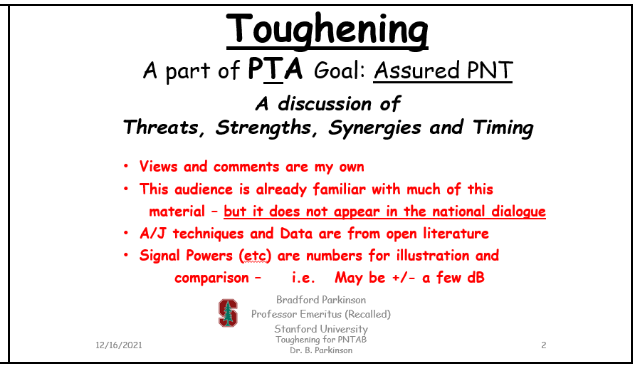
Slides 5-6

ADM Allen then introduced Dr. Parkinson to begin his presentation.

* * *

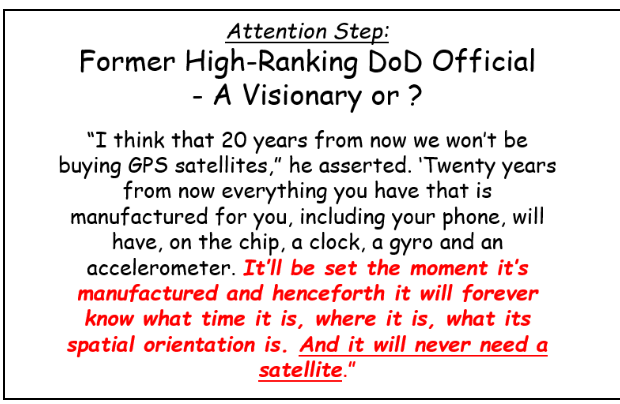
The Need to Protect, Toughen, & Augment GPS for All Users
Dr. Bradford Parkinson, *1st Vice-Chair, PNTAB*

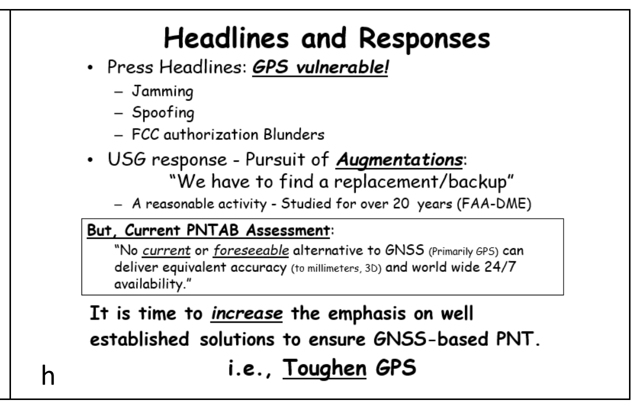
The cover slide depicts applications, including aviation, unmanned aerial vehicles (UAVs), cargo ships, and emergency responders, where their position is taken from GPS (Slide 1). But there are increasing numbers of threats to GPS, including jammers and spoofers, that place these applications in harm's way. Dr. Parkinson believes we should get ahead of that threat. The overall goal of the board is to Protect, Toughen, Augment (Slide 2). On the topic of toughening, Dr. Parkinson will review threats, strengths, synergies, and timing. It should be noted that these views and comments are his own and not the board's. While the audience is already familiar with much of this material, the national dialogue has been tilted in a certain way and he would like to get it re-tilted. The techniques and data here presented are well known and come from open literature. The specific figures presented and other data, are intended for illustration and comparison and, thus, it is possible some could be slightly off.



Slides 1-2

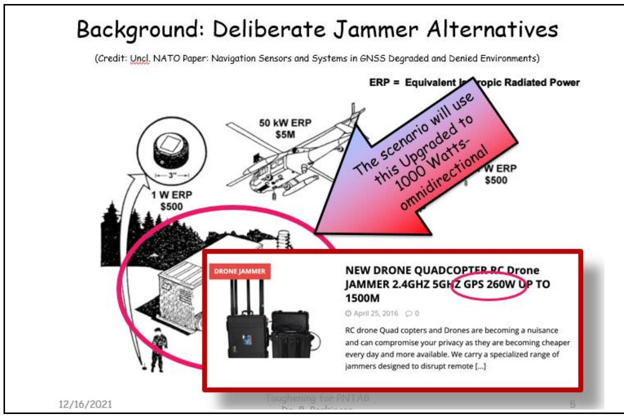
The attention step shown here is an example of public statements that have received a lot of media attention (Slide 3). A former high-ranking DoD official once said that in the future we wouldn't buy GPS satellites and instead would use a clock, a gyroscope, and accelerometers to determine PNT without needing GPS satellites. This statement resulted in press headlines about GPS being vulnerable and, in turn, a government response focusing on augmentations to GPS, such as pursuing of a backup (Slide 4). However, the board's assessment is that there is no current or foreseeable alternative to GPS, or other GNSS, that delivers high accuracy and is available worldwide 24/7. Therefore, the question is how we balance what we are doing, and Dr. Parkinson thinks it is time to increase our emphasis on well-established solutions to toughen GPS.

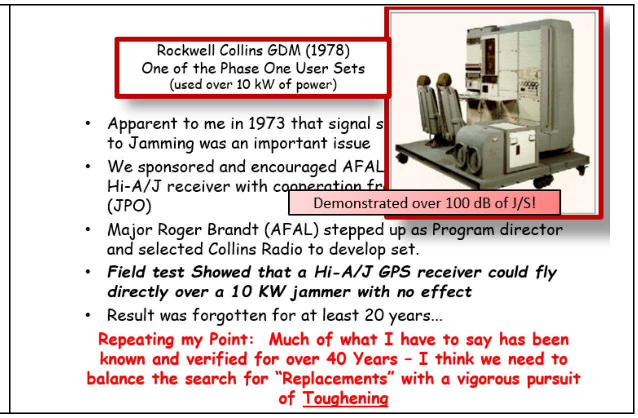




Slides 3-4

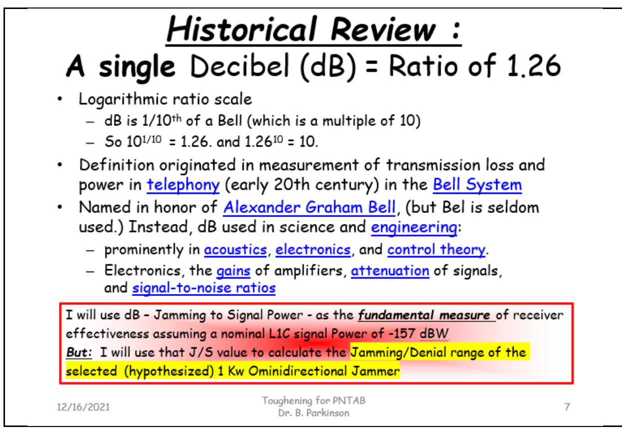
There are a wide range of available jammer threats to GPS, ranging from small 1W (Watt) jammers to large 100 kW jammers (Slide 5). The first example is a 1 kW jammer, which nowadays can be found on the internet for as little as $300. Back in 1973 it became obvious to Dr. Parkinson that the weakness of signals transmitted from space makes them susceptible to jamming (Slide 6). Therefore, the GPS Joint Program Office (JPO) sponsored the Air Force Astronautics Laboratory (AFAL), now Air Force Research Laboratory (AFRL), to build a high anti-jamming (A/J) receiver. A vintage (1978) receiver was used, which was large but served the purpose to demonstrate what we could do, including protection for a 100 dB jamming-to-signal (J/S) level. The point is that much of what he has to say has been very well known for decades.

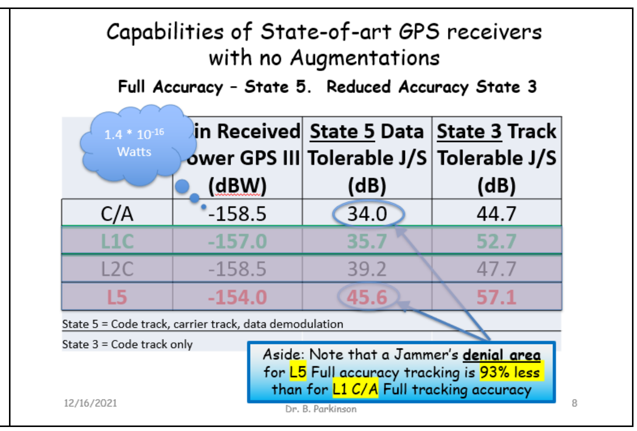




Slides 5-6

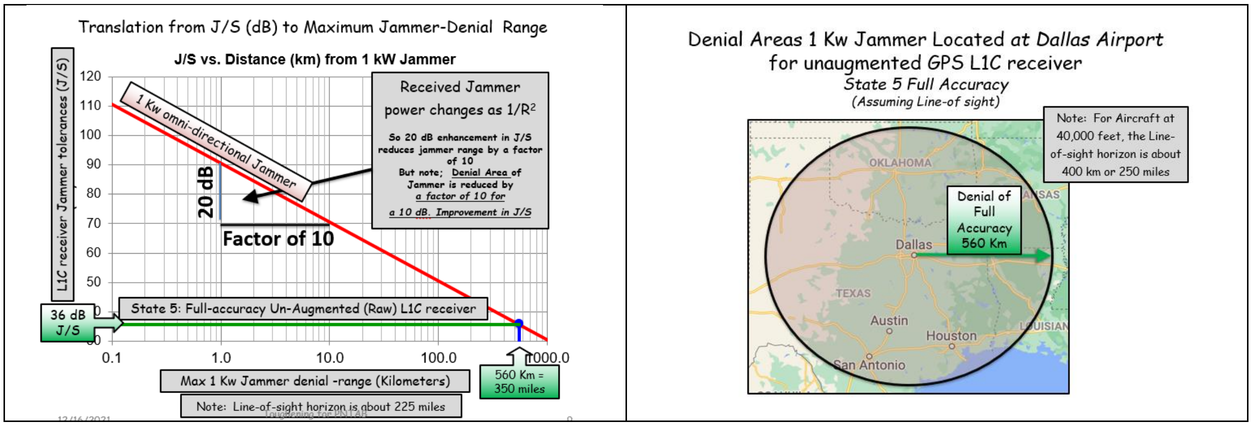
Decibels (dB) are used to express the logarithmic (base 10) power ratio of two on signals (Slide 7). Two signals whose power level differ by 1 dB have a power ratio of $10^{1/10}$, which is equal to 1.26. [Editor's note: Therefore, two signals differing by 10 dB have a power ratio of 10, two signals differing by 20 dB have a power ratio of 100, and two signals differing by 30 dB have a power ratio of 1000, etc. Also, two signals differing by -10 dB have a power ratio of 0.1, two signals differing by -20 dB have a power ratio of .01, and so on]. This briefing uses the decibel J/S as measure of receiver effectiveness for a nominal GPS L1C received signal power of -157 dB. He also used J/S to calculate the jamming/denial range of the hypothetical 1 kW omnidirectional (i.e., transmitting in all directions) jammer. Next, he compared the capabilities of un-augmented state-of-the-art GPS receivers (Slide 8). In this example, a GPS receiver tracking L1 C/A (coarse acquisition, the basic GPS signal) has a minimum receiver power of -158.5 dBW, which is equivalent to 1.4×10^{-16} W. The ability of this receiver to resist jamming is 34 dB (for full accuracy using code track, carrier track, and data demodulation), and if it can't achieve that the receiver can revert to code track only and resist jamming up to 44.7 dB though providing reduced accuracy. GPS L1 C/A is one of four civil signals that come from GPS satellites. When using the L2C (GPS 2nd civil frequency, for commercial applications such as surveying), L5 (GPS 3rd civil signal, for aviation), and L1C (GPS 4th civil signal, for interoperability with Galileo) signals the capabilities of this receiver are different. The GPS L5 signal provides the largest tolerance to jamming.





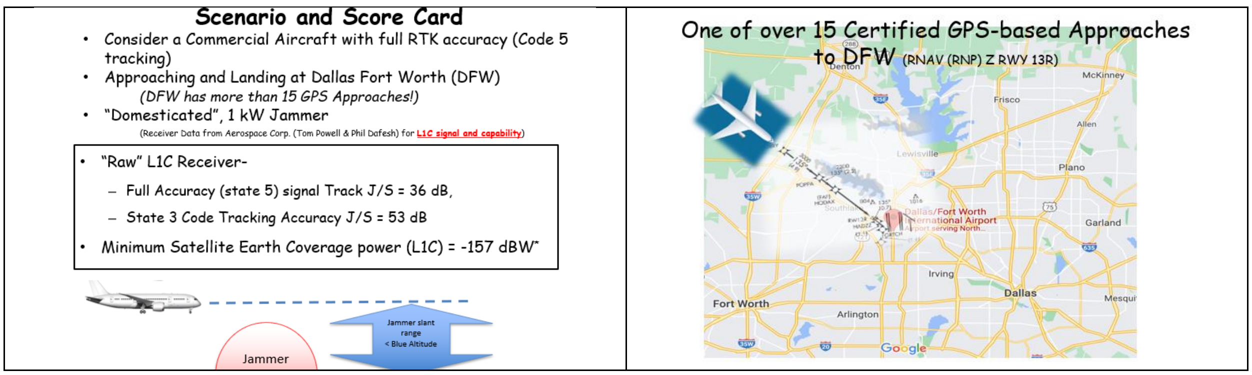
Slides 7-8

He then turned to discuss an example on how to translate J/S (dB) to the maximum jammer-denial range (Slide 9). The red line on the logarithmic chart shows the denial radius of a 1 kW jammer on an L1C receiver. As the distance between the receiver and the jammer increases, so does the receiver's tolerance to jamming. The green line indicates a 560 km radius (R), which corresponds to a 36 dB J/S tolerance (for obtaining full accuracy). The strength of the jammer's signal decreases with the square of the distance ($1/R^2$). Now let's place this 1 kW jammer in Dallas Fort Worth (DFW) Airport (Slide 10). The receiver's tolerance to jamming is 36dB J/S, so within 560 km of DFW this receiver will be denied full accuracy.



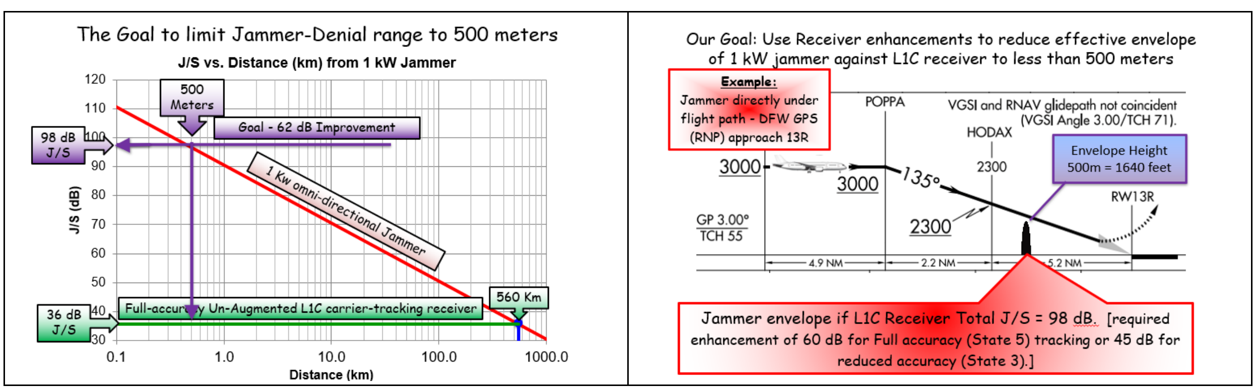
Slides 9-10

Let's consider a commercial airplane flying into DFW using the L1C receiver (where J/S is 36 dB for full accuracy [State 5] and J/S is 53 dB for reduced accuracy [State 3]) (Slide 11). In this scenario, the aircraft will follow one of over 15 certified GPS-based approaches to DFW (Slide 12).



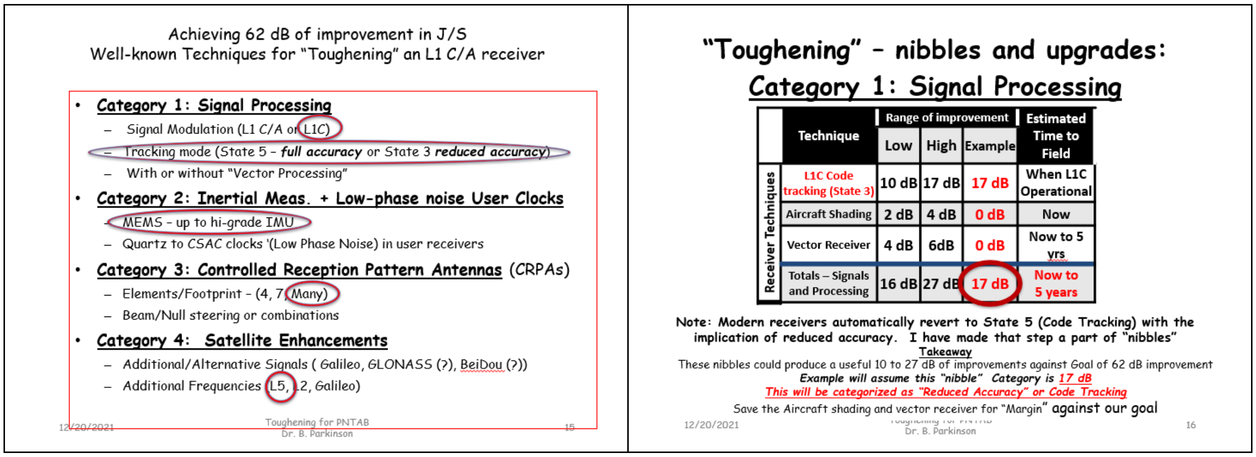
Slides 11-12

Now, let's assume we want to limit the denial range of the 1kW jammer to only 500 meters (m) (Slide 13). This would require a 98 J/S power ratio tolerance, which corresponds to an improvement of 62 dB J/S over the 36 dB J/S power ratio tolerance for full accuracy in our un-augmented L1C receiver. A 62 dB improvement in J/S would enable an aircraft following DFW GPS (Required Navigation Performance, or RNP) Approach 13R to remain totally unaffected should the 1kW jammer be placed ~ 3 miles ahead of the runway (slide 14).



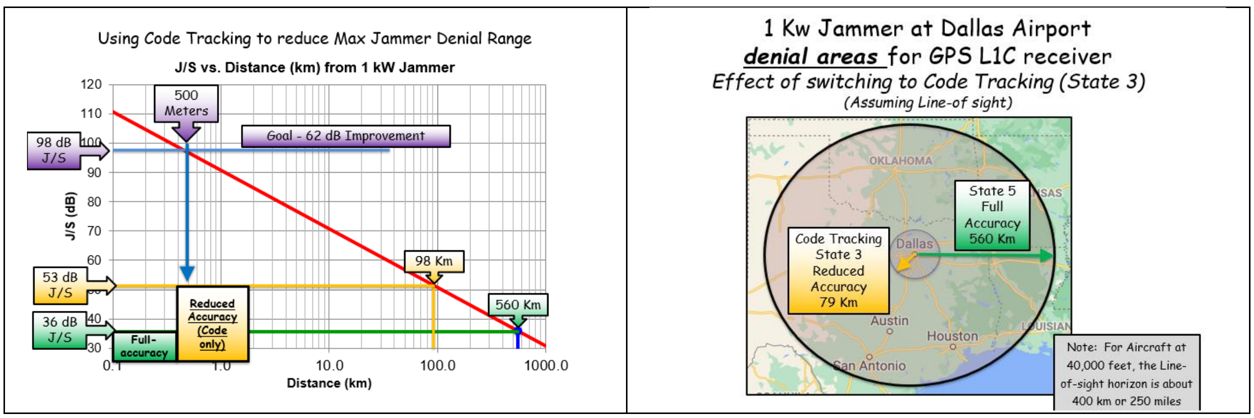
Slides 13-14

There are some techniques that can be used to toughen the receiver and increase the J/S power level tolerance (Slide 15). These include: (1) signal processing using different signal modulations (L1 C/A or L1C) and tracking modes; (2) inertial measurements and clocks; (3) controlled reception pattern antennas (CRPA), including having many elements to the receiver antenna; and (4) satellite enhancements (additional frequencies, such as L2C, L5, Galileo signals, etc.). If we look at Category 1 (Signal Processing), we can go from State 5 (full accuracy) to State 3 (partial accuracy) and pick up 17 dB in protection from jamming (Slide 16). This means that accuracy typically goes from a few centimeters (cm) to a few m. This is our first 'nibble' to toughen the receiver.



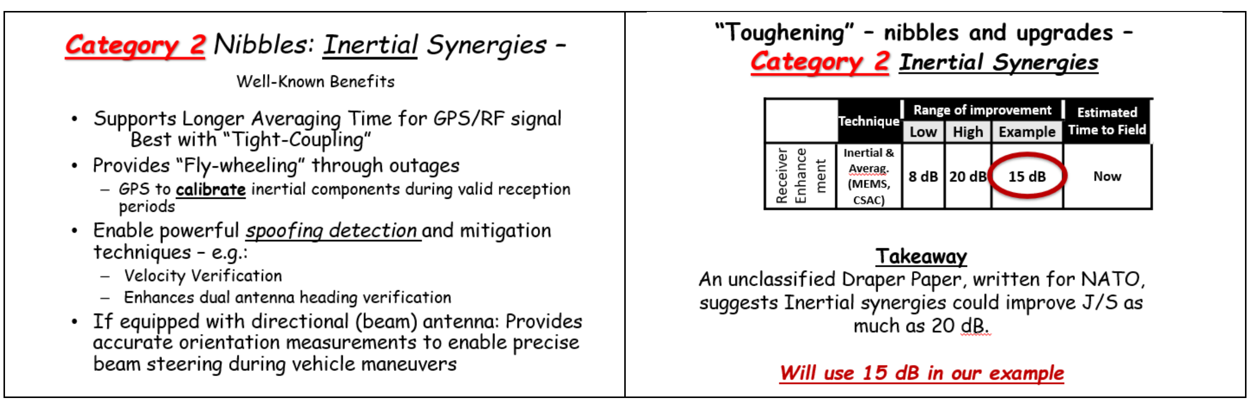
Slides 15-16

Therefore, when stacking this onto the J/S vs. distance chart for a 1 kW jammer, we have reduced the denial circle from 560 km to 98 km (yellow line in chart, Slide 17). When projecting the jamming 'bubble' in three dimensions, this means that an aircraft flying at 40,000 feet (ft) will not enter the denial area until 79 km from the airport (Slide 18).



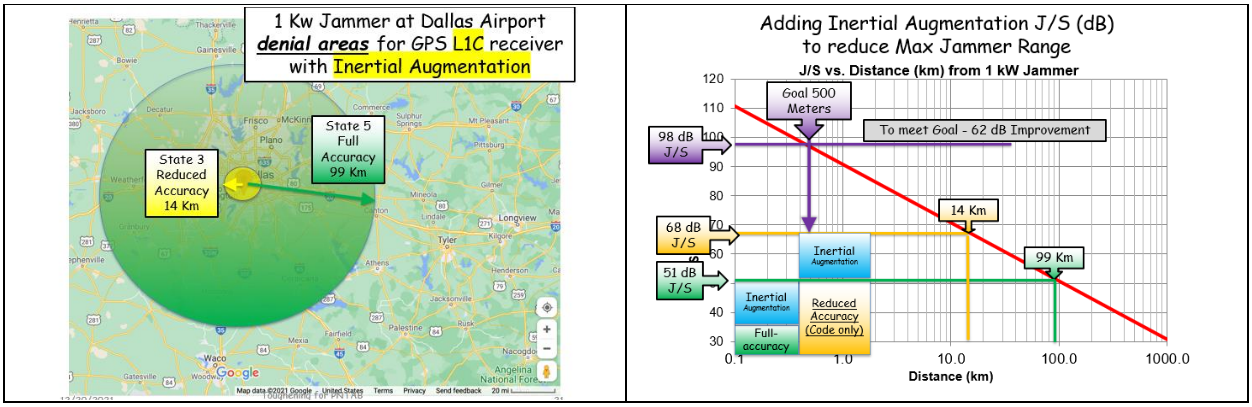
Slides 17-18

He then turned to inertial systems as another 'nibble' to toughen receivers (Slide 19). Inertial systems support longer averaging time for GPS signals because they allow you to 'tight-couple' and narrow the bandwidth and, hence, exclude noise. It provides for fly-wheeling through the outages and enables to detect spoofing. When combined with a directional (beam) antenna in the receiver, these inertial components allow to 'steer' the beam in exactly the right direction. When reviewing the available literature, you will find claims of J/S improvement up to 20 dB (Slide 20). Dr. Parkinson will use 15 dB to show what the impact is.



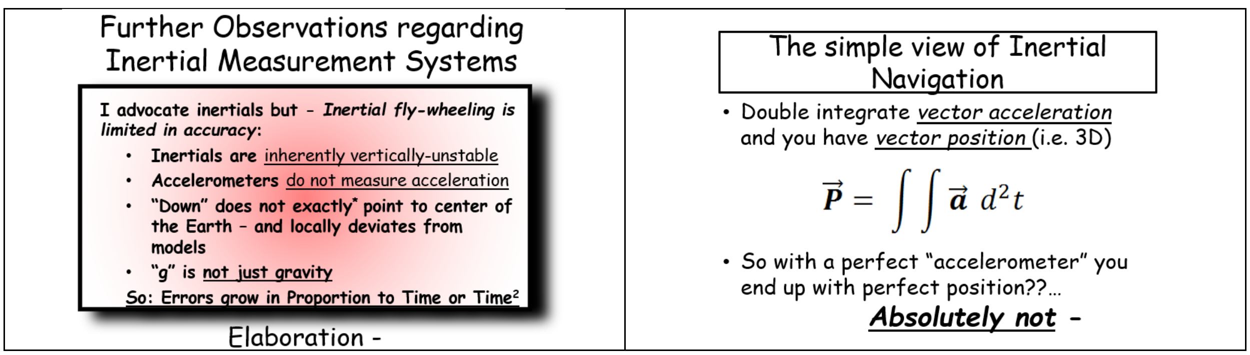
Slides 19-20

The 15 dB improvement using inertial strategies reduces the denial area from 560 km to 99 km for State 5 tracking (full accuracy), and to 14 km for State 3 tracking (reduced accuracy) (Slide 21). Shown on the J/S vs. distance chart for the 1 kW jammer, we can see the progress we've made (Slide 22). The green line shows the improvement when using the inertial augmentation with State 5 tracking (full accuracy), whereas the yellow line shows the improvement when using the inertial augmentation State 3 tracking (reduced accuracy).



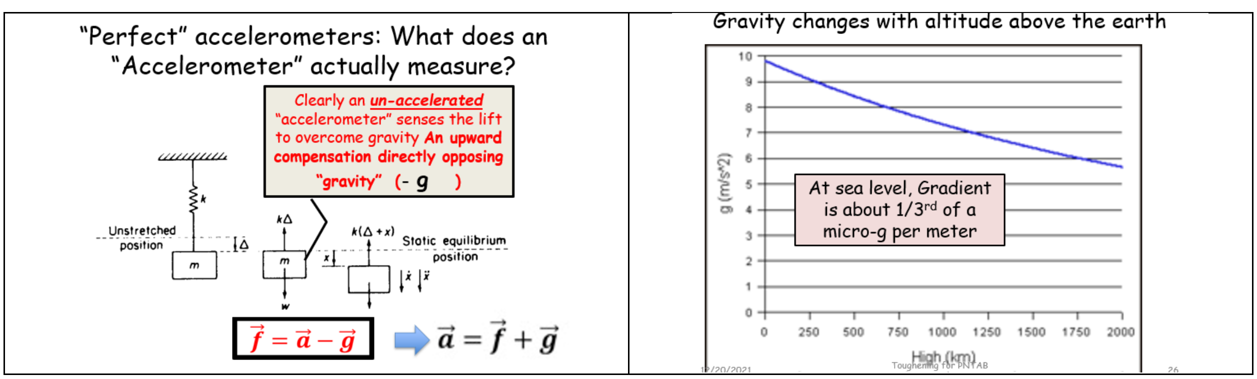
Slides 21-22

While Dr. Parkinson advocates for the use of inertial, we need to understand there are some limitations to their use (Slide 23): (1) They are inherently unstable vertically; (2) Accelerometers don't actually measure acceleration. They are specific force sensors; (3) 'Down' does not exactly point to the center of Earth because Earth is not a perfect sphere; and (4) what we call 'g' is not just gravity, because it includes the centripetal acceleration to the fact that we are on a merry-go-round due to Earth's rotation. This acceleration makes us a little 'lighter' the closer we are to the equator. All these must be accounted for. The simple view of an inertial navigator is that you take the acceleration and then you integrate it twice to get a position vector. However, we need to elaborate this further (Slide 24).



Slides 23-24

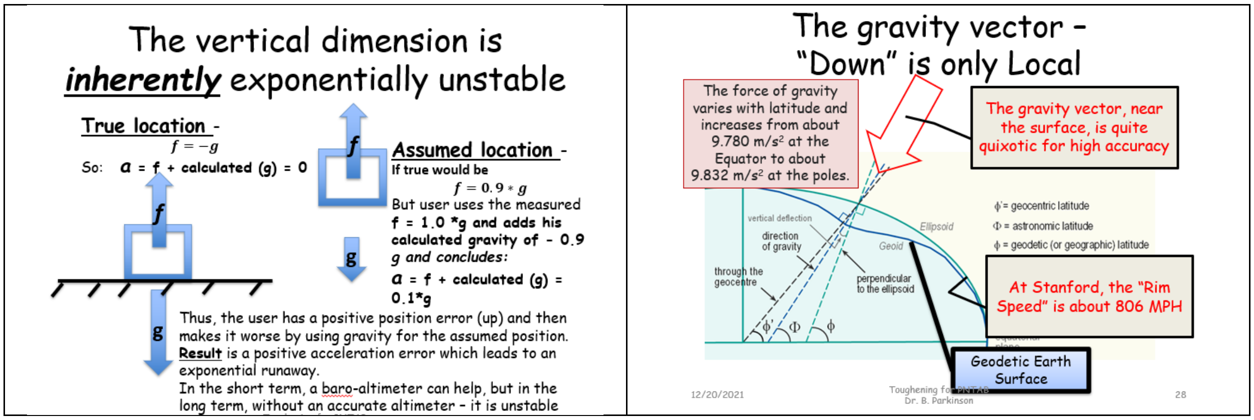
In this example, an unaccelerated 'accelerometer' will measure 1 g (9.81 m/s^2) at sea level (Slide 25). When accelerating, if we want to calculate the acceleration, we need to take what the accelerometer is measuring (the force '**f**')[1] and add what the '**g**' vector actually is, and that calculation has a lot of problems. The gradient of gravity, as you move above the Earth, changes by 1/3 of a micro-g (.0002 g) for every 1 m change in altitude (Slide 26).



Slides 25-26

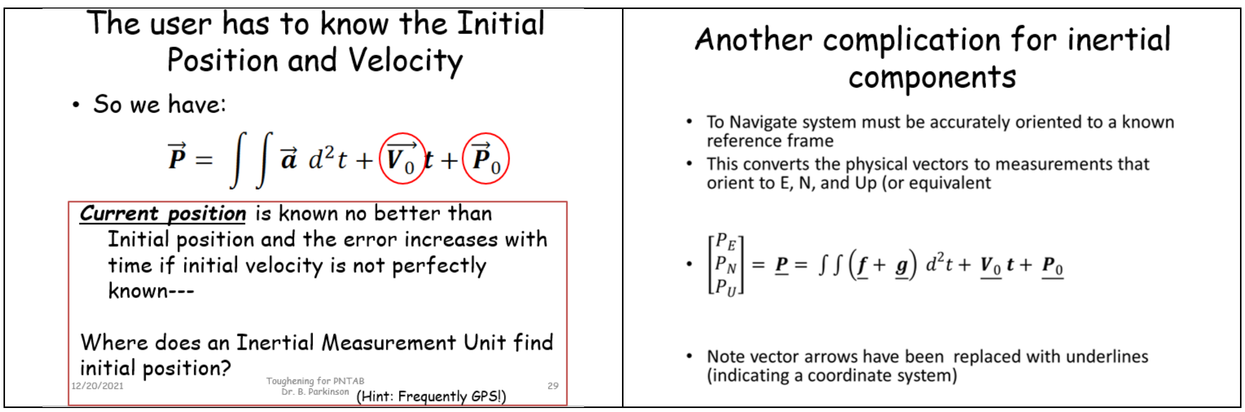
[1] Ed. note: vectors are indicated in **bold**.

This change does not seem a lot, but for that reason the vertical dimension is unstable (Slide 27). This is because when moving vertically and calculating the acceleration (**a**=**f**+**g**), the true location and the assumed location will have different values for **g**, thus resulting in a different calculated acceleration **a**. Also, when looking at **g** as an inertial measurement unit, "down" isn't really "down" (Slide 28). Which way **g** is pointing and its magnitude varies depending on where you are on the ellipsoid and how close you are to mountains, Moon tidal effects, and other disturbances.



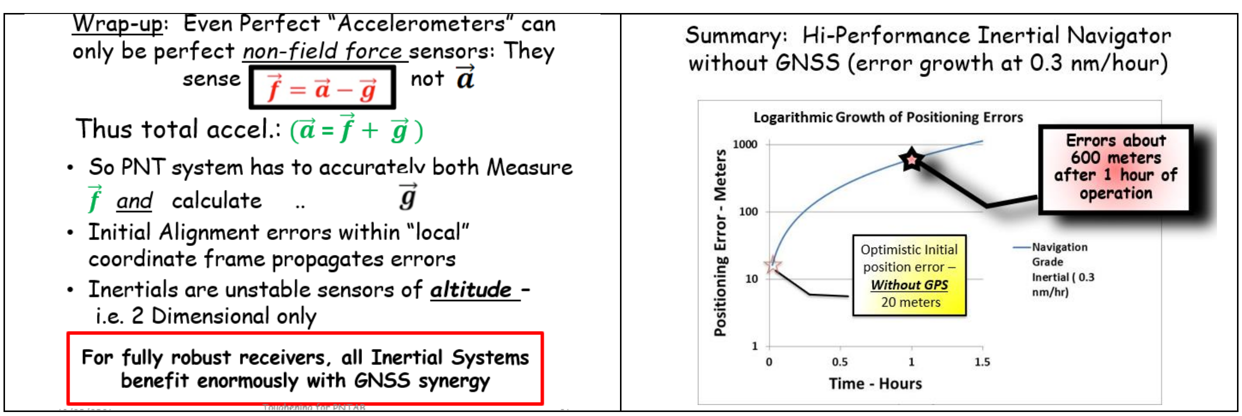
Slides 27-28

Also, when integrating for the position, you must know the initial position and velocity (Slide 29). However, the error will increase if these are not perfectly known. Another complication is that you must place all these measurements on a coordinate reference frame (Slide 30).



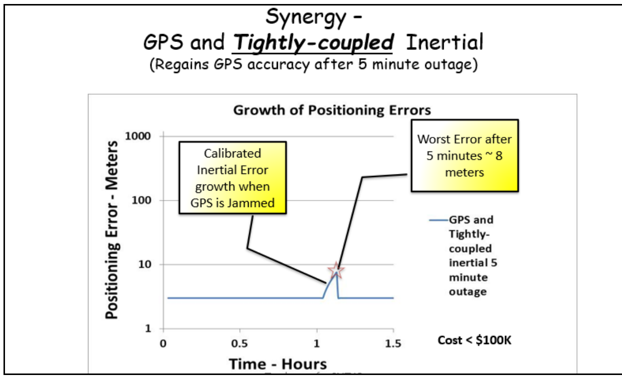
Slides 29-30

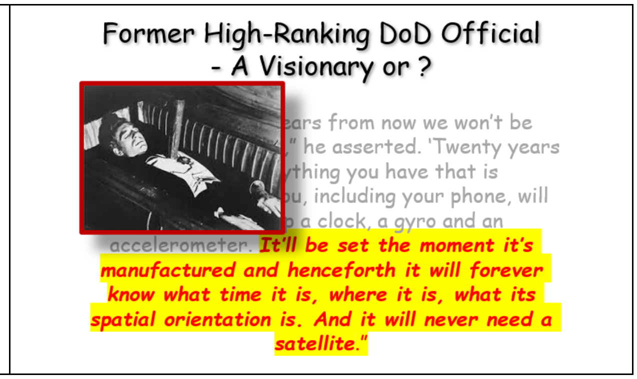
The net result is that total acceleration (**a**) is not measured by accelerometers (Slide 31). Therefore, a PNT system needs to accuracy measure the force (**f**) and calculate the gravity vector (**g**). In addition, initial errors in alignment will further propagate these errors. The conclusion is that all inertial systems benefit enormously by working with GNSS. A very good inertial navigator, without GPS, will have an error growth of approximately 0.3 nautical miles per hour, or 0.6 km/h (Slide 32).



Slides 31-32

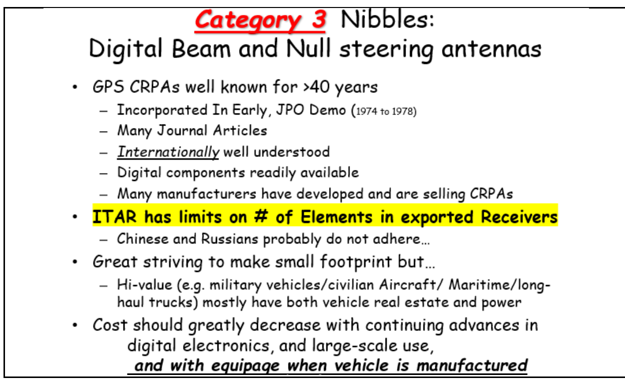
An inertial system tightly coupled with GPS, will only have an error of 8 m following a 5-minute (min) GPS outage due to jamming (Slide 33). In summary, the statement mentioned in Slide 3 about inertial systems replacing GPS is incorrect (Slide 34).

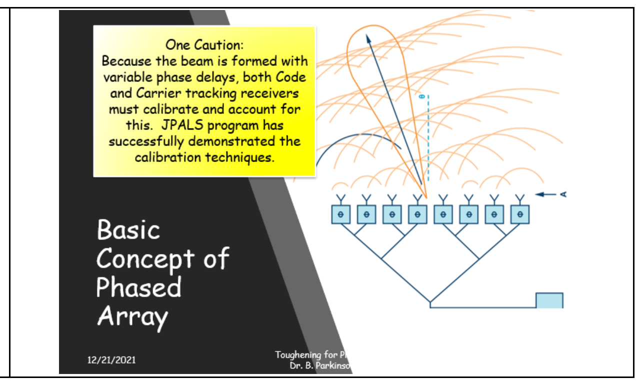




Slides 33-34

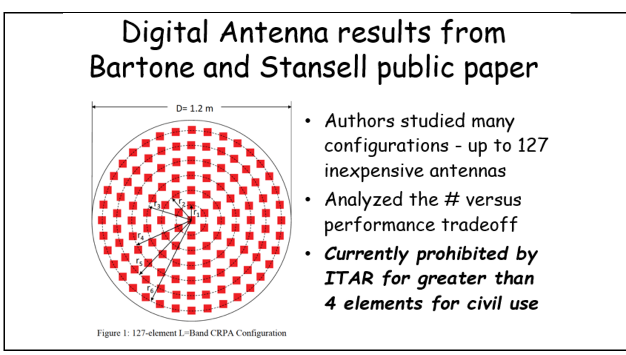
The next area we are going to cover are the Category 3 'nibbles' to improve J/S (Slide 33): Digital-beam and null-steering antennas. This technique has been well known for over 40 years. They were incorporated into an early GPS JPO demo (see slide 6). However, International Traffic in Arms Regulations (ITAR) has a limit on the number of antenna elements that can be included in receivers for export, which is enforced by the US but probably not by our adversaries. As a result, the anti-jamming protection capability available to users worldwide is limited. As a result, there is a lot of pressure to get into small footprints [diameter of the antenna phased array]. Boeing says it will give you about 8 inches (20 cm), but he contends they should give us about 1 m. The concept of an antenna phased array is simple: we put a whole bunch of antenna elements and they have behind them variable phase delay that feeds into our receiver (Slide 36). As a result, they can in essence 'shape' the beam in a certain direction. However, when using the phase delay, you need to be careful and make sure both code and carrier tracking receivers are calibrated to account for this.

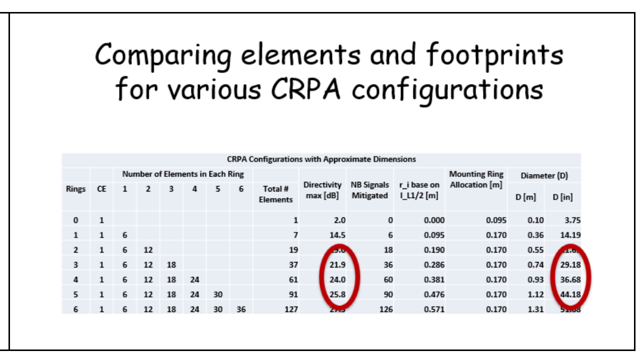




Slides 35-36:

C. Bartone and T. Stansell have published a paper on digital antennas (Slide 37). They looked at many configurations with up to 127 inexpensive antenna elements and analyzed the number of antennas vs. the performance. Currently U.S. International Traffic in Arms Regulations (ITAR) prohibit greater than four antenna elements for civil user. The paper shows that if you go to a larger number of antenna elements, the performance improves greatly (Slide 38).



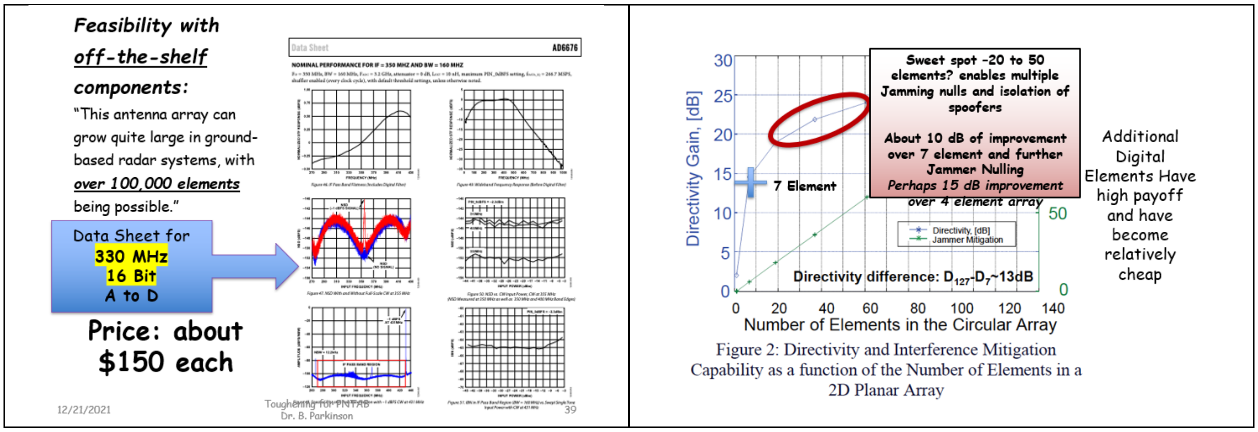


CRPA Configurations with Approximate Dimensions

Rings	CE	Number of Elements in Each Ring 1	2	3	4	5	6	Total # Elements	Directivity max [dB]	NB Signals Mitigated	r_i base on l_L1/2 [m]	Mounting Ring Allocation [m]	Diameter (D) 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	[illegible]	18	0.190	0.170	0.55	[illegible]
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	[illegible]	126	0.571	0.170	1.31	[illegible]

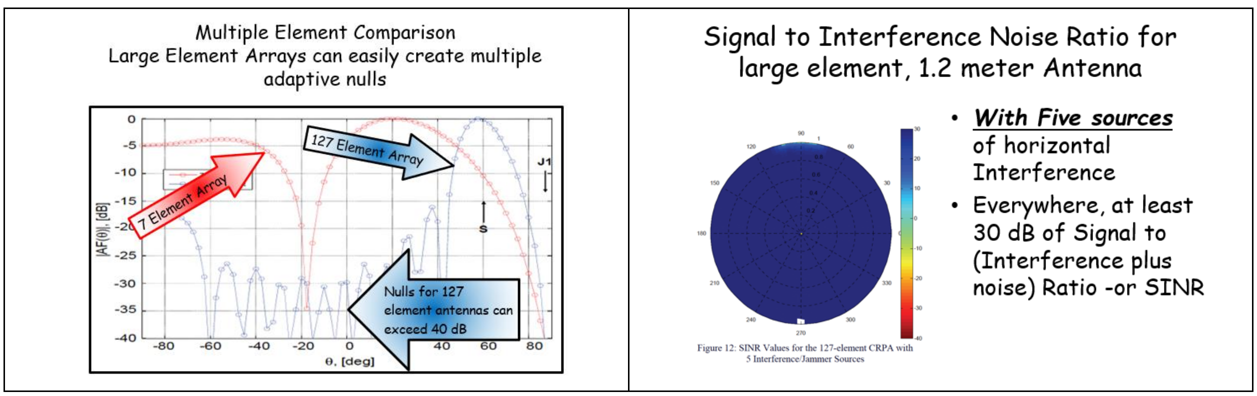
Slides 37-38

If you look at feasibility in using off-the-shelf components, you can find an ‘A to D converter’, the hardest part in this, for about $150 each. Therefore, the cost is no longer prohibitive (Slide 39). If you look at the sweet spot in terms of directivity gain, it seems to be around 20-25 antenna elements (Slide 40).



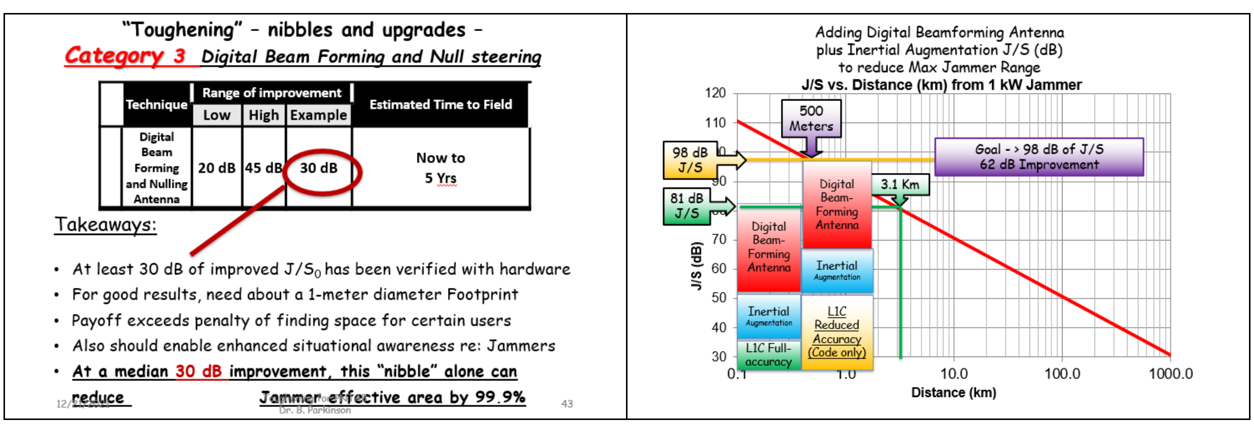
Slides 39-40

If you look at the patterns, we can get nulls as 40 dB (Slide 41). If you look at the tolerable J/S, you can get as much as 30 dB (Slide 42).



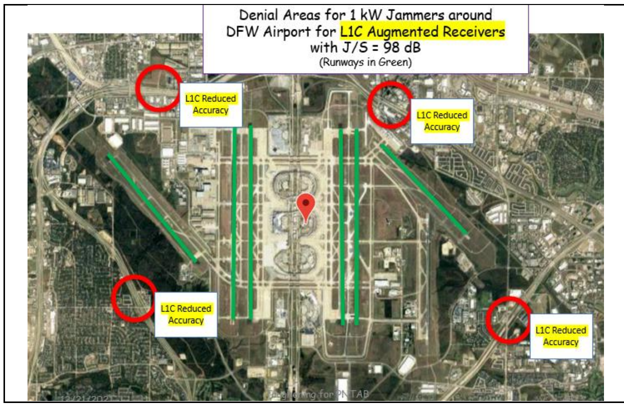
Slides 41-42

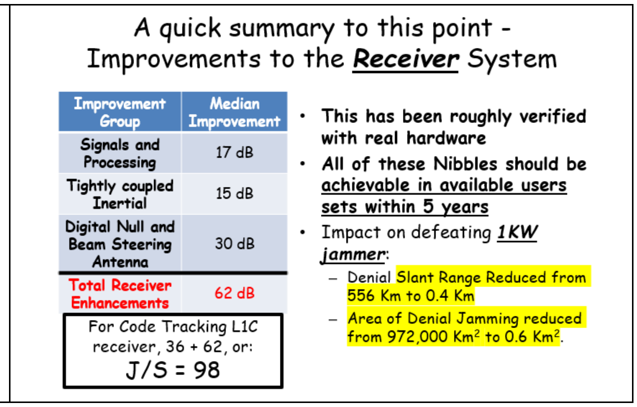
In summary, a 30 dB improvement in J/S has been verified (Slide 43). For good results, Dr. Parkinson recommends a one-meter diameter footprint for the phased array antenna. At 30 dB, this ‘nibble’ alone can reduce the effective jamming area by 99.9%. Going back to our J/S vs. distance chart for a 1 kW jammer, when incorporating this ‘nibble’ (red box on the chart) to the inertial augmentation (blue box), we reach the goal of 98 dB improvement in tolerable J/S from a 1 kW jammer and still obtain L1C ‘State 3’ reduced accuracy (yellow box) at 500 m distance (Slide 44). Moreover, L1C ‘State 5’ full accuracy (green box) can be achieved at 3.1 km of the 1 kW jammer when using the inertial augmentation and a digital beam forming antenna.



Slides 43-44

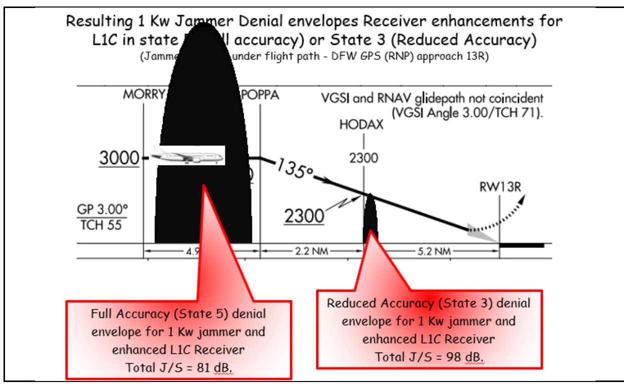
This chart (Slide 45) shows DFW airport, with the runways marked in green and the jamming radius marked in red. Inside this jamming radius, reduced accuracy (State 3) is not possible for an L1C Augmented Receivers (with J/S = 98 dB) due to four 1 kW jammer located outside the airport. Compare this to Slide 18 (jamming radius on an augmented L1C receiver caused by a 1 kW jammer). Thus far in the briefing we have shown how receiver enhancements improve the tolerable J/S by 62 dB for State 5 (full accuracy) and 98 dB for State 5 (partial accuracy) (Slide 46). All these nibbles could be achieved in user sets within five years.

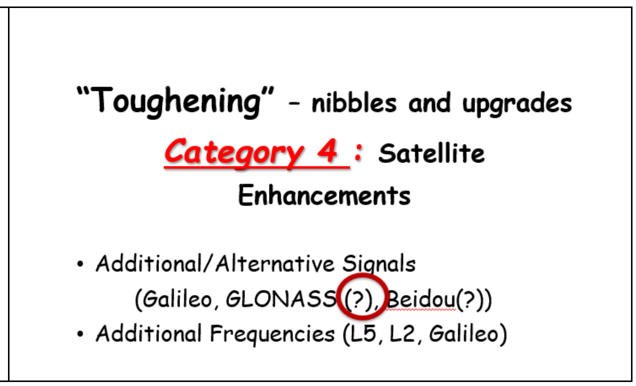




Slides 45-46

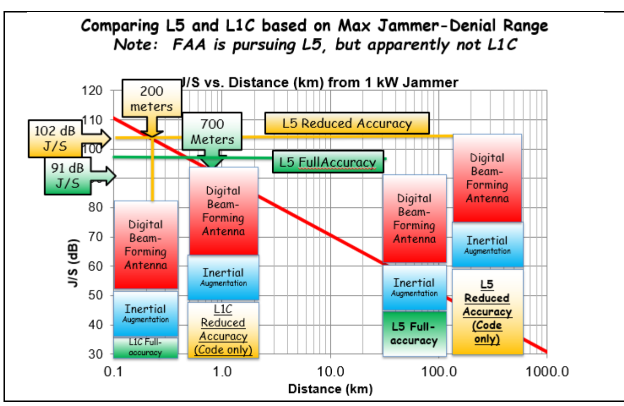
This chart (Slide 47) shows the same approach path to DFW with the denial envelope for full accuracy (State 5) and partial accuracy (State 3). The only other thing to talk about are the Category 4 nibbles, which are satellite enhancements (slide 48).

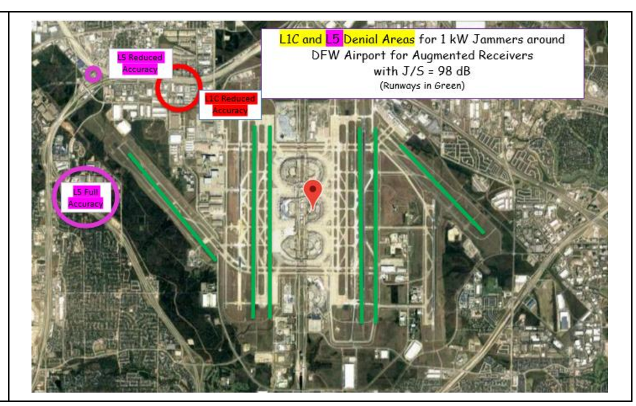




Slides 47-48

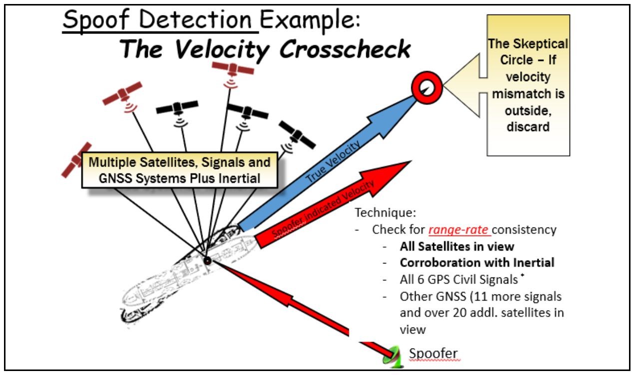
If you look at the chart for J/S vs. distance for a 1 kW jammer for the L5 signal (which the Federal Aviation Authority [FAA] is pursuing), you'll see that the two bar charts move up to the point where we are now dealing with denial radii of 200 m for State 3 (partial accuracy) and 700 m for State 5 (full accuracy) (Slide 49). If we put this on the DFW map, the purple circles show the partial tracking (200 m) and full tracking (700 m) denial circles for the GPS L5 signal (Slide 50). In essence, there are techniques to eliminate the threat of a 1 kW jammer.





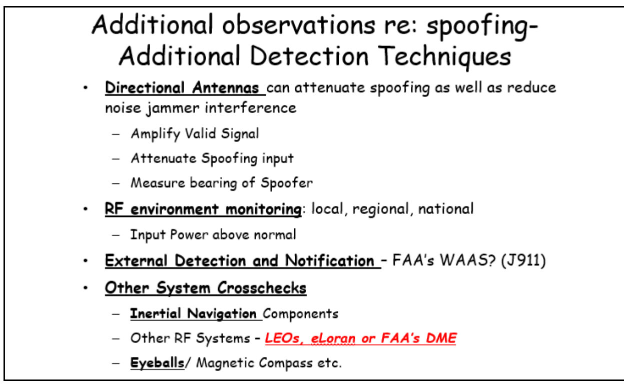
Slides 49-50

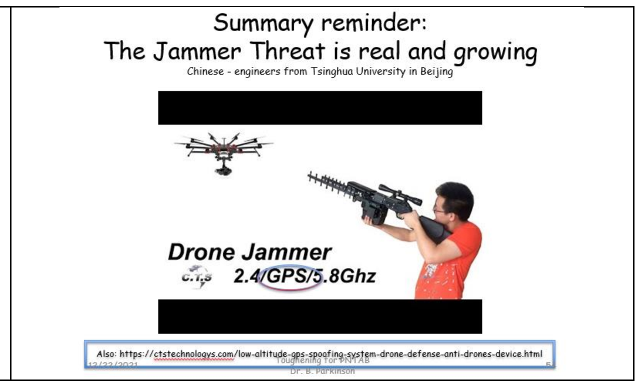
These techniques can also help with spoofing. An inertial unit can help mitigate spoofing by matching the GPS-derived velocity measurements (Slide 52).



Slides 52

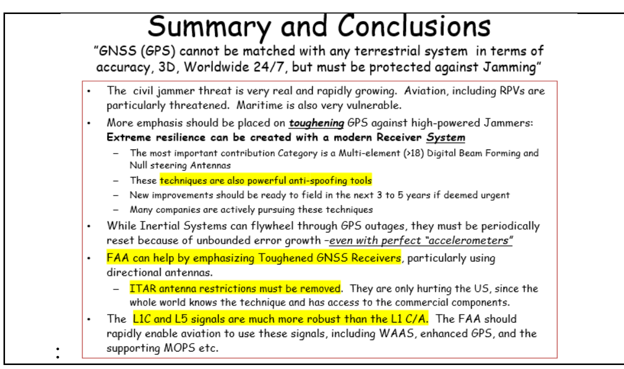
There are additional techniques we can use to detect spoofing, including directional antennas, Radio Frequency (RF) environment monitoring, and external detection and notification to users (Slide 53). The wrap-up is that the jammer threat is real (Slide 54). This is another example pulled from the internet: a device that is supposed to eliminate the navigation capability of a drone. This is an actual picture of the device. The website is shown at the bottom. And unfortunately, this is just one of two dozen or so devices for spoofing available for sale to the public.

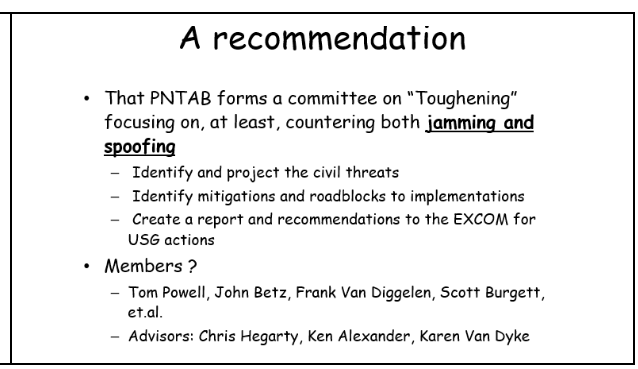




Slides 53-54

So, for summary and conclusions (Slide 55): (1) The civil jammer threat is very real and rapidly growing. Aviation and UAVs are particularly threatened, but maritime use is also vulnerable; (2) More emphasis has got to be placed on hardening GPS, where the most important contributor is the multi-element (> 18 antenna elements) digital beam forming and the null-steering antenna; (3) Inertial systems can help a great deal, but they are not replacements for GPS in terms of accuracy; and (4) The FAA can help by working with the RTCA (formerly the Radio Technical Commission for Aeronautics) to get certification for robust receivers, by ensuring the GPS L5 and L1C signals are incorporated into their Minimum Operational Performance Standards (MOPS). Therefore, Mr. Chairman, Dr. Parkinson's recommendation is that the board establish a subcommittee that can focus on the 'Toughen' aspect on GPS and how to counter jamming and spoofing and identify any roadblocks to the implementation of these measures and create a report and recommendation to the PNT Executive Committee (Slide 56). So, let's reemphasize toughening and develop affordable multi-element antennas, and remove them from the munitions list so we can do what everyone else in the world is already doing.





Slides 55-56

Q&A / Discussion:

Mr. Shane noted there has been controversy regarding the criteria to identify harmful interference as it relates to the frequency band adjacent to GPS primary signals. DOT has done testing using the 1 dB J/S ratio as the criteria to assess harmful interference. Mr. Shane asked Dr. Parkinson to explain what the 1 dB criterion represents and whether it is an appropriate measure for harmful interference?

Dr. Parkinson responded that the 1 dB J/S criterion represents a 25% increase in noise floor or a 25% reduction in strength of the signal coming from the satellite. Yes, it is an appropriate criterion for common-use GPS receivers. However, the types of GPS receivers affected by this 1 dB J/S tolerable interference are not the high-end anti-jamming receiver we are talking here, which can tolerate up to 50 dB in J/S but are also much more expensive and complex to installations. The issue with common GPS receivers is that when interference happens, the receiver will in many cases revert to code-tracking and provide partial accuracy [Ed. Note: what was referred to as 'state 3' throughout the briefing] but the user doesn't realize this while it takes up to 43 min for the receiver to reestablish lock obtain full accuracy. When people with communications background conduct interference testing, they are used to deal with bit error rates, etc., but don't understand that to do a real test they need to get down to cm-level tracking accuracies. Unfortunately, this is not the way most of the interference tests were done. In his opinion, the only valid testing conducted for GPS adjacent band interference was the testing conducted by DOT. So, in terms of relating to the internationally accepted 1dB J/S criteria, in his opinion that's what should stand to protect the vast number of receivers that are out there.

ADM Allen referred to Dr. Parkinson's comment about the munitions list and ITAR and asked if he could add more detail and clarity on the challenges as they relate to domestic and worldwide use of GNSS.

Dr. Parkinson responded that ITAR is a much broader set of regulations within the U.S. that reflects an attempt to not allow exporting technology that could be harmfully used against the U.S. The reasoning is that, in the case of GPS, a high A/J capability might be used by an adversary to harm the U.S. But this restriction was put in place decades ago and is administered by the Dept. of State (DOS). Once a restriction is placed in ITAR it is very hard to remove, but he thinks we should take it on to try to remove it. Not everyone will need a multiple element antenna, but anyone around the world that's competent enough can already build such antenna using commercial-off-the-shelf (COTS) components. Therefore, with the ITAR restriction on GPS we are currently just restricting our ability to make commercial airliners absolutely jamming proof.

ADM Allen asked if there are any similar restrictions in other countries.

Dr. Parkinson responded that some countries have reflections of our regulations. He believes Canada is one such example.

(Member in the audience, allowed by the Chair) asked to what degree should we standardize testing.

Dr. Parkinson responded that he is leery of that since it that would have precluded the use of carrier-tracking receivers. Having some guidelines is one thing, but when trying to put standards in a highly bureaucratic framework it becomes cumbersome.

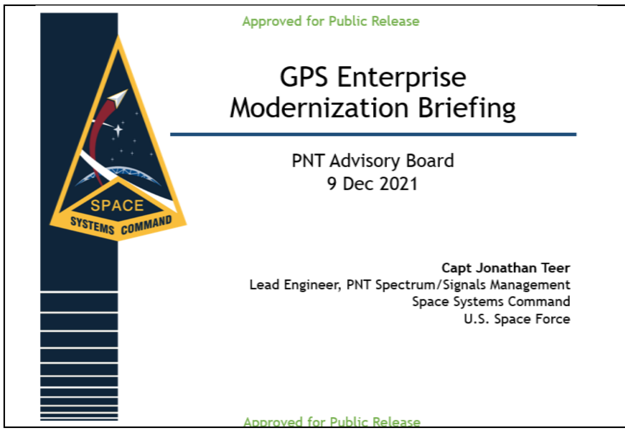
Mr. Murphy shared that RTCA is working on standards for next generation GPS receivers. Those standards do not specify the use of toughening techniques, but rather specify the general environment under which such tests should be conducted.

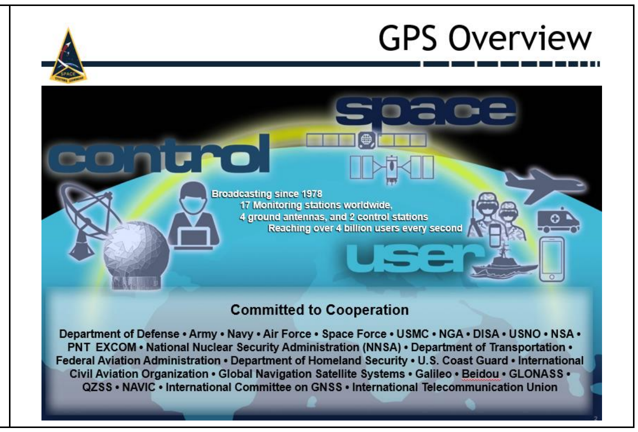
Dr. Parkinson said he would be open to changing his views in case of certified receivers. His concerns apply more generally.

* * *

GPS Program Update
GPS III/IIIF Payloads & Capabilities
Capt Jonathan Teer, *Lead Engineer, PNT Signals Management, Space Systems Command, U.S. Space Force*

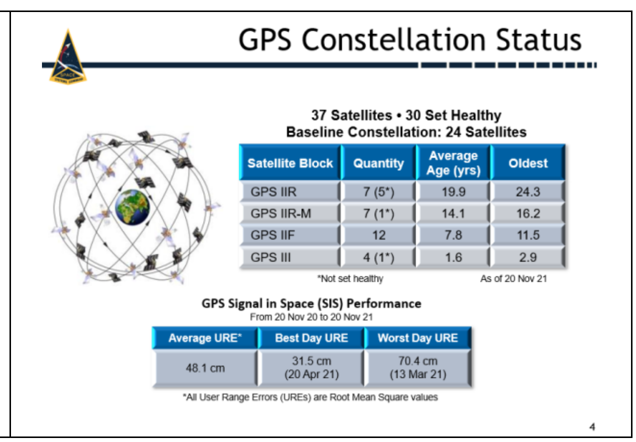
Capt John Teer introduced himself as the Lead Engineer for the PNT Spectrum/ Signals Management branch of the USSF Space Systems Command (SSC) (Slide 1). He thanked the PNTAB for the opportunity to present a brief overview of the GPS program status and future plans (Slide 2). He provided an overview of the three main segments of GPS – the control segment, the space segment, and the user segment. GPS is a system of systems. It is made up of three systems, each of which is a system into itself. The space segment is composed of upwards of 30 satellites broadcasting various GPS signals since the late 1970s, which are freely available to use by anyone around the globe. Additional signals have been added since and legacy signals have been improved. The GPS ground system is robust with more than 20 segment components fielded around the world to monitor and control the space segment, where determining the precise location of each satellite is a fundamental component of satellite-based navigation. We are all a part of the user segment. Whether we are using the signals on our cellphones or applications that obtain timing from GPS, we knowingly or unknowingly use GPS each day. The user segment of GPS is vast and varied. None of this happens without collaboration and cooperation amongst the three segments. Even with the reorganization from Space and Missiles Systems Center (SMC) 1.0 to SMC 2.0, to now SSC, we continue to maintain partnerships domestically and internationally.





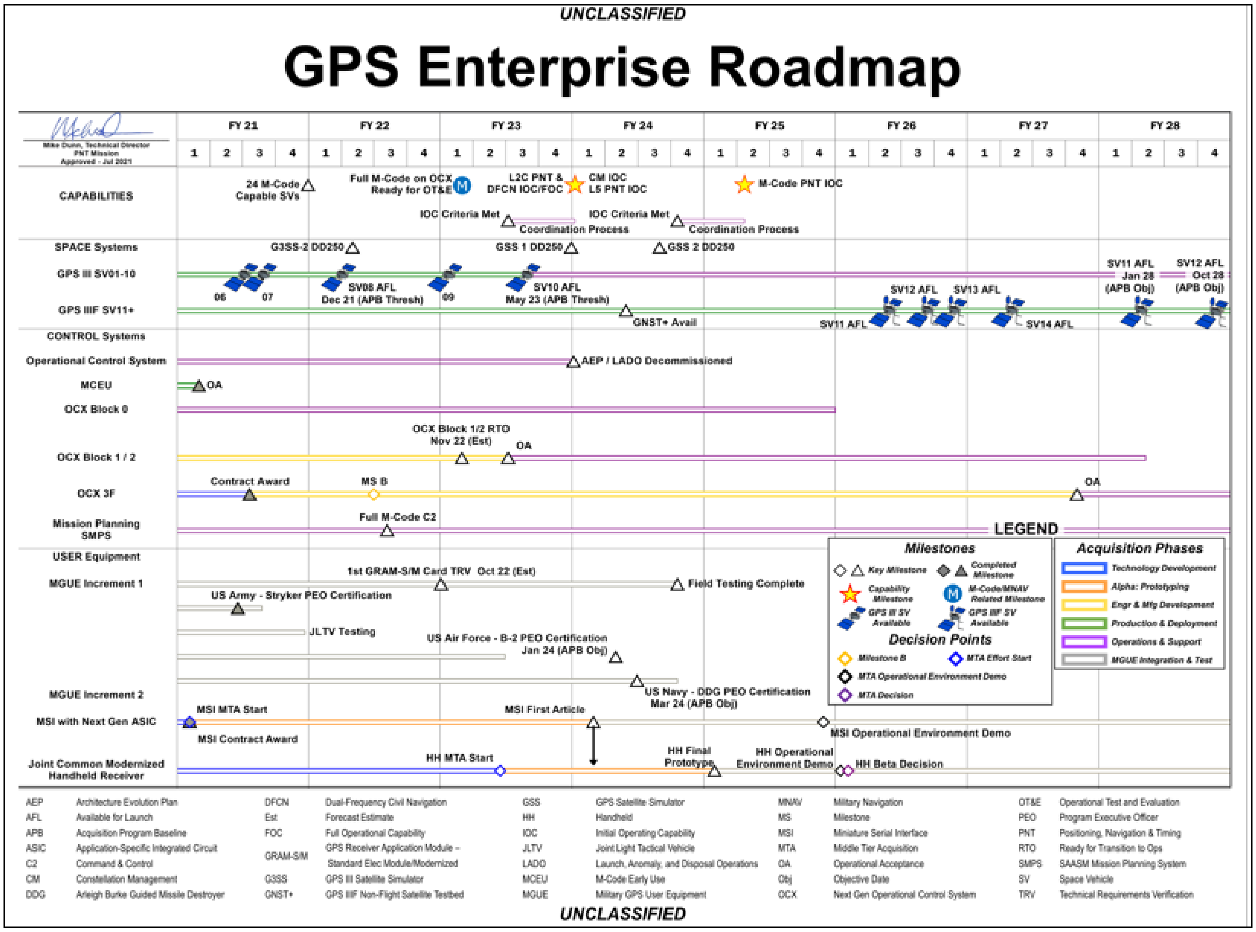
Slides 1-2

GPS is leveraged around the world for a vast array of purposes (Slide 3). It is estimated that GPS has over 4 billion daily users worldwide. In 2019, an RTI International report determined that the retrospective benefits of GPS from the last 25 years generated roughly $1.4 trillion in economic benefits for the private sector. It is estimated that GPS generates these benefits on the order of $1 billion per day. SSC works hard every day to maintain the accuracy, integrity, availability, and continuity of GPS. Capt Teer then provided information on the signal and space accuracy performance of the GPS constellation (Slide 4). The next generation of GPS (Block III) is here. Thanks to the recent launch of GPS III SV05, there are now 37 GPS satellites on orbit. There are no longer any GPS IIAs in the active constellation. There are currently 30 satellites as part of the active constellation, with the rest in either preparation for operations or in a backup status. There is a wonderful problem that satellites are outliving their design life, and the new generation of satellites is expected to follow a similar trend. The constellation continues to provide signal-in-space performance at 48.1cm, which has continued to improve as more GPS III satellites are launched.



Slides 3-4

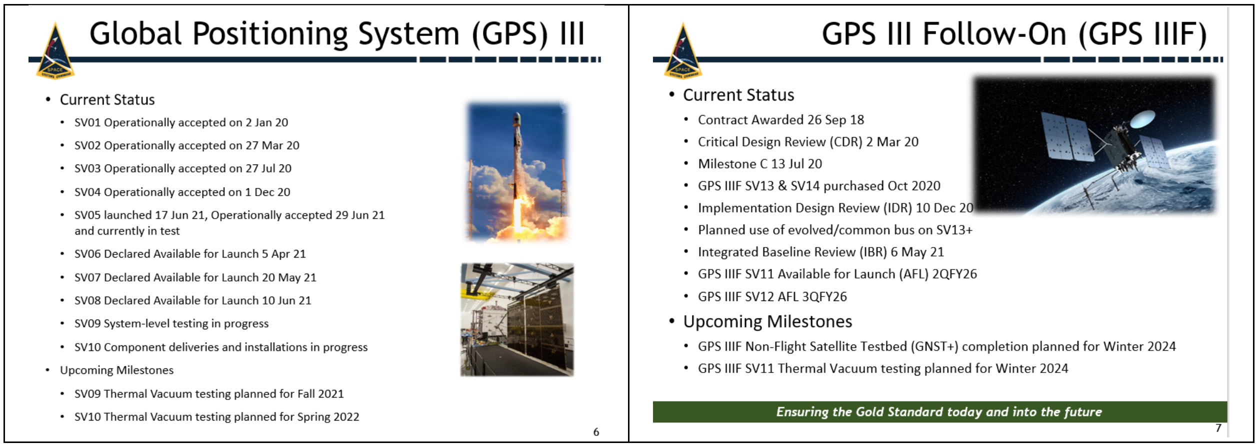
The GPS Enterprise Roadmap reflects the many programs in planning or execution to enable more PNT capabilities across the PNT segment (Slide 5). Each GPS segment is continuing to be upgraded to deploy modernized capabilities, while continually replenishing the GPS constellation to ensure there are 24 or more operational satellites at least 95% of the time. SSC is continuing to synchronize how and when capabilities are being used and delivered to the end user, since in most cases they require changes to three different systems (space, ground, and user segments). Prototyping and planning stages are always underway to consider how to continue to evolve the GPS system architecture into one that is even more robust and resilient than it is today. Not only is GPS the backbone of PNT architecture, but for ways to protect, toughen, augment, and expand PNT capabilities.



Slide 5

It's an exciting time for the GPS III program (Slide 6). New satellites are more capable than the GPS IIRs and GPS IIFs and add additional signals for the civil community. GPS III satellites will provide increased accuracy and signal power, improve signal integrity and have a longer design life, and a new L1C signal. The fifth GPS III satellite was launched in June 2021 and achieved 12 days operational acceptance from launch. Space Vehicles (SV) 06, SV07, and SV08 are available to launch and are waiting on a ride. The production line is currently working on GPS III SV09 and SV10.

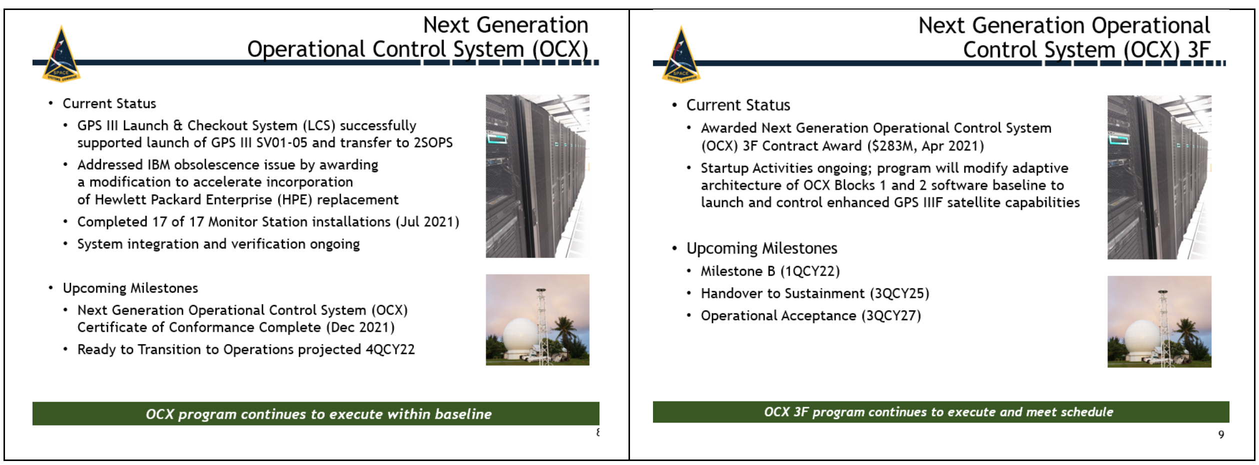
In 2018, Lockheed Martin was awarded a contract to build 22 GPS IIIF satellites (Slide 7). The design phase and Critical Design Review (CDR) were completed in March of 2020. At this point, early production is underway on GPS III SV11 and SV12, which are considered research and development (R&D) spacecraft. In October 2020, the first contract option was exercised for the GPS IIIF program and kicked off production for SV13 and SV14. The first GPS IIIF SV11 will be available for launch around the second quarter of FY26. GPS IIIF will also include two additional hosted payloads, the SAR payload and the laser retro-reflector array payload. The SAR payload will enable faster detection and broader coverage of distress signal sources. This allows SAR operations to get to victims faster. The SAR payload is furnished by Canada.



Slides 6-7

The Next Generation Operational Control System (OCX) is under incremental development (Slide 8). The GPS III Launch & Checkout System (LCS) successfully supported the launch and checkout of GPS III. The next increment, OCX 1 and 2, which will be a single delivery, will have a modernized architecture, advanced security capability, and enhanced command and control. The most significant capability of OCX Blocks 1 and 2 will be its ability to control and monitor all modernized signals. As previously mentioned, many new signals are being broadcast today, and OCX will allow them to be fully monitored. Block 1 and 2 development is complete, and after very extensive and robust testing, it should be ready to transition to operations in late 2022.

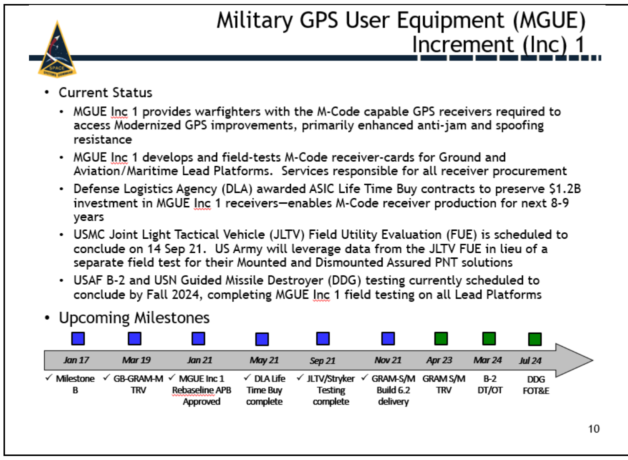
OCX 3F is a modification to the OCX baseline to support launch and control of enhanced GPS IIIF satellites (Slide 9). It will provide better cybersecurity, improve anti-jamming capability, and enhance signal strength and accuracy, as well as the ability to connect with more satellites and shrink operations crew sizes. OCX 3F contract was awarded in April 2021. Contract startup activities are ongoing.

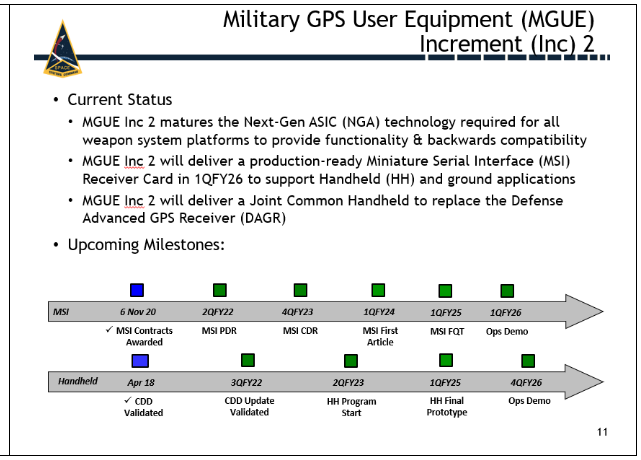


Slides 8-9

SSC is responsible for a small percentage of overall GPS user equipment, specifically Military GPS User Equipment (MGUE), which developed the core technology needed to acquire, track, and process M-Code signals (Slide 10). MGUE Increment 1 developed a ground-based receiver card that will be integrated into over 100 military systems. It also developed an aviation and maritime card.

The MGUE Increment 2 program is developing a next generation Application-Specific Integrated Circuit (ASIC) that will significantly reduce the size, weight, power, and cost of future user equipment (Slide 11). The MGUE Increment 2 program will also develop the first handheld M-Code receiver. With these two programs, SSC completes the GPS triad to enter the M-Code user era.





Slides 12-13

The strong team at SSC includes operators, engineers, program managers, and more to uphold the gold standard of PNT for the world. Capt. Teer thanked the PNTAB for their time and asked for any questions.

Q&A / Discussion: None.

* * *

National Security Council (NSC) Briefing
Maintaining GPS as Critical Infrastructure
Ms. Caitlin Durkovich, *NSC, Executive Office of the President*

ADM Allen introduced Ms. Caitlin Durkovich, the Director of the NSC. He and Ms. Durkovich served together in the Department of Homeland Security (DHS) during the Obama Administration. She is a strong supporter of what the PNTAB is doing, and they worked together during the transition of administrations to better acquaint everyone with issues regarding PNT. He thanked Ms. Durkovich and welcomed her to present.

Ms. Durkovich thanked ADM Allen for the introduction and remarked how wonderful it was to be here. She appreciated the introduction and the opportunity to participate in the first PNTAB meeting of the year and the first under the Biden Administration. She specifically complemented ADM Allen, Mr. Miller, and the entire team for putting together a robust agenda. It has been a long couple of years because of COVID-19, and it is valuable to have meetings once again in person. She began by thanking everyone for the important work they do every day to keep our country safe and prosperous. PNT services are an integral part of our lives and will continue to be foundational to our economic and national security. Resilience is more important now than ever. Ms. Durkovich served as the Assistant Secretary for Infrastructure Protection at DHS for the last four years of the Obama Administration, where she had the opportunity to work on a range of issues, but none more important than the work done to secure and enhance the resilience of PNT systems. It provided her the opportunity to participate in PNT EXCOM meetings and work very closely with the NCO and Greg Winfree and Karen Van Dyke at DOT on important issues to reduce vulnerabilities. She congratulated Dr. Winfree on his appointment to the PNTAB. She added that it was great to see so many familiar faces and welcomed those she hadn't yet met to connect further.

Ms. Durkovich began by saying she is encouraged by all that has happened in this space since she left government. There remain plenty of challenges, both old and new, which is why she is honored and privileged to be back in government serving on a tremendous team that remains committed to enhancing the security and resilience of our nation's critical infrastructure. PNT is part of that. The President and his team are focused on addressing some of the most significant challenges we face as a nation. This ranges from the growing threats from foreign adversaries, to climate change, to our aging and failing infrastructure, and to enhancing the vitality of our supply chains. As Senior Director for Resilience and Response for the NSC, Ms. Durkovich can say that progress in these areas depends on many factors, but certainly strengthening resilience of our nation underpins all of them. Her team has discussed extensively what is meant by "resilience" – this is a word, certainly over the last several years, that has gained importance and is used in a lot of different forums. They are working on a set of resilience principles within the NSC that they hope to promulgate. When talking about resilience, this refers to resilience of federal institutions, private sector partners, academia, state and local governments, citizens, and partner nations. Resilience is both the ability to anticipate threats and vulnerabilities, and to be prepared to respond and not just bounce back but bounce forward. What we have witnessed over the course of the last several years, the COVID-19 pandemic, incidents like the Colonial Pipeline, Hurricane Ida and other natural hazards seen on a regular basis, have demonstrated that we are only as secure and resilient as the weakest link, and that our collective resilience as a nation requires shared responsibility across all aspects of society. It requires that we all work together to advance resilience.

The topic of resilience has perhaps never been more relevant in the modern era. Arguably, not since the energy crisis of the 1970s or World War II (WWII) have Americans been so severely impacted by disruptions to vital services and supply chains that we depend upon. We have all lived through the COVID-19 pandemic and are acutely aware of our dependence not just on foreign manufacturing, but also on our global transportation systems to deliver goods and commodities, ranging from toilet paper to medical supplies and computer chips. Every American has experienced supply chain impacts firsthand over the course of the last year.

There have been other crises that have also tested our resilience. Early in the Biden Administration, we were tested by the winter storm that crippled the Texas power grid. It showed the country and even the world the impacts of both extreme weather and what happens when a power grid is not resilient. This spring, millions of Americans in the eastern US experienced firsthand the impact of a criminal ransomware attack on one of the nation's most important pipelines, an asymmetric attack that originated beyond our shores, targeted our information technology system, and had far reaching physical and economic impacts. The incident laid bare for all of us to see the significant vulnerabilities in our critical infrastructure, driven in part by the increasing convergence of our cyber and physical domains in our interconnected ecosystem, as well as the very real threats that we face from both state and non-state actors. These events are having a significant impact on how we think about preparedness and incident response in the federal government. Cyber events are no longer simply cyber events, nor are physical events merely physical events. These events are connected and hybrid in our increasingly interconnected society. This interconnectedness is not just about data information, but it is also about power and other vital services, such as PNT.

As we move to electrify and digitize broader swaths of our economy, transportation being a good example, the interdependencies and cascading effects of disruption are going to continue to grow. As this group knows, gone are the days when we can take comfort in our geographic position alone. We are interconnected and interdependent, not just with ourselves, but with the rest of the world. This creates not just opportunities, but as we are all aware, threats, which is why we need to work together to address them. There are many demands in Ms. Durkovich's role in the NSC, but she underscored that she would find time to address and engage with the experts from outside the government to help the White House (WH) understand the challenges that we face, and more importantly, the opportunities that present themselves for us to address them. She emphasized that she is here to engage with the PNTAB about its highest priorities.

Assuring PNT and the economic and strategic benefits it brings to this nation is a priority for this administration. It has the attention not only of Ms. Durkovich's director, but also the Homeland Security Advisor and the National Security Advisor. As stated in the Space Priorities Framework, which was released just this week, the US will enhance the security and resilience of space systems that provide or support US critical infrastructure from malicious activities or natural hazards. In particular, the framework tasks the government to work with the commercial space industry and other non-governmental space developers and operators to improve the cybersecurity of space systems, to ensure efficient spectrum access, and to strengthen the resilience of supply chains across the nation's space industrial base. The NSC is working closely with colleagues at the NSpC to implement the framework, and in particular, SPD-7, which reaffirms the PNT EXCOM, the NCO, and the PNTAB. In a separate but related course of effort, the NSC continues to track and to support the implementation of Executive Order (E.O.) 13905, "Strengthening National Resilience through Responsible Use of PNT Services," which was promulgated in February of 2020. This E.O. seeks to ensure the nation's critical infrastructure, such as our energy, financial, and transportation sectors, are resilient to disruption of GPS or other sources of PNT, including time signals over the internet. Regarding the last point, Ms. Durkovich thanked the National Institute of Standards and Technology (NIST) at the Department of Commerce (DOC) for its work to identify and promote responsible methods of PNT services that appropriately manage risk. This is something new that happened in Ms. Durkovich's time away from government. This effort included releasing a foundational PNT profile to help organizations identify and mitigate risks for assets that are dependent on PNT services. She also thanked NIST for its provision of precision time services that are one thousand times more accurate than its internet time service and, if need be, could serve as a backup to GPS. DHS also deserves some credit, as they have served as co-lead with NSC on several of the National Defense Authorization Act (NDAA) actions to assess additional PNT services beyond GPS. DHS has also been instrumental in engaging with critical infrastructure owners and operators to ensure that they understand and take steps to mitigate the vulnerability from PNT overdependence.

In closing, Ms. Durkovich reinforced the Administration's commitment to protect and secure the nation's critical infrastructure, whether through targeted investments, revamped policies, or engagement with Congress on new legislation to include the Investing in Infrastructure Jobs Act. Working together, she is confident that we can continue to take a significant step towards continuing to build a more resilient and secure infrastructure that includes PNT. The imperative has never been more important in our modern history. She thanked the group again and asked for questions.

Q&A / Discussion:

ADM Allen asked for Ms. Durkovich's views on the intersection of resiliency in PNT vis-a-vis some of the projects and the infrastructure plan moving forward as there has been a lot of interaction with the PNTAB through Ms. Karen Van Dyke and senior members of DOT.

Ms. Durkovich thanked ADM Allen for the question and responded that this is a new experience for her to have the ability to influence and shape a trillion-dollar, generational investment in our nation's infrastructure. There is a WH-led process that is going to unfold over a long period of time, which is going to ensure that resilience is a key aspect of these investments. As we start to think about the design and build phase of this, how are we engineering in that resilience and security from the beginning? The WH is working closely with the Office of Management and Budget (OMB), with friends from the Climate

Policy Office and Mayor Mitch Landrieu (Senior Advisor and Infrastructure Coordinator), to ensure that there is language that sets expectations for what we expect as we provide this money to our state and local partners, that we build on our existing policy guidance, and that we continue to think about and learn from lessons of the past. We aim to understand both the complexity and the interconnectedness of our infrastructure, the lifespan of our infrastructure, and that we're accounting for it from the beginning, baking in that security and resilience. OMB is going to issue some guidance that will go out to departments and agencies, so that as they start to push this money out, that they are accounting for security and resilience. Over time we will continue to evolve the guidance and the expectations. We are part of the process. It is climate focused, but it is also natural hazards focused.

ADM Allen added that the PNTAB looks forward to seeing the principles of resiliency mentioned previously. The PNTAB has focused on three principles of resiliency: Protect spectrum, Toughen receivers, and Augment PNT services. The board will continue to engage on that dialogue moving forward.

Ms. Durkovich continued that the work on resilience principles have just begun within the Executive Office of the President (EOP), and that they look forward to engaging with partners in the spring, including the private sector, state and local government, and academia. They may bring together a Resilience Summit, with more details to come, as they recognize the importance of engaging with partners on this front.

ADM Allen then recognized Dr. John Betz, who recently led an extensive task force report on the current and future use of the GDGPS system in terms of greater accuracy and PNT.

Dr. Betz thanked Ms. Durkovich for a great presentation. As the NSC thinks about alternative sources of PNT as part of the resilience framework, how is the NSC assessing the different aspects of various PNT sources? For example, their resilience to threats that might be unique to them, instead of to the current sources. The coverage across the nation, the accuracies that they provide, how is the NSC getting their arms around those multiple dimensions and prioritizing what are the right alternative sources to pursue?

Ms. Durkovich responded that it is a great question that highlights the complexity of the issue and why it is important to involve the entirety of the interagency and user base. The NSC leads a process within resilience and response that is specifically focused on PNT, so it affords them the opportunity to bring together the stakeholders to both understand what emerging threats are and how they may impact those various segments. It involves the intelligence community, the technical community, and this is an issue where there has been sufficient work to ensure the right people are at the table. They are beginning to institutionalize a process where, as they look at these alternatives, they look both at threats today and tomorrow. They consider not only the potential impact of the threats, but also the ways to mitigate and respond to those threats from the beginning. Ms. Durkovich added that she would like to think they are aware of the significant single point of failure in our country, and that as we continue to look at our resilience, we have to do it with eyes wide open with where we might face some vulnerabilities.

Dr. Winfree asked with regards to GPS specifically but resilience generally, how can the university research community start to engage with this Administration and the NSC on these topics, so they are included as a part of these dialogues at the front end.

Ms. Durkovich thanked Dr. Winfree for the question and for the work that he does in academia. This is a whole of nation effort to get us where we need to be with resilience. A big part of how Ms. Durkovich views resilience is the identification and anticipation of threats or vulnerabilities, so we are not caught off guard. From the security side of the house, we have a sense of healthy paranoia, and we have to bring that healthy paranoia to the resilience side of things too. As we begin to build out and transform our transportation systems or energy/electric systems, the work that academia can do is think about where might we see disruption? Where are we going to run into challenges? The example that she uses, early on when talking about autonomous driving, she would go to panels like this and there would be a lot of conversation about the benefits, how cool it is, the timeline for rolling it out, passenger safety, but there was no conversation about security or resilience. When thinking about self-driving cars, if in a major storm all of the signals and sensors were wiped out, the car couldn't be driven. Those conversations weren't happening. She emphasized that it is incumbent on academia and communities like this to raise those issues, not just to study the benefits but to understand the vulnerabilities and where we need to begin building resilience to them.

Mr. Shane thanked Ms. Durkovich for the presentation. It is encouraging to all of the board to hear the Biden Administration's focus on maintaining the integrity of PNT. The PNTAB has focused on "own goal"-type threats, where as a result of proceedings at the Federal Communications Commission (FCC), we end up with adjacent band problems or interference. Mr. Shane asked directly whether the NSC has an appetite for looking at the underlying legislative or governance framework that produces conflicts. He added that some believe that the system is broken at the moment, and there are no neutral decision makers, rather champions competing with each other. They are doing what they should do under their enabling legislation, but the net result could be a compromising of the integrity of PNT. He asked again if the WH has an appetite for taking a hard look at that.

Ms. Durkovich said that was a great question, and that it is an issue that the WH is looking at. The NSC has been leading that conversation along with the National Economic Council (NEC) and other parts of the WH. There is inherent tension between the economic progress and national security. Ms. Durkovich is very well briefed on the issue and is aware of all of the studies done by DOT, DoD, and others that are assessing the proposed network that Mr. Shane referenced. The studies raise a lot of concern and many questions. Ms. Durkovich is also pleased that the provision in the FY21 NDAA asked the national academies to explore the issue more fully. The review is ongoing. What is encouraging is that there is now a chair of the FCC, Jessica Rosenworcel, who was confirmed earlier this week. There is not yet a full commission, but this is an agenda item that is first and foremost for them when they are able to convene. Ms. Durkovich has been encouraged by the very candid conversations happening in the WH between the NEC and the NSC on this. They are focused on it, but the most important priority at the moment is to ensure there is a full commission and that this matter can be brought back to them.

Mr. Shane asked about the recent wakeup call from Russia, which makes concerns about adjacent band interference look quaint in terms of resilience of PNT. Mr. Shane acknowledged that Ms. Durkovich may not be able to share much about the subject but asked if there is anything that she could share about what the administration is thinking about this threat.

Ms. Durkovich responded that she is limited in what she can say in this forum, but she noted that it does have the attention of the president, the National Security Advisor, and the Homeland Security Advisor. The NSC is convening a process along with colleagues at Pound Cyber to work very closely with the Cybersecurity & Infrastructure Security Agency (CISA) and the sector risk management agencies to ensure they're both prepared and that owners and operators of critical infrastructure are also prepared to manage threats from nation states, foreign adversaries, and other all-hazards threats. There is a lot of attention on the issue right now.

Mr. Goward thanked Ms. Durkovich for coming and noted that PNT resilience is a complex issue. The good news is that there is congressional support for many of the items discussed. The 2018 National Timing Resilience and Security Act called for a terrestrial timing system at a minimum, plus other systems to complement and back up GPS. The Transportation Committee is interested in having the Government Accountability Office (GAO) look into GPS dependence in transportation systems and so forth. The DOT and institutions like Dr. Winfree's (Texas A&M Transportation Institute, TTI) in industry have all the expertise that could be needed to solve complex problems like this. Mr. Goward noted that it seems to be a matter of leadership support in terms of getting initiatives going to take the bullseye off GPS as a strategic target, and to protect the nation in the event of anything happening to the system that could cause temporary or prolonged disruption. Mr. Goward asked Ms. Durkovich if she sees the administration committed to carrying through on the requirements of the National Timing Resilience and Security Act and providing complimentary capabilities.

Ms. Durkovich responded by reiterating that PNT is a priority for this administration. It has the attention of both the National Security Advisor and the Homeland Security Advisor, and it is a process that is run within Ms. Durkovich's directorate. Yes, it is a priority.

Mr. Goward offered his assistance on behalf of the Resilient Navigation and Timing (RNT) Foundation, as they have written several white papers on how the process to do these kinds of things can be streamlined and some additional considerations.

Ms. Durkovich thanked Mr. Goward.

Dr. Penny Axelrad thanked Ms. Durkovich for the presentation. Her question concerned the resilience and backup to GPS. GPS does so many different things that the idea of having a single backup doesn't make much sense. She asked Ms. Durkovich how the NSC is identifying the specific things that need to be backed up for resilience that are application specific and how those are prioritized.

Ms. Durkovich remarked that it was an excellent question and that she agreed with the basic premise – that the goal is to be resilient, and not just come up with a redundant capability, but multiple redundant capabilities. This is where the work of the responsible use of PNT comes in, but also all the great work that NIST and DHS are doing to identify where some of the most significant vulnerabilities are, and where we need to target resources and investments. As much as we need to focus on existing uses and enhancing the resilience of those systems, as we move forward in building this once-in-a-lifetime, generational infrastructure, we need to ensure we understand the challenges we're facing now and don't create the same problems moving forward. The work of the interagency, including DOT, to identify the areas of greatest vulnerability and where to target investments.

Mr. Shields began by saying he spent his whole career in industry away from government, but he wanted to pick up what Mr. Shane started. Mr. Shields has been working on the software side of automated driving since 2014. Communications is a core that is needed in that industry. There is an underlying problem that a lot of Silicon Valley colleagues don't understand, in that a mistake in software in the automotive industry can kill someone. The entire engineering staff at the FCC came from cellular, and 99.9% reliability in cellular was great, but we don't want every thousand miles for there to be an automated driving accident. In the last few years, there are three big issues we're aware of with the FCC: the Ligado issue, which isn't just about Ligado, but that the FCC doesn't understand safety of life. Making a 911 call next to a Ligado tower would not go well. There is now a C-band issue which has gotten attention as well. From the automated driving side, the 75 MHz and 5.9 GHz bands were allocated 20 years ago, and they have been working diligently for all that time to ensure safety within those bands. With the FCC decision last year to remove some of that band, what is left over is useless. The automotive industry specifically worked through to protect that band for safety system and vehicle control, and that FCC decision has killed the possibility of safe automated driving. These are three generic examples of why the issue is not the decisions themselves, but the FCC structure and priorities. Mr. Shields asked if there is anything the Administration can do to help change the structure of how the FCC looks at safety of life?

Ms. Durkovich noted that she first wanted to speak to the general problem and then speak more about the specific issue. She thanked Mr. Shields for coming to the table with government partners and highlighted that this was what makes advisory boards like this so special. Ms. Durkovich spends a lot of time thinking about this issue as the US transitions its energy system, considering the electrification and digitization and new entrants to this ecosystem that don't have the benefit of 20 years of intelligence briefings in government. We are living in a very different world than we were at the advent of the internet, than in 2000 or 2010, and the risk environment is complex and rapidly evolving. It is incumbent on government and others in the critical infrastructure sector who have been involved over time to help bring the rest of the players along, and to recognize that more and more our critical infrastructure is synonymous with national security. Without a functioning critical infrastructure, it is hard to have a secure and economically healthy nation. Broadly, there is a lot of work to build an apparatus, like we have built around critical infrastructure protection, to bring new players in.

Ms. Durkovich thinks that this applies to some of our regulatory bodies as well. The evolution of the world that we live and operate in has changed how we think about these things. It can't just be an economic driver; we must think about the safety and security. She believes there is an opportunity to continue to help all parts of industry and government understand the tension and considerations that we need to make when having the conversation about an economic issue or benefit. That's something that is a priority for Ms. Durkovich as she works with new players that are rushing to be a part of this generational investment. We have to give them some healthy paranoia and that can be done across the rest of government as well, both on the security issue but also the safety issue.

ADM Allen remarked that over the last 5-6 years, there have been many conversations about what is trying to be achieved with GPS. When looking at other GNSS, they evolve differently than GPS does with regards to military use and civil use. That presents challenges for how the system is built out and managed. The PNTAB represents civil users but has nothing to do with building the infrastructure that supports it. There are foreign GNSS participants on the board, and there have been interesting discussions around the Chinese BeiDou and European Galileo looking at this as an opportunity they can provide internationally. It gets into a discussion of soft power and where we're going. We've had issues related to company receivers and limitations in exporting that technology by ITAR. We keep talking about GPS being the gold standard, but a lot of people would say that there are parts of Galileo and BeiDou that are eclipsing the capabilities that GPS has. Has the administration had any sort of higher-level discussion on that front?

Ms. Durkovich thanked ADM Allen for raising awareness and visibility of this issue. She will take that back for consideration and action. The differing systems have always been a part of the conversation, with both the opportunities and the challenges. She thanked ADM Allen again for raising the issue.

ADM Allen thanked Ms. Durkovich again for joining.

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DoD Perspectives and Priorities for the PNT Advisory Board

Mr. Fred Moorefield, *Deputy Chief Information Officer, Command, Control, and Communication (C3), DoD CIO, Co-Chair, PNT EXCOM Executive Steering Group*

ADM Allen introduced Mr. Moorefield's presentation by saying he was unable to attend in person, but that he provided a video instead. PNTAB senior leaders have been in conversation with leadership across government.

Mr. Moorefield began his presentation by thanking the board for the opportunity to speak today. He is happy to virtually join this meeting of the PNTAB. He congratulated the newest members of the advisory board and thanked them for their service. He expressed excitement at the opportunity to make a few comments from the DoD perspective as the DoD co-chair of the PNT Executive Steering Group (ESG). Meetings have been very difficult to convene over the last few years, so it is encouraging that the board is able to engage in face-to-face discussions of such vital topics as the state of the national PNT infrastructure. The work of this advisory board is very important, as it allows board members as PNT experts, the time to evaluate in-depth the issues facing national PNT resources and provide recommendations to the federal government regarding ways to both improve services and counter potential problems.

Achieving and maintaining resilient PNT services is important to the nation and its critical infrastructures. PNT is vital to military, economic, scientific, and public activities of all kinds. The benefits of continuously available spatial awareness and timing enable the most sophisticated modern technologies to function smoothly, while also simply getting people and things where they need to be on time. It is a national priority and our mutual objective to see that national PNT resources should be protected from national and hostile disruption. As has been seen in recent press articles, the DoD has taken a strong interest in the DoD-PNT Enterprise as a focus area for the department. That enterprise encompasses a modernized GPS system, and a range of complementary non-GPS PNT capabilities integrated into resilient PNT applications within DoD systems. These applications are tailored to specific system configurations and are designed to meet a wide range of missions and threats to execution of navigation warfare operations. The overall approach to these efforts is detailed in a strategy for the DoD-PNT Enterprise signed by the DOD-CIO and issued to the public in an unclassified form on August 15, 2019. The strategy document defines a DoD-wide effort to integrate multiple diverse sources of PNT information along with modernized GPS services into flexible, agile PNT applications in virtually all DoD systems and platforms. The goal is to provide robust and resilient PNT applications, which will be tailorable to individual platforms and mission needs, and which will deliver the necessary Navigation Warfare (NAVWAR) effects to US and Allied forces to successfully accomplish their missions anywhere in the world.

GPS remains the cornerstone DoD PNT capability, and must continue to be modernized to meet warfighter needs. The DoD has invested heavily in all three segments of the system: space, control, and user equipment. There are 24 M-Code capable satellites on orbit now, with the launch of GPS III SV5 in June 2021. DoD remains on track to deliver OCX by the end of 2022. DoD has pushed hard to initiate the development and fielding of M-Code capable user equipment to take advantage of capabilities resident in the other modernized segments. This effort will make GPS much more robust in dealing with both cyber and jamming threats. The DoD is further implementing this strategy using what is known as Modular Open System Approach (MOSA), which will enable system designers and producers to deliver adaptable PNT solutions that operate with similar plug-and-play flexibility to what people are used to with personal electronic devices. This MOSA approach will also significantly shorten the lead times and decrease the integration costs to integrate new PNT capabilities into fielded weapon systems.

Congress has taken note of the PNT Enterprise strategy, and as evidence of their strong interest, in late 2020, asked the DoD to detail their progress toward its implementation. On June 28, 2021, in response to section 1611 of the FY21 NDAA, the DoD delivered to Congress the DoD Implementation Plan for Resilient and Survivable PNT Capabilities and Applications. The plan was briefed in detail to Congressional defense staff during the summer, and the DoD is maintaining a dialogue with those staff members today as plans progress.

Much of what is done in DoD is specific to military and is not applicable to commercial firms or the general public. Yet while in the navigation warfare environment military troops face is intense, it is analogous in many ways to the challenging environment in which our national critical infrastructure functions every day. Risk of disruption to domestic, commercial, and civil operations from interference to GPS signals by hostile or natural sources or prolonged threats of cyber intrusion must be assessed, understood, and positively addressed. It is precisely in this area and at this time, where awareness and understanding of the dual-use nature of GPS and of PNT technology in general are essential. "Dual-use" in this context refers to technologies which are highly useful for both military and civilian purposes.

For GPS and related PNT technology within the broader international community, it has been comfortable for years to focus only on peaceful civil and scientific endeavors. Unfortunately, the international cooperation that is necessary to sustain such focus, without accounting for its military applications and their potential hostile aspects, can no longer be assured. We must be more careful in our interactions as we observe an increase in global military threats to potential applications of PNT, which has been widely reported in the press. In the case of a modernized GPS and similar systems now being implemented by many foreign nations, the value of information sharing must be balanced with national security concerns. With regards to GPS use domestically, prudence dictates thoughtful integration designs and consideration of complementary PNT information sources to sustain PNT service in the event GPS service is disrupted for any reason. With regards to GPS in the context of other foreign systems, sharing of GPS information with foreign nations must be informed by knowledge of the consequences of the susceptibility to disruption or misuse for military purposes. Unfortunately, unconstrained collective efforts to improve GNSS for peaceful uses ignore the reality that information sharing can equally and dangerously undermine international security. As with the internet, those who have become dependent on precise GPS and related PNT services must now reactively create protections and remediations to deal with increasingly real threats from sources we had not previously anticipated.

This is where the work of this advisory board is essential. The study tasks undertaken on behalf of the EXCOM can provide great benefit to global security and prosperity if they take full consideration of these evolving realities, understanding fully that they are set in the context of the broader interagency process. He then began to review the DoD inputs to study tasks to the PNTAB on behalf of the EXCOM. First, of course everyone is aware of the interference threats posed by Ligado. He did not dwell on those risks, other than to note that the PNTAB is imminently capable of assessing the anticipated effects of Ligado transmissions both above and below the GPS L1 band. This includes the direct effects of Ligado on GPS-enabled civil operations, as well as their overall effect on the noise floor itself. Second, Ligado is not the only source of potential interference to GPS. Hostile or natural sources of interference can affect GPS signals at any time. This board can both assess the resilience of such vital operations as the national air space system to GPS disruption, as well as recommending alternative civil PNT capabilities to ensure continuity of operations for other communication and transportation operations which rely on PNT services. This will also be of great value across the government and our economy. Third and possibly most important, this board is uniquely capable of engaging with colleagues at NASA and the National Science Foundation (NSF) who are responsible for the operations of the Very Long Baseline Array (VLBA), and the Satellite Laser Ranging (SLR) services which provide foundational data to GPS. A vital task that could be undertaken by the PNTAB would be to assess the physical and cyber risks inherent in open foreign access to such systems that may threaten the integrity of this critical data and undermine GPS accuracy. He thanked the group for their attention and support, and he looks forward to seeing the great results that will be produced over the term of the board.

ADM Allen followed the presentation by referring to Stormy Martin’s comments about the NCO worklist items, which will play into the discussion tomorrow about work items moving forward and potential committee structure. He asked for comments from the group.

Q&A / Discussion:

Mr. Shane noted that he didn’t understand the last point about assessing the impact of foreign access to a variety of systems that seem critical to the functioning of GPS. He drew the parallel to the question ADM Allen had asked to Ms. Durkovich regarding foreign GNSS. He suggested this be addressed with further discussion tomorrow.

ADM Allen responded that in general, the PNTAB talks a lot about the vulnerability of GPS, the signal, and GNSS. It is an attack surface for a lot of different threats, including cyber. The inference there is that the board needs to be out there understanding the risks to the system itself, not only to GPS but to GNSS in general. If it’s an embedded chip in the system, then access to the data and everything else should be considered. This can be discussed further tomorrow.

Dr. Parkinson added that it is a tricky area for this board to understand and shared his skepticism that the board is constituted or has the correct security clearance to do that job justice. He agreed with the value of the undertaking if the board has access to understand and do something about it.

ADM Allen clarified that it would have to be in the context of the threat to civil users and critical infrastructure. There are new PNTAB members including those who work in the power/ energy sector, and perhaps the discussion can be driven in that way.

Dr. Parkinson added that certainly in terms of jamming and spoofing of civil signals, that having access to the information can allow threats to be assessed. He noted that there are deeper implications here about issues that are not the purview of this board, and they relate to the fundamental operations of GPS. The PNTAB is not in that business other than to guard against any disruption.

ADM Allen noted that the landscape of what the PNTAB may consider has changed dramatically and given that the board has not met in 18 months, further discussion around boundaries should be undertaken.

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U.S. / Russia Technology Resilience Gap
Mr. George Beebe, *VP and Director of Studies at the Center for the National Interest*

Mr. Beebe began by thanking the group for the invitation to speak today. He joked that many may remember the old Sesame Street song, "one of these things is not like the other," and that he fits the bill for that in today's presentations. He is not a technologist, not an engineer, not an expert in the technical details of PNT, but did grow up near the U.S. Coast Guard (USCG) academy, which may be his best qualification to speak. Mr. Beebe is what used to be called a "Sovietologist," who was trained to be an expert in the Soviet Union. He joined the Central Intelligence Agency (CIA) in 1986, not long after Mikael Gorbachev became General Secretary of the Soviet Communist Party. His career spanned more than 20 years in government at a time when unforeseen developments happen over and over again. The Berlin Wall fell in 1989. The Soviet Union collapsed. Liberal market-based reforms in Russia failed in the 1990s. "Color Revolutions," as they were called, happened in former Soviet republics around the periphery. The US was surprised by 9/11 in 2001. The US was surprised that they failed to find weapons of mass destruction in Iraq. The US was surprised by Russia's invasion of Georgia in 2008, its annexation of Crimea, and its covert invasion of Ukraine in 2014. Things have continued to evolve in the US-Russia relationship since then. Russian forces are now massing near the borders of Ukraine, threatening to invade, and threatening a direct confrontation with the US. The stakes in all this are very high. What Mr. Beebe learned watching all of this over the years is that there is a common reason for a lot of these surprises. It wasn't because experts didn't understand the particulars of what was going on. However, individual areas or factors that were known very well as narrowly focused specialties, happened to also be connected to other factors that were not well understood. Those interconnections created feedback loops, dynamics that created outcomes that none of the individual specialists saw coming. The reason that Mr. Beebe shares this today is for the PNTAB to consider the interconnections between PNT and bigger issues going on right now that could produce an unforeseen outcome that could be quite tragically disastrous for the US and the world.

A few years ago, Mr. Beebe wrote a book about US-Russian relations and the shadow war that has gone on between countries for quite some time. He approached this topic in an unusual way, starting with an outcome and trying to work backwards, to do what he called a "pre-mortem," a pre-history of something that hadn't happened. He assumed in the book that the US was at war with the Russians, and he asked how the US might get to that position. The US certainly doesn't want to go to war with Russia, and the Russians understand very well that a direct military confrontation with the US would more than likely turn into a nuclear confrontation, which would be bad for them and for everyone. If it's completely irrational to be in a war, how could war happen, nonetheless? To answer this question, he looked at World War I (WWI). It was a tragedy that people at that time didn't think was possible. In fact, the most popular book in the few years leading up to 1914 was a book that argued that war had become obsolete, that war between the great powers in Europe couldn't happen because they were so interconnected. There was so much economic and cultural exchange and mutual dependence that it would be an entirely irrational act for there to be a war. War happened, nonetheless. What Mr. Beebe was surprised about when he went back to look at what led to that outcome was the role that technology played in that spiral into conflict. It was a technology he hadn't considered much before - railroad technology. Railroad technology transformed military mobilization, and it also put an imperative on the great powers of that time to make sure that they mobilized quickly in any sort of potential conflict situation. If they didn't, railroad technology on the side of their adversaries would put them at a decisive disadvantage. Once there was a trigger, a very small incident in Sarajevo, that kicked off a series of events that historians have called a trap. It was a perfect storm of factors that combined to reinforce each other and put the great powers of Europe on a determined path toward war that they couldn't control. He asked if the situation right now might be analogous, where a series of factors that don't seem related to each other may combine to produce an outcome that neither party wants.

He asked the audience to imagine a situation in which tensions are rising dramatically between the US and Russia over Ukraine. He noted that this shouldn't be particularly hard to imagine right now. Russia believes that a possible US military alliance with Ukraine, either formally through the North Atlantic Treaty Organization (NATO) or de-facto through a military partnership that exists in all but a treaty form, is an existential threat. Russia believes that they will not tolerate the threat of a formidable military adversary on their borders in a region that they consider integral to their culture, their history, their economy, and their military security. They signal their resolve to the US to prevent this from happening. They mass well-armed forces near the Ukrainian border and announce that the US is crossing a red line. They demand legal guarantees that the Ukraine will not be in a military alliance with the US or NATO. The US looks at this through the prism of a different world war, not WWI but WWII. What did the US learn from WWII? The US learned a very important lesson – that appeasement only encourages aggression. If governments show weakness by trying to find some middle ground with an adversary, they will exploit it, and the possibility of war goes up, not down. The US is determined not to make that mistake right now with Putin or the Ukraine. The US responds saying that they will not respect Russian red lines in Ukraine. Russia has no right to veto whatever kind of military relationships that the Ukraine wants to have. Instead, the US shows toughness, stands up to Putin, and tells Russia that there will be consequences for invasion. The US threatens explicitly to impose draconian economic sanctions on the Russians and specifies other punishments that are not open to the public but have been clearly communicated to President Putin. In meeting with Ukrainian leaders, the US signals our ironclad support for Ukraine's territorial sovereignty. The US expects and hopes that this will deter war and reduce the chances of a confrontation.

There was a similar dynamic with a similar form of the Soviet Republic in 2008. The US was worried that the Russians were going to attack Georgia [Caucasus] for a variety of reasons. The US did much the same thing with Georgia that they are doing with Ukraine today. They sent high level officials, the Secretary of State, the Vice President, senior Congressional staff advisers. There was a bilateral meeting between President Bush and the Georgian President. The US warned the Russians of all the bad things that would happen if they used military force against the Georgians. The US expected that this would reduce the risk of conflict. What happened? It was the opposite. The Russians grew much more alarmed that Ukraine was going to be a part of the NATO alliance. The Georgians did something that we didn't see coming. The Georgians thought, "wow, we're really important to the US, they keep telling us we're important to them." This emboldened them. They thought that if they got into war with the Russians, that the US would support Georgia. They attacked positions in two parts of their country which had declared independence and separated from the Georgian central government, where there were peacekeepers who were trying to prevent the emergence of conflict between the central Georgian government and the separatists. In the course the attack, they killed some Russian peacekeepers. The Russians responded in full force. They sent a large invasion force almost immediately into Georgia. They used cyber-attacks to take the Georgian government offline and prevent its functioning. They won that war decisively in a few days. The US held an NSC meeting about what to do. Steve Hadley, who was the National Security Advisor at the time, went around the room to every principal on the NSC and said, "should the US go to war with Russia to push back that invasion?" Looking at that situation, the US realized it had a real military disadvantage there. Getting US forces to Georgia to go onto the battlefield on the ground, in the air, or through the sea, was difficult. Geography matters even if the US military is far more capable than Russia's. When it comes to fighting a war so close to Russian borders, the US is at a real disadvantage. The US president found himself in a situation that no president should be in. He got a decision memo that says to accept what the Russians have done in a rather humiliating fashion or to go to war with the Russians, who have escalation dominance on every level of that ladder, up to nuclear exchange.

Mr. Beebe then asked how the US could find itself in a similar situation with the Ukraine today, and what that has to do with PNT. Obviously, there's a similar dynamic going on with how opposed the Russians are to Ukrainian membership in NATO or its alliance with the US less formally. They are also resolved to do something about this. Mr. Beebe argued that it is not accidental that as tensions have been rising over the past several months, that the Russians chose to conduct an Anti-Satellite (ASAT) test. They used a ground-launched anti-satellite missile that successfully destroyed its target, and they did that despite specific protests and warnings from the US, before and after the fact. There were complaints that they were being bad citizens of space, being irresponsible and reckless, creating debris that could harm their own cosmonauts on the International Space Station (ISS). Why would they do that? Mr. Beebe suggested this was a signal to the US in two ways. One was that Russia knows how dependent the US is on space-based systems. Russia knows that if the US loses those systems, the US comes to a grinding halt, not just on the battlefield abroad, but in the US domestically. Russia can create an absolute crisis for the US, should they want to, and the only thing holding them back is their own will. Russia feels so strongly about it that they are willing to face the risk that the damage might do to their own cosmonauts. Did the US get that message? Mr. Beebe doesn't know, but what this points to is a dynamic the US could get into that they may not understand. The US is looking at the Ukraine right now and saying they are not going to go to war with the Russians, but they are going to impose penalties like kicking the Russians out of the international payment Swift system. The US can threaten Russia's ability to earn money from natural gas exports abroad that they're so dependent on. The US can try to isolate Russia in many ways from the international economy and diplomatic system. That should sober them up. The Russians are sending the US a message in that context, and that message is not only that Russia is in a position to defeat the US in the battlefield, but that it can also bring activity in the US to a grinding halt.

Mr. Beebe doesn't believe that this is the way it's going to play out. Is he worried that it might? Yes, absolutely. This points to a vulnerability that the US can and should do something about. The Russians have done something about it for their part. Several years ago, they built a redundant land-based backup for PNT. They recognized the potential risks of overdependence on space-based systems. They wanted something redundant, resilient, and nowhere near as vulnerable to attack and disruption, whether intentional and unintentional, as space-based systems. They invested a lot of money in this system. In conclusion of all of this, Mr. Beebe referred back to the importance of looking beyond the narrow areas of specialty and look at the interconnections with other factors that creates a system dynamic and feedback loop that produces a dynamic we don't see coming. This is not theoretical. This is playing out right now in real life on the world stage, and it underscores the seriousness of the issue that the PNTAB is dealing with. It's not just one thing that impacts US military capabilities or commercial day to day interactions. It's a moment that could have a significant effect on whether the US ends up in a confrontation that has existential implications for everyone.

ADM Allen thanked Mr. Beebe for the thoughtful and provocative presentation and opened the floor for questions.

Q&A / Discussion:

Mr. Shane asked what Mr. Beebe believed was the value of the lesson learned in WWII about appeasement in today's context.

Mr. Beebe responded that the issue here is not that the lesson about appeasement being irrelevant, rather that it is not always relevant. Not every situation in dealing with foreign adversaries is a replay of Munich. It puts the burden on governments as decision makers in the world to observe the difference and understand when they are in a situation where there's an adversary bent on attack regardless of what is done. In that situation, there is no choice but to fight them. There are other situations defined by international relations theory experts as the "security dilemma," where things that governments do that they think are proven defensive measures to protect themselves, but those defensive measures are seen as a threat by an adversary, therefore causing a spiral. If governments create a situation where the adversary feels like it is cornered and has no choice but to fight back, they wind up in a war that they didn't want or expect as a result. That is the danger with Ukraine and Russia right now. Things the US thinks are defensive, Russia finds aggressive and threatening, and vice versa. The only way to solve that is through combination of signalizing resolve and finding a diplomatic way out of the spiral, which is not an easy balance to strike.

Dr. Parkinson remarked that it was a startling and wonderful talk. When looking around the world with other situations that might seem analogous, like Taiwan. Dr. Parkinson asked if Mr. Beebe would like to comment on the Taiwan situation.

Mr. Beebe responded that the Taiwan situation is a bit different than Ukraine and Russia. Taiwan is even more important for the Chinese as they see it than Ukraine is for Russia. China has bigger ambitions vis-a-vis Taiwan than Russia and Ukraine. Russia would love to incorporate Ukraine back into its orbit some way officially, in an ideal world, but they recognize that they don't live in that ideal world, and there is no way that Ukraine is going to come back into Russia's orbit officially or unofficially. Ukraine is too divided inside itself between Ukrainian nationalists concentrated in the West of the country and the people who are culturally and linguistically Russian in Ukraine's east. It's unlikely to get a country that is Pro-Russia, particularly after the last 8 years of war that caused a lot of hatred towards Russia. Russia doesn't necessarily want to re-take Ukraine, but they want to make sure it's not an outpost of the US military, which they find threatening. In Mr. Beebe's opinion, which is not universally shared, it is possible to look at the example of Austria in 1958. In 1958, Austria was half occupied by Allied powers and half occupied by the Soviet army. The initial plan was to divide Austria in two like East and West Germany, but Eisenhower decided that he didn't want to go to war and advocated for Austrian neutrality. In the Austrian State Treaty, all foreign forces were to leave Austria and not come back. That worked and avoided direct confrontation between the US and the USSR. It also worked out well for the Austrians, leading to a path of growing economic prosperity. The US reached a compromise that wasn't taken as weakness or incentive to take all of Austria or invade, but instead decreased or eliminated chances of war. Mr. Beebe continued that the Chinese consider Taiwan as part of China and have been explicit about that, and the only question is how long that is going to take. It is a different situation from Ukraine, and it doesn't look like there is a compromise would satisfy all parties, so the US has less room to maneuver there. It is a different question if the US should deal with this by ending their policy of strategic ambiguity. These are different circumstances in important ways, and there are even harder choices about how to deal with Taiwan.

ADM Allen noted that the railroad technology Mr. Beebe had referred to as a physical technology. Increasingly, we deal with technology that is agnostic to physical borders. He asked Mr. Beebe how these analogies move forward when considering international legal frameworks that are inadequate for dealing with these situations, asking "what is an act of war in cyberspace or the space domain?" ADM Allen added that he had been stationed at the Loran C station in Thailand, and that as a navigation system that everyone uses, there was no cause for attack. Now, there are duplicative navigation systems both nationally and regionally. He asked Mr. Beebe if he has insight into where technology has driven us from physical to virtual borders and how to navigate those challenges.

Mr. Beebe responded that we are now in a much more complex environment. After leaving government service, he became the president of a major technology company and got immersed into the cyber world. He learned two big lessons there – that every system is vulnerable to hacking, and it cannot be stopped if your adversary is determined to hack in the system. The second big lesson is to see lesson number one. To deal with threats, we cannot eliminate all vulnerabilities, but we can make hackers jobs more difficult and develop a resilience strategy. If we assume systems will be taken out, how do we operate? In a cyber and borderless environment, non-state actors can have important effects. Ukraine in 2014 had a popular uprising in Kiev that overthrew the government there because the European Union (EU) said to the Ukrainian government that privileged trade relationships were only permitted with the EU or Russia, not both. The West, including the US, held diplomatic talks to find a way out of this situation and reached some agreements with the Russians, Ukrainians, and Europeans to avoid the flare-up. However, a private militia launched an attack in East Ukraine against local governments, and the local governments fought back, winding up in a civil war in Ukraine that the Russians jumped into with both feet because a non-state actor didn't want diplomatic talks in Geneva to succeed. Mr. Beebe continued that we are facing a similar situation in the cyber domain. Non-state actors can cause reactions, prevent outcomes, and stir up trouble that they find useful for various reasons. The difference between acts of war and acts of espionage are no longer clear. Today, most espionage intelligence comes from the digital domain, but if we penetrate a Russian computer network and gather all kinds of information, we could also be using that same penetration to sabotage those networks, and the Russians do not know the ultimate purpose. This causes a spiral of activity by accident. If Russians want to gather information on military targeting plans that employ things like space-based targeting systems, and they want to gather information, we don't know whether they are gathering information our taking our systems offline. This is a situation where all these factors mean we're particularly vulnerable to escalation, and prudence dictates that we can't just assume it won't happen. We are truly in a brave new world. Mr. Beebe thanked the group and closed his presentation.

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Morning Session Wrap Up
All Members

ADM Allen asked for comments from the PNTAB prior to wrapping up the morning session.

Mr. Shane commented that the morning's presentations set the bar high for the rest of the meeting. He thanked everyone who was responsible for organizing the speakers. He was particularly surprised that when ADM Allen asked the NSC director whether she was aware of the soft-power challenge from other GNSS, that it was news to her. It told Mr. Shane that we have a lot of work to do in terms of advocacy and communications.

ADM Allen added that had we not had the board meeting, he wouldn't have asked that question. Dr. Costa had provided an example of what Galileo was doing in Brazil that inspired that question.

Dr. Costa added that it's not only in Brazil, but in Mexico, Chile, and other Latin American countries.

ADM Allen said that the notion of soft power is an important one to consider.

Mr. Goward added that China is giving away BeiDou receivers. Emergency responders in neighborhoods that have BeiDou equipment continue to point out newer and more advanced capabilities in their system. China is going all-in on PNT as an element of soft power.

Mr. Shields noted that he doesn't know where the US is at in terms of GPS technology, but that he wouldn't be surprised if we are anywhere close to where China is, as they are pushing the audio industry hard to make BeiDou the primary GNSS worldwide for automotive. They claim all of BeiDou can be updated over the air to provide new capabilities, and that short messages can be included so that tailored applications can specifically augmented to receive messages like dangerous road conditions. This is an attractive proposition to automotive companies.

ADM Allen thanked Mr. Shields for the thought and closed for lunch break at 12:15pm.

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Galileo High Accuracy Service
Dr. Ignacio Fernandez-Hernandez, *Galileo Authentication & HAS Manager, European Commission*

Dr. Fernandez-Hernandez thanked Dr. Frank van Diggelen for the invitation to brief to U.S. PNT Advisory Board. He also thanked the key contributors to the GPS program, from whom he's learned a lot over the years. This briefing includes a description of the Galileo HAS services being developed, test results obtained over the last month, next steps for Galileo over the next couple of years, and then possible US-EU cooperation. The Galileo HAS is a Precise Point Positioning (PPP) service. The purpose is to provide orbit, clock, and bias corrections (for both code and soon also carrier phase) for Galileo. We also have the capability to monitor GPS so, in principle, these corrections can also be provided to GPS as this improves the positioning performance. We use, in order to transmit these corrections, the Galileo E6-B signal (transmitted at a carrier of 1278.75 MHz) at a bit-rate of 448 bits-per-second (bps) per Galileo satellite, as a transmission channel. In addition to that we have a real-time ground connection channel through which with Galileo HAS corrections are transmitted with Radio Technical Commission for Maritime Services (RTCM)-like format. We also expect to provide ionospheric corrections of sufficient accuracy in order to have PPP and facilitate convergence, but these will only be transmitted over Europe due to our current limitations in monitoring capability. In top right, he showed the Galileo HAS architecture, where a high accuracy data generator is receiving data from our Galileo Sensor Stations (GSS) monitoring stations provided by the European Space Agency (ESA). Also note the ULS (uplink stations) that upload the message to the satellites and then transmitted to the users. In the bottom right, he noted the infrastructure that is deployed around the world, including 14 GSS, five ULS with four antennas each, and the main centers where the Galileo orbit and clock corrections are calculated.

Galileo HAS is being implemented in three phases (Slide 4). Phase 0 is a testing phase that started last year. In this phase there is no commitment to performance. Something to consider is that Galileo HAS is a modest (in cost) service compared to others, the reason being we are currently using existing infrastructure. The capability to transmit the refresh corrections was inherited from a now de-scoped Galileo safety-of-life service. Phase 1 is our initial service phase. In addition to the services in Phase 0, we will be able to provide corrections to GPS L2C, phase biases, as well as performance commitments. We also expect a convergence time of 5 minutes or less, although this will also depend on the performance of the receiver. Phase 2 is what we call our full operational capability, or full service. In this phase the service will be global, we will add the GPS L5 signal, and we will provide ionospheric corrections in Europe. There will also be additional infrastructure to enable global coverage. If things go well, Phase 1 will start in 2022, and Phase 2 is foreseen to start around 2024.

	Phase 0 SIS Testing	Phase 1 Initial Service	Phase 2 Full Service
Coverage	EU+	EU+	Global
Orbit corrections	Y	Y	Y
Clock corrections	Y	Y	Y
Code biases	Y	Y	Y
Phase biases	N	Y	Y
Galileo corrected signals	E1, E5a, E5b, E6	E1, E5a, E5b, E5, E6	E1, E5a, E5b, E5, E6
GPS corrected signals	L1, L2P	L1, L2C	L1, L2C, L5
Horizontal accuracy requirement 95%	N/A	<20 cm	<20 cm
Vertical accuracy requirement 95%	N/A	<40 cm	<40 cm
Availability	N/A	99%	99%
Convergence time requirement Global, no ionosphere (Service Level 1)	N/A	<300 s	<300 s
EU, ionosphere corrections (Service Level 2)	N/A	N/A	<100 s
Ground channel	N	Y	Y
Ground reference stations	14 (GSS)	14 (GSS)	To be defined
Max. sat. downlinks (448 bps)	20 (ULS Ant.)	20 (ULS Ant.)	To be defined
Authentication	N	N	Y
Start	**2020**	**2022**	**2024+**

Slide 4

In Slide 5 we are presenting the first test results with Galileo HAS, which have not been published yet. These results are from Sep. 2020 and are representative of what we expect in Phase 1. The first table shows the aggregate RMS (root mean squared) orbit and clock errors [Ed. note: see below]. The values provided are for both Galileo and GPS. For both systems, the corrections are in the order of 5 cm. The second and third table provide more detail for Galileo and GPS on a per-satellite basis. The values range in the order of a few cm, with a total average for all satellites below 5 cm for Galileo. The value is slightly worse for GPS, but that's not the fault of GPS but rather the tracking infrastructure we inherited.

Test results: corrections accuracy

GALILEO EGNOS
NAVIGATION MADE IN EUROPE

- Results from Sept 2020, but representative of current performance
- Aggregate (all satellites, all epochs) RMS error *after* HAS corrections:

Constellation	Radial (N), RMS [cm]	Along (T), RMS [cm]	Across (W), RMS [cm]	1D RMS [cm]	Clock-StdDev (1-Sigma)[ns]
Galileo	3.2	6.9	5.1	5.3	0.15 (4.5 cm)
GPS	3.2	9.9	4.9	6.6	0.26 (8 cm)

$$RMS_{1D} = \sqrt{\frac{RMS_N^2 + RMS_T^2 + RMS_W^2}{3}}$$

- Per-satellite SISE, Average and 95%, Galileo E1-E5a (as per Gal SDD, global avg.):

Sat	E12	E24	E09	E04	E08	E30	E13	E07	E15	E11	E26	E33	E03	E31	E02	E36	E27	E25	E21	E05	E19	Gal all-sat avg.
Avg [m]	0.057	0.045	0.067	0.059	0.047	0.039	0.032	0.029	0.029	0.083	0.042	0.05	0.047	0.028	0.037	0.047	0.038	0.038	0.035	0.064	0.056	0.046
P95 [m]	0.118	0.076	0.167	0.114	0.079	0.069	0.061	0.055	0.055	0.186	0.071	0.1	0.111	0.075	0.06	0.108	0.082	0.088	0.073	0.149	0.103	0.095

$$SISE_{GlobalAverage}(t) = \sqrt{0.96910 \cdot R(t)^2 + CLK(t)^2 + 0.01545 \cdot (A(t)^2 + C(t)^2) + 1.96881 \cdot CLK(t) \cdot R(t)}$$

- Per-satellite SISE, Average and 95%, GPS L1C/A-L2P (as per Gal SDD, global avg.):

Sat	G15	G11	G09	G03	G22	G17	G18	G13	G12	G20	G21	G27	G19	G24	G05	G28	G31	G07	G10	G30	G16	G32	G06	G25	G01	G26	G08	GPS all-sat avg.
Avg[m]	0.055	0.097	0.056	0.069	0.051	0.066	0.101	0.069	0.056	0.052	0.057	0.095	0.124	0.066	0.042	0.06	0.072	0.043	0.093	0.15	0.066	0.05	0.116	0.058	0.093	0.089	0.081	0.075
P95[m]	0.11	0.426	0.107	0.148	0.1	0.229	0.239	0.155	0.102	0.113	0.107	0.19	0.193	0.137	0.078	0.102	0.117	0.08	0.285	0.224	0.129	0.096	0.2	0.153	0.169	0.196	0.15	0.16

Slide 5 (Enlarged for readability)

The following two charts [Ed. Note: still on Slide 5] shows what we believe is a significant improvement for GPS, and the same results for Galileo. Again, this is to be expected as the constellation is newer.

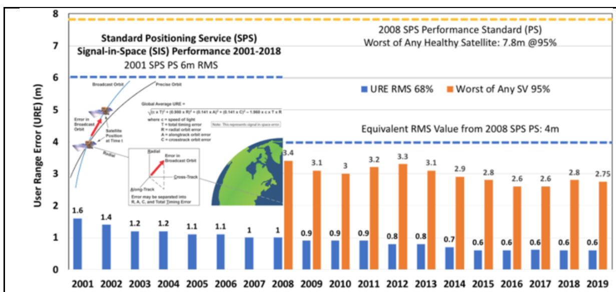


Figure 1.19: Standard Positioning Service (SPS) Signal-In-Space (SIS) ranging errors (SISRE) performance from 2001 to 2019. The steady decreasing error indicates improving accuracy over the time period.

Source: Chapter 1 "Introduction, Early History, and Assuring PNT (PTA)" Bradford Parkinson, Y. Jade Morton, Frank van Diggelen, James Spiler Jr., From: "Position, Navigation, and Timing Technologies in the 21st Century", Morton, van Diggelen, Spilker, and Parkinson, IEEE-Wiley 2020.

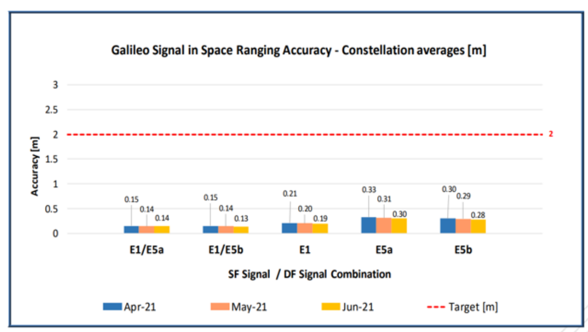
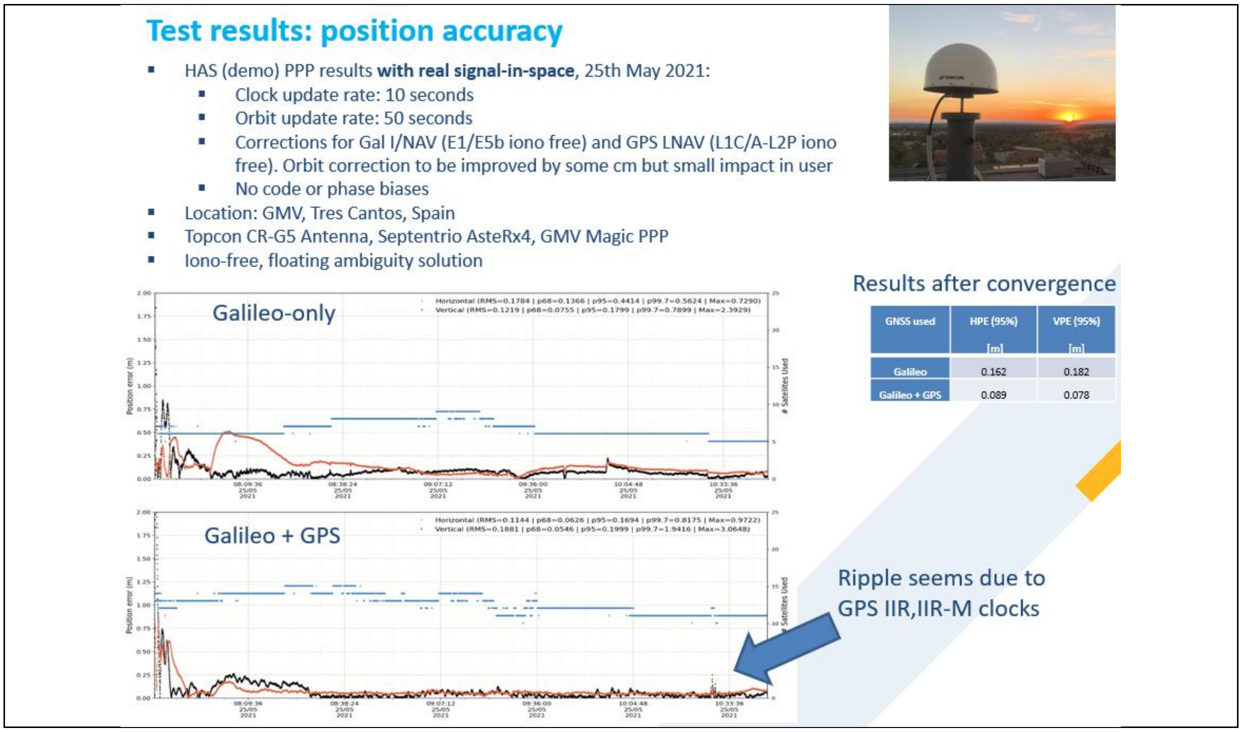


Figure 8 : Monthly Galileo SIS Ranging Accuracy (95th percentile) "over all satellites" (constellation average), measured during the reporting period

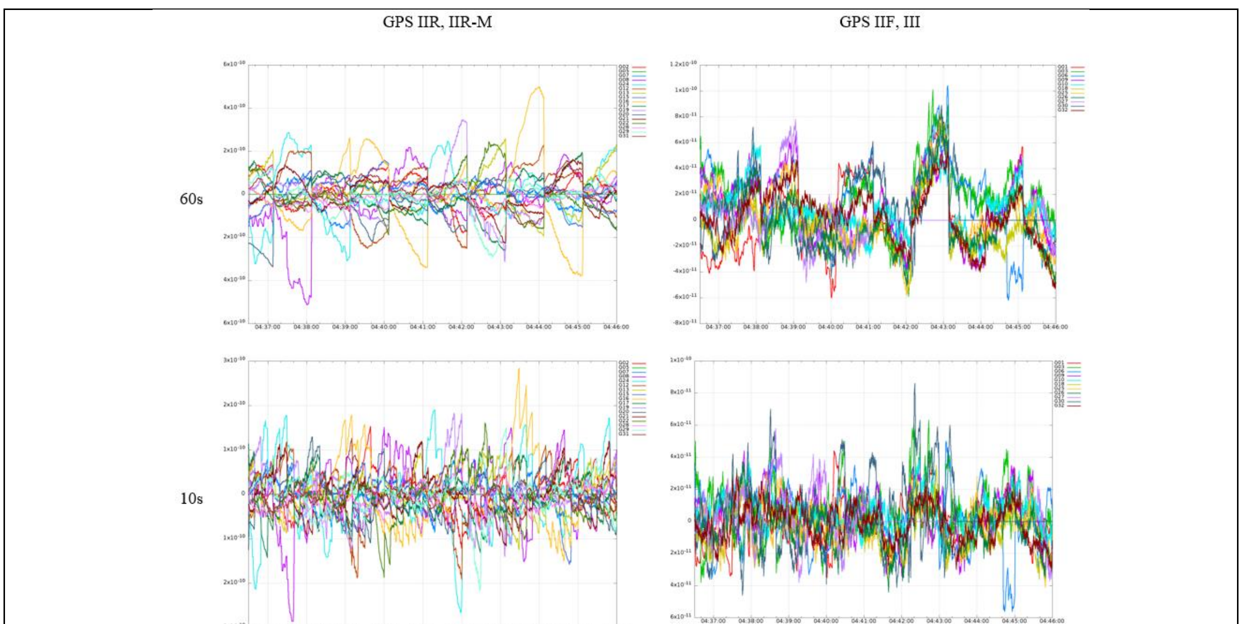
Pop-up charts embedded in Slide 5

In slide 6 we can see some results of Galileo HAS in the positioning domain, as well as when combining GPS and Galileo. For this test, we were only transmitting clock and orbit updates and no ionospheric corrections. As expected, since there are less signals for the Galileo-only scenario, the results are worse that when combining GPS and Galileo signals. The table on the right shows the Horizontal Position Error (HPE) and Vertical Position Error (VPE), which for Galileo are always below the 20 cm we have as a requirement.



Slide 6

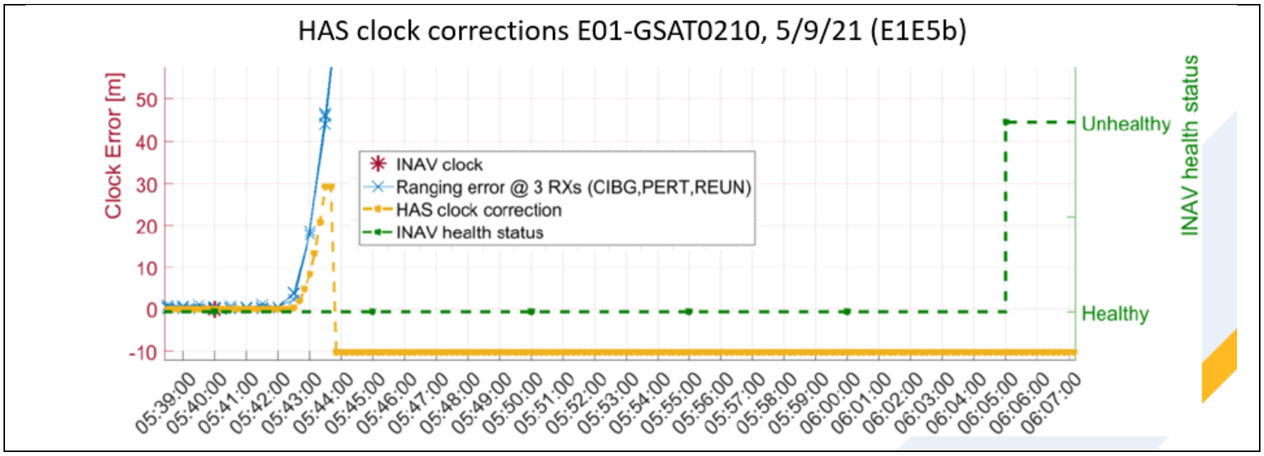
Slide 7 explains the interesting effect of the small ripple in the previous slide. For GPS IIR and IIR-M, the satellites have been in space longer and as expected the clock performance is worse compared to the newer satellites and therefore must be corrected more often. Since we are only correcting the clocks every 10 seconds, we see there is a small degradation that is causing the ripple in Slide 6. This can be seen in more detail in the bottom left plot. On the right, we can see the performance of the newer IIF and III GPS satellite vehicles, where the performance is much better and similar to the Galileo satellites.



GPS reconstructed clock errors for Blocks IIR, IIR-M, IIF, and III, shown with update rates of 60 and 10 seconds

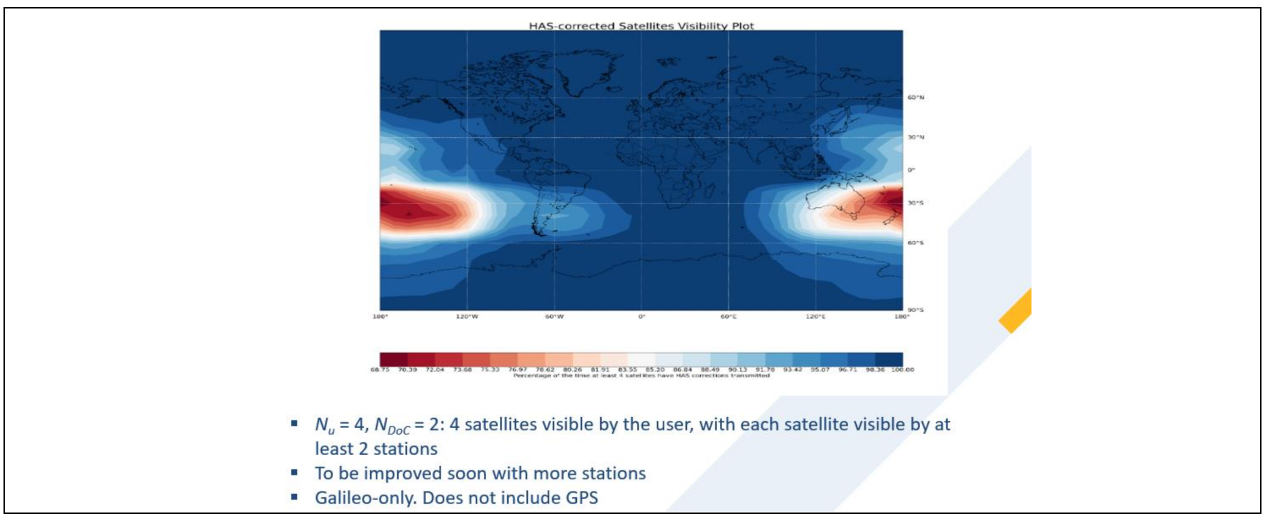
Slide 7

This is another interesting effect of Galileo HAS (Slide 8). Because we are monitoring the satellites with shorter times, in theory HAS is able to detect satellite events and anomalies. However, we need to be clear that we are far from claiming we can provide any type of integrity, but an advantage of having PPP services in the PNT is that because of the fast monitoring we can detect satellite anomalies. In this particular case, we are looking at an anomaly that was observed in a Galileo satellite over the past months. The ranging error started growing a lot and the Galileo engine was able to correct the error until that satellite was declared unhealthy some 20 minutes later. This could also be the case for other GNSS and other PPP services.



Slide 8

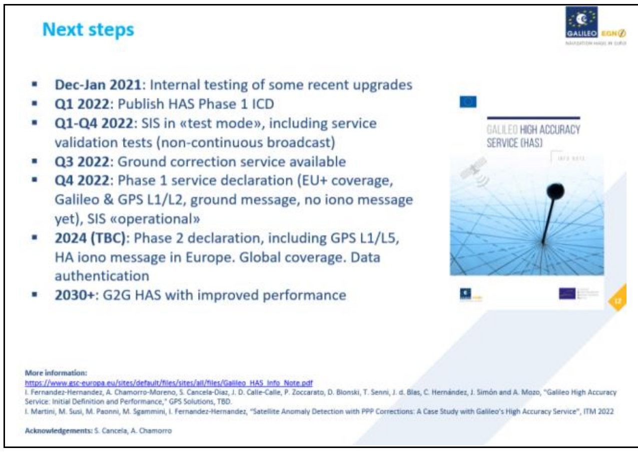
Slide 9 show the coverage that, in theory, we can obtain with the current infrastructure. We are measuring the availability of having at least four Galileo satellites visible by the user and in view of at least two ground stations. As we can see, Galileo HAS covers much beyond the EU. We expect improvements when more stations (as planned) are added.

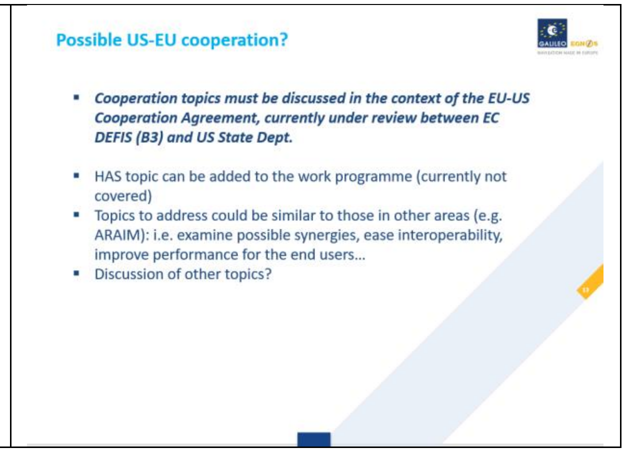


Slide 9

Our next step is to test upgrades we've made and then publish the HAS Phase 1 Interface Control Document (ICD) (Slide 10). For the rest of 2022 we plan to transmit the signal, but not continuously. After mid-2022, we expect the ground correction service (provided through the internet in an RTCM-like format). And, if everything goes well, by the end of 2022 we plan to declare the Phase 1 service available (see Slide 4 for details). Finally, in the 2024 timeframe, we plan to have declaration for Phase 2 with HAS full operational capability, including data authentication. We are authenticating the Galileo nominal broadcast message, but not yet the high accuracy. Eventually, in the following decade Galileo will transition into its second generation (Galileo 2nd Generation, or G2G).

Regarding potential U.S.-EU cooperation, when he checked with my colleges at the European Commission (EC) about discussing this topic, they clarified that there is a framework to discuss it within the EU-US Cooperation Agreement, which at this time is under review between European Commission Defense Industry and Space (DEFIS) Unit B3 and U.S. State Department, and we hope will be soon renewed (Slide 11). As part of this extension/enhancement of the cooperation agreement, high accuracy services in general could be added to the work program (currently they are not covered). There are other topics that are already covered, such as the topic of Advanced Receiver Autonomous Integrity Monitoring (ARAIM) being covered in the U.S.-EU WG-C.





Slides 10-11

Q&A / Discussion:

Mr. Betz noted that at the end, Mr. Fernandez-Hernandez mentioned that in the 2030 timeframe, G2G will provide additional performance. Mr. Betz asked if Mr. Fernandez-Hernandez could say anything about what in G2G will lead to that additional performance.

Mr. Fernandez-Hernandez replied they expect to have a wider network and better tracking performance of the HAS signal. As attendees may already know, we had to take out the pilot to use it for authentication purposes. This is under discussion and he cannot go into more detail.

ADM Allen asked what it will take to get this into agenda of US-EU discussions and for the anticipated timeline.

Mr. Fernandez-Hernandez responded that in the upcoming months there is a need to renew the cooperation agreement, and as part of this renewal there is a need to define a new framework with more concrete elements. In parallel to that, the current agreement is still in force with several working groups in place, so there are things we could trace down to these working groups. The focus should be to define a long-term plan for cooperation over the next few months.

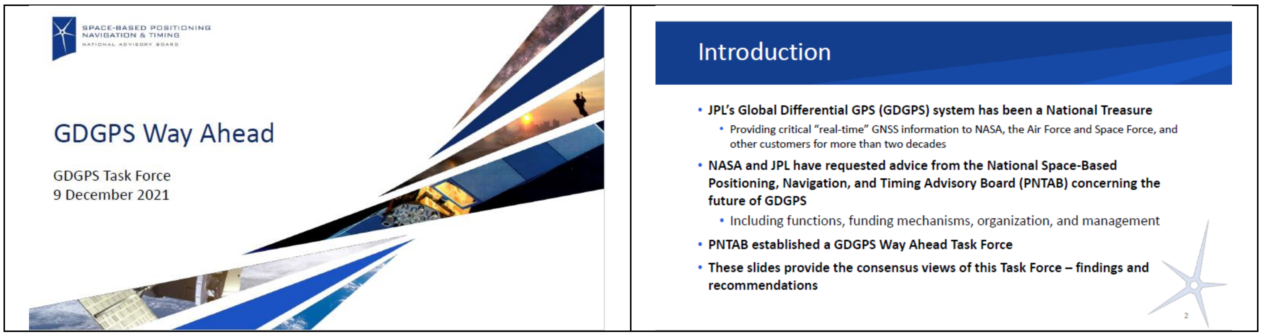
Mr. Moore referred to the test results slide (Slide 5). He asked if Mr. Fernandez-Hernandez could give an indication of the time of convergence to reach those figures. Earlier, he had given a general figure of five minutes. Mr. Moore asked for more information on the specific convergence times for both.

Mr. Fernandez-Hernandez responded that in the testing phase, we are more focused on the performance of orbit and clocks. At a system level, it can be several hours, and at the user level, we can converge in the order of less than half an hour. In the case of combined Galileo and GPS, the convergence was quicker. Those results, however, were not optimized for convergence. We were also using two frequencies, not three, which would help to converge faster.

* * *

Global Differential GPS (GDGPS) Task Force
Preliminary Fact-Finding Report
Dr. John Betz, *Chair, GDGPS Task Force*

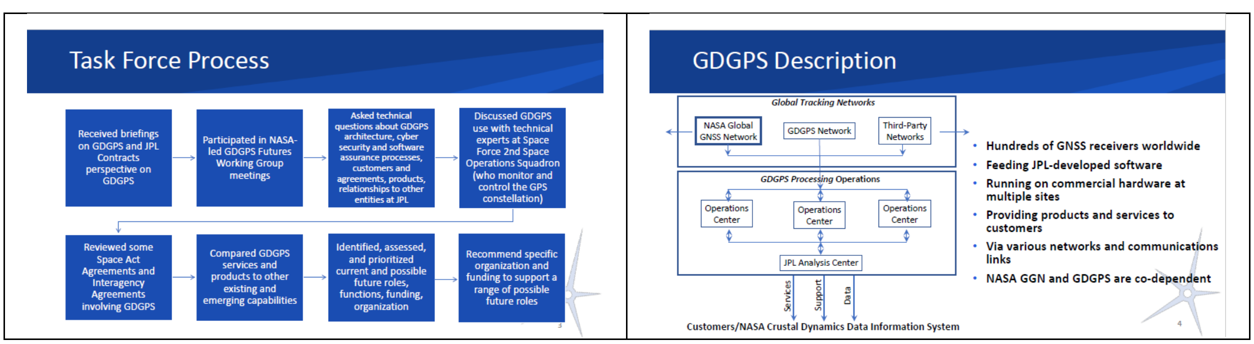
Dr. Betz began by identifying his purpose in giving a report on the task force that was set up under FACA for the board (Slides 1-2). It was a detailed study on the GDGPS system, what the Task Force (TF) did, how they reached their conclusions, and final recommendations. GDGPS stands for Global Differential GPS and has been operated by the Jet Propulsion Laboratory (JPL) for more than 20 years. It provides critical real-time information on GPS and GNSS to USAF, USSF, and commercial customers. As GDGPS has evolved and NASA and JPL have reexamined priorities in their operations, questions were raised about the future of GDGPS. This presentation should be considered advice from our board concerning various aspects of how it should be funded, organized, and maintained. PNTAB established this TF with Dr. Betz as Chair, Dr. Todd Walter as co-chair, SGEs and representatives from across the PNTAB, and a consultant.



Slides 1-2

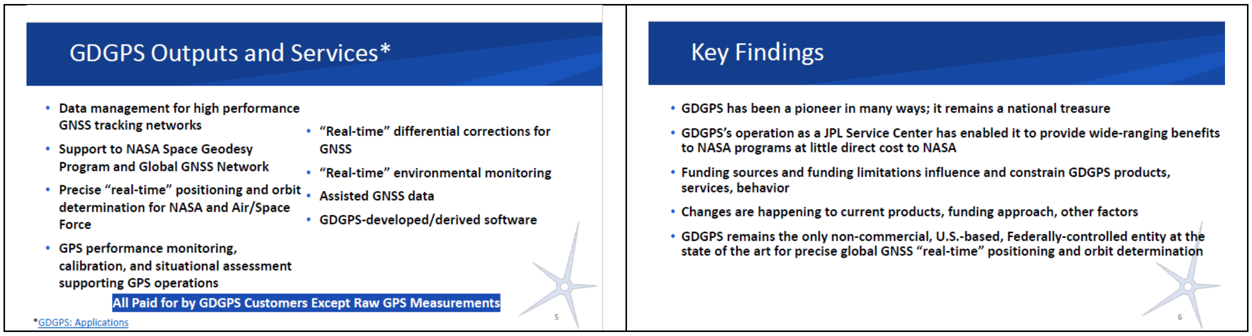
The TF began with detailed briefings on GDGPS and JPL contracts on how GDGPS operates and how funding and contracts work (Slide 3). In parallel, NASA developed their own Working Group that looked at similar topics from the NASA perspective. The PNTAB TF asked technical questions about GDGPS architecture, cyber security and software assurance processes, products, and relationships to other entities at JPL. The TF met with the 2nd Space Operations Squadron (2 SOPS) to discuss how GDGPS data is used to help the analysis of the GPS constellation. The TF reviewed contractual documents used to set up arrangements between GDGPS and various commercial and government organizations through Space Act Agreements/ Interagency Agreements. Then they compared GDGPS services and products to other existing and emerging capabilities. Based on all that information, the TF brainstormed what GDGPS could do in the future, as well as how to prioritize and assess those aspects based on users in the GDGPS community.

Dr. Betz then reviewed the basic components of GDGPS (Slide 4). GDGPS is fed by a set of global tracking networks, the most fundamental and essential of which is the NASA Global GNSS Network (GGN), with 70 receivers. GDGPS operates 7 of its own receivers. It also taps into third-party networks around the world, particularly those run by the International GNSS. That combination of hundreds of GNSS receivers worldwide is fed into the GDGPS processing operations, which consists of three identical but physically distinguishable operations centers all interacting with an analysis center. Out of that comes a series of services, support, and data, provided to customers. Raw GPS measurements are also delivered to NASA's Coastal Dynamics Data Information System (CDDIS). In summary, GDGPS encompasses hundreds of receivers, that feed JPL-developed and operated software. GDGPS runs on commercial hardware across multiple sites, providing products and services to customers via various networks and communications links. One important aspect to emphasize about GDGPS is the symbiotic relationship between the GGN and GDGPS, which co-dependently share data, maintenance, and software development.



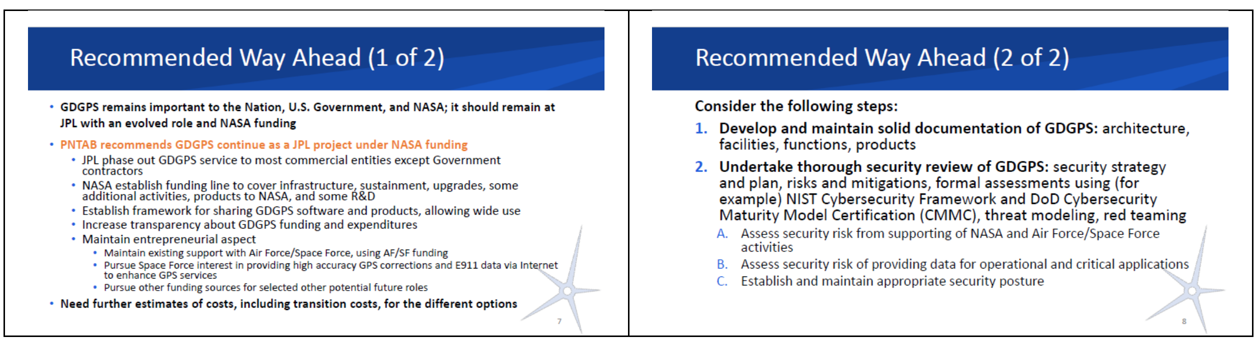
Slides 3-4

GDGPS has a variety of outputs and services (Slides 5-6). There is data management for high performance GNSS tracking networks. GDGPS supports NASA's Space Geodesy Program and GGN. GDGPS provides precise "real-time" positioning and orbit determination for NASA and USAF/ USSF activities, with only seconds of latency. GPS performance monitoring, calibration, and situational assessment supporting GPS operations. For commercial customers, there are "real-time" differential corrections available for GNSS around the world. For research applications, there are a variety of "real-time" environmental monitoring activities going on. Many cellphones use GDGPS corrections when dialing E911. GDGPS has pioneered many high-accuracy applications of GNSS data in software that has gone on to be used in other systems. Because of the way the program is set up at JPL, these outputs and services are paid for by GDGPS customers except raw GPS measurements. When looking at the big picture, GDGPS has been a technical pioneer in many ways and remains unique in important ways to the US. GDGPS's operation as a JPL Service Center has enabled it to provide wide-ranging benefits to NASA programs at little direct cost to NASA. External customers pay for a vast majority of GDGPS operations. Funding sources and limitations influence and constrain GDGPS products, services, and behavior. Due to changing circumstances, changes are also happening to current products, funding approach, and other factors. What became clear to the TF is that GDGPS remains the only non-commercial, US-based, federally controlled entity at the state of the art for precise global GNSS "real-time" positioning and orbit determination.



Slides 5-6

Based on that assessment, the GDGPS PNTAB TF made two recommendations (Slides 7-8). First, GDGPS remains important to the nation, US government, and NASA; it should remain at JPL with an evolved role and NASA funding. In particular, the PNTAB TF recommends that GDGPS be moved from a Service Center to a JPL project, and that at least its core capabilities be funded directly by NASA, rather than by individual customers. That would involve the careful phase out of GDGPS service to most commercial entities except government contractors. NASA would need to establish a funding line to cover infrastructure, sustainment, upgrades, products to NASA, and some R&D that is essential to GDGPS' future. As a result of removing the Service Center constraints, there would likely be opportunity to establish a framework for sharing GDGPS software and products, allowing for wider use. One of the things that made GDGPS great has been the ongoing entrepreneurial aspect. The TF would like to see GDGPS maintain their existing relationship with USAF/USSF and to pursue more opportunities for collaboration, including provision of high accuracy GPS corrections and E911 data via internet to enhance GPS services. The TF recognizes that they have not dug deeply into the costs of doing this, so they recommend to NASA and JPL to further explore transition costs in their own analysis.



Slides 7-8

Regardless of whether that recommendation moves forward, the PNTAB TF also asks NASA and JPL to consider developing and maintaining solid documentation of GDGPS, including its architecture, facilities, functions, and products. The TF also recommends undertaking a thorough security review of GDGPS, given the importance of GDGPS and the increasing threats to software systems. As two final cautions, the TF notes that properly managing the transition of GDGPS funding is essential, as is assured long-term stability of NASA funding. As an advisory board, the TF presents these recommendations with the acknowledgement that NASA and JPL have the final decision. Dr. Betz thanked the GDGPS staff and specifically highlighted the contributions of Dr. Yoaz Bar-Sever for his tremendous leadership over the years. He thanked the group for their attention and asked for any questions.

Discussion:

ADM Allen noted that this effort was the first significant undertaking of research for the PNTAB. As a Federal Advisory Committee, the PNTAB is here to give advice. ADM Allen asked the board to consider these recommendations for vote tomorrow to be provided to the NASA Administrator under FACA Title V.

Mr. Miller noted on behalf of NASA that Mr. Larry James, as principle from JPL, is recused on this issue. Mr. Miller thanked the board for their work and acknowledged the difficulty of the challenge at hand on how to structure GDGPS so that it continues to provide national benefit. In addition to 2SOPS, GDGPS is an important tool at DOT for monitoring GNSS signals. The TF has provided a set of options and alternatives to consider, and following the discussion tomorrow, these recommendations can be reviewed by the NASA Administrator and the PNT EXCOM.

Mr. Younes agreed on the value of GDGPS, noting that NASA is not the only user of this system. He agreed with the suggestion to take the issue to the EXCOM, seeing GDGPS as an interagency partnership opportunity rather than a sole NASA effort.

Dr. Betz noted that the TF understood that value of GDGPS is widespread.

ADM Allen thanked Dr. Betz for the briefing and suggested further discussion be continued tomorrow.

* * *

A Resilient National Timing Architecture
Mr. Dana Goward, *RNT Foundation & PNTAB Member*

Mr. Goward remarked that he saw no need to remind anyone at the meeting about the essentiality of GPS, nor of the vulnerability of these signals and the many threats arrayed against GPS signals, satellites, and users. However, it is worth noting that despite the fact that there is information and knowledge that something should be done to address this, we as a society often fail to take action on that knowledge in order to prevent bad things from happening. For example, for decades it was recommended to add a mal-odorant to natural gas, but it took losing an entire school of children in 1937 in New London, Texas for that to actually happen. More recently, we had more than 100 commercial aircraft hijacked before 9/11, and industry officials thought it would be prudent to harden cockpit doors. Again, action wasn't taken until after a catastrophic event. In New Orleans, before hurricane season every year, the Army Corps of engineers would go around and tell locals, "when the levees fail, you need to have a hand axe in your attic." Not if the levees would fail, but when. It was known that the levees wouldn't stand up to a major hurricane, but action wasn't taken until after the fact. The US has cycled through periods of readiness and unreadiness for pandemics, and we are now almost 1 million people short of where we should have been as a result of COVID-19. As a final example, Texas has had cold weather during the winter for hundreds of years, yet there are power systems that fail during extreme weather conditions.

To bring it down to the PNTAB's area of interest, there has been documentation since 2001 that GPS is vulnerable, that there was a wide variety of threats arrayed against it, and that we need to do something to reinforce the system in terms of protecting, toughening, and augmenting. Here we are 20 years later with almost all of those threats realized: threats against the satellites in place right now and overt promises to make those threats real. We have yet to take action. There are other nations that have either implicitly or explicitly taken action to implement or maintain systems as backups to GPS that are less vulnerable, including Saudi Arabia, South Korea, Iran, and Russia. Russia explicitly said in its last radionavigation plan its intention to maintain Chayka (Russian equivalent to Loran) coverage as an alternative to space-based systems. The United Kingdom has a national timing initiative going on that is comprised of space, terrestrial, and fiber technologies. China is way out ahead of everyone else on this, not only just for timing, but for PNT overall. They have a comprehensive, holistic PNT plan that involves exceptionally well-measured fiber connections, three levels of satellite PNT, and an extensive set of terrestrial broadcast systems to provide PNT to military and civilian users.

It's not as though the US has not expanded on what we've known since 2001. We've told ourselves we need a holistic approach, a system of systems, in order to protect the nation and our technology. An interagency working group developed a graphic in 2008 that the Chinese used as a model for their own plan. More recently, the DoD has developed a Layered PNT Architecture Construct with various types of orthogonal PNT systems delivering service and supporting each other. The US Congress has been interested and engaged with this issue over the years. It has had access to the same information as us and gotten progressively more and more involved, to the point that in 2018, it mandated the administration take action to develop a complementary part of the National Timing Network to add to and reinforce the space segment. While it mandated that it happen by December of 2020, that date has come and gone, but the legal requirement remains in effect. It looks as though $15 million will be provided to "start a program" for a GPS backup in 2022.

The RNT Foundation published a whitepaper last October on how to construct a national timing network that is hard to disrupt. Despite trying not to look at other people's work, they came to the same conclusion that a combination of space, terrestrial, and fiber-based systems would be a good basic infrastructure to protect technology and deliver time using diverse methods and modes, not all of which could be disrupted at the same time. One of the authors, Dr. Marc Weiss, is a retired theoretical physicist from NIST who was famous for designing one of the first clocks that went up on a GPS satellite. Dr. Patrick Diamond is a member of the PNTAB and a network engineer. This document is available online for those interested. The authors postulate that using readily available technology, the nation could have timing at 100 nanoseconds in major metropolitan areas and better than

500 nanoseconds nationwide for something less than $100 million per year using relatively easy to implement service contracts. In January 2021, DOT released the Complementary PNT and GPS Backup Technologies Demonstration Report, which found similar architecture conclusions including satellite, terrestrial broadcast, and fiber, also adding local high-precision broadcast to the mix. RNT Foundation developed a second whitepaper in October 2021, which postulated that if the government were to go out and request services, what kinds of things would it consider when going out to issue a Request for Proposals (RFP).

Since that time, more folks have weighed in on the subject, which Mr. Goward finds encouraging. NIST released a report in November 2021 that looked at dependencies in critical infrastructure, only looking at GPS timing impacts on stock exchanges, electrical grid, and telecommunications. One key phrase to highlight from the report is that "the impact of a long lasting, widespread GPS outage on mobile phone networks would likely be staggering." Long-term in this context means something more than 24 hours. NIST issued another report on the same day about resilient timing architecture, and while they only discussed current systems, they also talked about space-based assets, terrestrial broadcasting, and fiber to deliver this fundamental framework. The PNTAB has opined on several occasions that the nation should establish a timing complement to GPS. That was reinforced and supported by the National Security Telecommunications Advisory Committee (NSTAC) in its most recent report to the president. The Alliance for Telecommunications Industry Solutions (ATIS) has also reinforced this with letters to Congress in 2017 and 2021.

There has been some discussion about whether taking the bullseye off GPS by providing a framework for national timing is something within the federal government's role. Mr. Goward argues that it is, based on the common defense and general welfare clause. Dr. Scott Pace had suggested to him that perhaps the "weights and measures" clause of the Constitution might also apply. When the US made GPS free for all, it established highly precise wireless time as a free public utility and public good. Since that time, the EU, China, and Russia have confirmed that philosophy. When utilities are insufficiently reliable, the utility should be reinforced. That doesn't necessarily mean that it's going to crowd everybody else out of the picture. Mr. Goward believes the US government has the responsibility to provide the utility, the sovereign signals, and the information that it says it would, and that it would require a space-based and terrestrial architecture to combine into a national timing architecture. Upon that basis, that technological infrastructure, others will build to meet their various more refined and specialized needs. It will provide a framework that will encourage innovation, new opportunities, and greater resilience for all. It will make us much less vulnerable to threats from adversary nations who are willing to exploit our single point of failure. Mr. Goward thanked the group for the opportunity and opened the floor for questions.

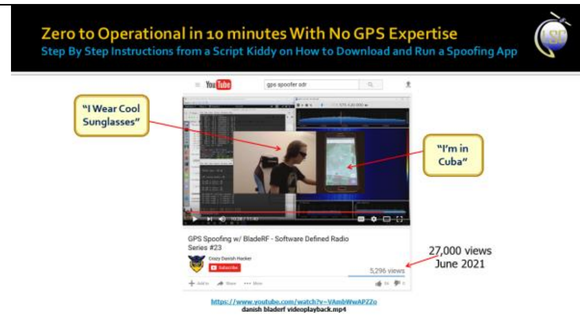
Q&A / Discussion:

> Dr. Filjar thanked Mr. Goward for a very interesting outlook on such an important topic. Dr. Filjar has seen quite a lot of studies in Europe about the vulnerabilities of the financial system in relation to satellite systems because financial services are among the major utilizers of satellite communications. He asked Mr. Goward if there is any concern or systemic overview of the risks for financial services and banking systems here in the US.
>
> Mr. Goward responded that there are risks for everyone. Those risks are mitigated differently for every user and segment. The NIST paper talked about stock exchanges, which was an interesting way to approach it because when we look at the financial sector, we bifurcate it to stock exchanges in Chicago, New York City (NYC), or San Francisco with high volumes that can buy atomic clocks and dark fiber to synchronize themselves and their systems to each other and UTC (Coordinated Universal Time) should they choose. While stock exchanges certainly use GNSS, they are not nearly as vulnerable because they have so many resources. However, there's another part, the rest of us, that are not in Manhattan or Chicago, that rely on Automated Teller Machines and credit card transactions and banking, which all rely on networks. Networks rely on wireless connection, and wireless connections are very much dependent on GPS and GNSS timing. Yes and no, there are varying degrees of concern, but with a holistic approach and the kind of infrastructure proposed that would be easily used and adopted by all, everyone would benefit.

* * *

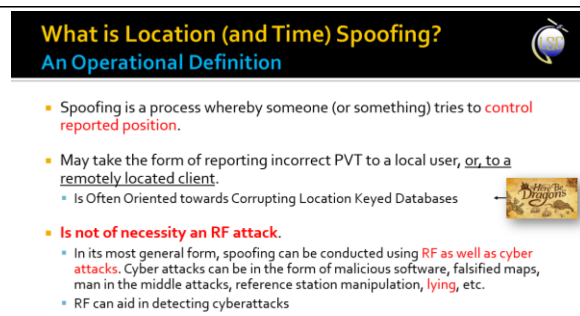
GPS & Galileo Civil Signal Authentication
Mr. Logan Scott, *President, Logan Scott Consulting*

This briefing will discuss GPS and Galileo civil signal authentication as well as 5G. The first thing to understand is that spoofing is not just about the GNSS receiver, it's about perception (Slide 3). When people think about spoofing, a lot of times they're thinking about a person following instructions on how to download a spoofing app and ten minutes later claiming they're in Cuba (Slide 4).



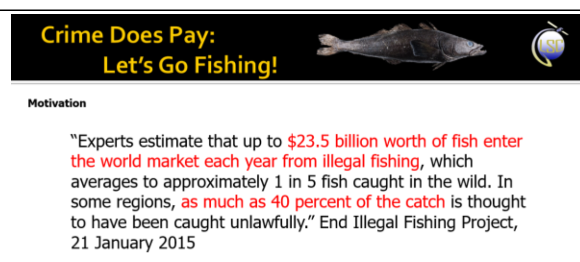
Slides 3-4

The reason for that are software defined radios (SDR). Slide 5 shows a couple of inexpensive SDRs. The LIME SDR is around $130, and the other one is about $400. They are inexpensive and capable of generating very specific waveforms. When we look at location and time spoofing, he likes to have an operational definition (Slide 6). It's basically trying to control the reported position either locally in the receiver or to some other remotely-located client. He would argue that the place where the dragons are is when talking about inputs to location-keyed databases or Automated Information Systems (AIS). Also, spoofing is not necessarily an RF attack. It could be RF as well as cyber. However, RF can aid in detecting these cyberattacks.



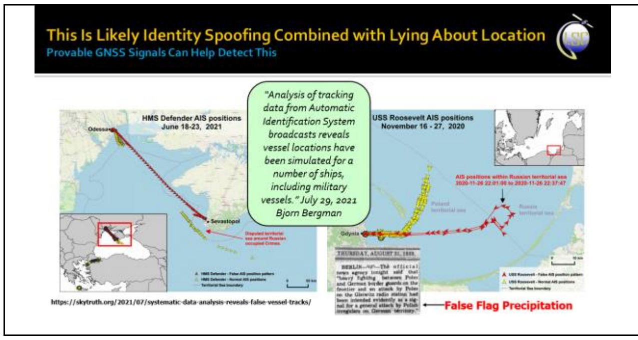
Slides 5-6

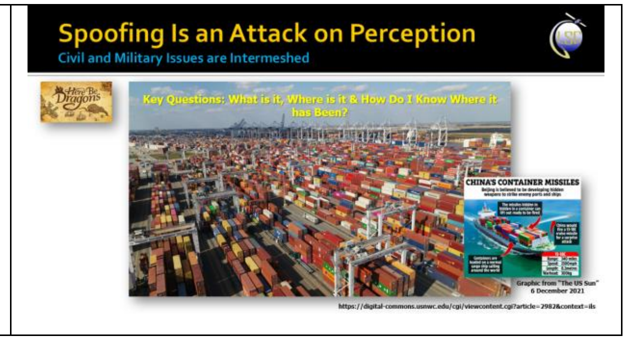
There are a lot of motivations for spoofing to cover criminal activities (Slide 7-8). One example is illegal fishing, where it is estimated this is worth up to ~$20 billion/yr. On slide #7, the red circles in the chart are suspected RF attacks.



Slides 7-8

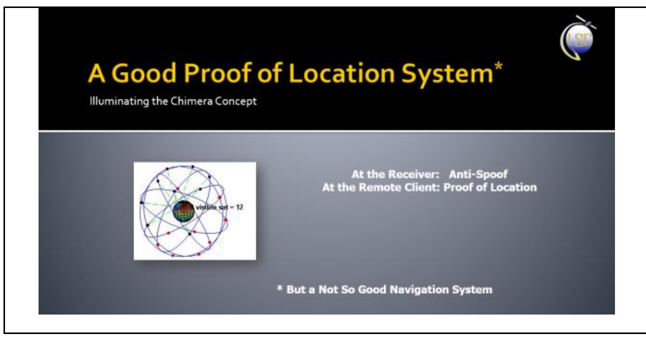
The next example (Slide 9) is one of non-RF spoofing that happened near Crimea, where Russia claimed NATO warships had entered its territorial waters. The yellow lines show the location of a warship whereas the red line is where the AIS said it was. This is very pernicious and reminded him of an incident prior to WWII where German soldiers dressed in Polish uniforms and attacked a German radio station, which was then used by the Nazi regime to justify its attack on Poland. There are a lot of nasty things that are going on in Ukraine at this moment, and this is just one example. Again, spoofing is an attack on perception. In slide 10, when he looks at the shipyard, he sees a location-keyed database where key questions we should ask are what is in those containers, where are they now, and how do we know where they have been? Also, there are concerns about China developing hidden weapons that could be used to strike ports and ships. Therefore, it is important to harden civil systems.

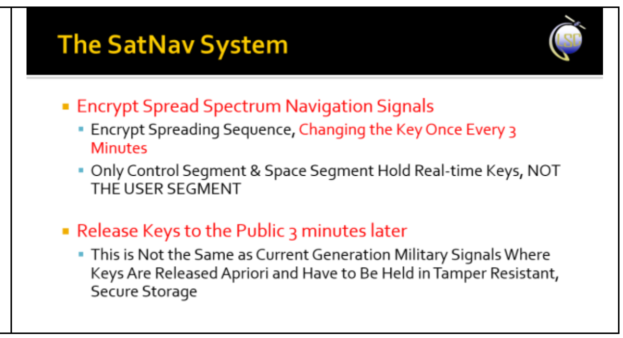




Slides 9-10

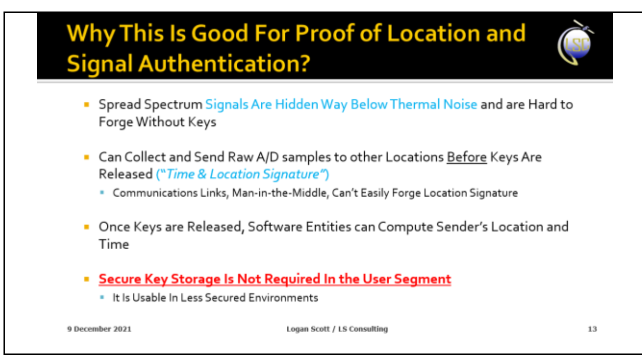
Let's move on to discuss some of the elements of a solution (Slide 11-12). We're going to talk about a hypothetical system, which is anti-spoof at the receiver but requires proof-of-location at the database in the remote client. Imagine something like GPS, where we are going to transmit fully encrypted signals and we are going to change the key every three minutes. The space and control segments know what these keys are, but we are not going to tell the user segment. This is not like a military system where you have pre-distributed keys. So, what can we do with that?

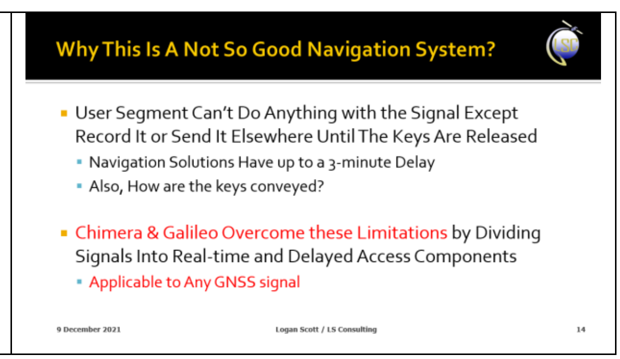




Slides 11-12

This turns out to be a good proof-of-location system because the signals are hidden well below the thermal noise, and therefore are hard to forge unless you have the keys (Slide 13). Therefore, the user can record the signal and distribute it to other locations knowing that it will be more difficult for someone to forge the signal. Once the keys are released (3 min later), the software entities can go off and computer the location. You don't need secure key storage within the user segment. However, this is not such a good system for navigation because of the 3 min delay (Slide 14). Another issue is how the keys are conveyed. So, when we talk about Galileo and the Chimera System, they overcome these limitations by dividing the signals into a real-time component and a delayed access component. These techniques are applicable to any GNSS signal.



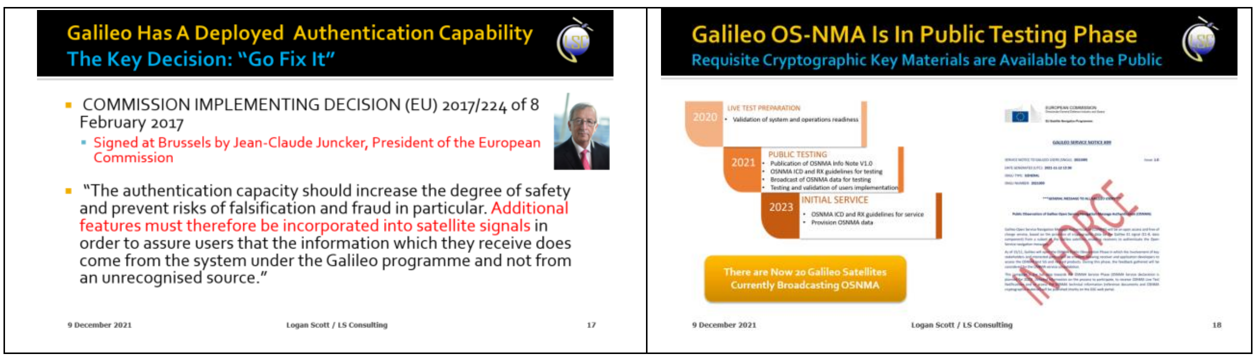


Slides 13-14

Let's talk about some practical systems (Slide 15). These usually involve two aspects. One is data authentication where you are proving that data stream is correct, which is straightforward (Slide 16). The other one is ranging authentication, which is more difficult but probably the more important one. What you are doing is establishing the provenance of the pseudoranging codes. This is typically done by introducing cryptographic-based watermarks into the signal. This is a complex modification to perform on a non-SDR satellite, but straightforward when the satellite is SDR-capable. As far as the receivers go, it's a modest modification so you can take a snapshot.

Slides 15-16

In 2017 Galileo approved a signal authentication capability (Slide 17). The Galileo Open Service Navigation Message Authentication (OSNMA) is currently in the public-testing phase and being broadcast by 20 Galileo satellite vehicles (Slide 18). There is an intention to go operational in 2023. The key materials you need to process this signal is publicly available.

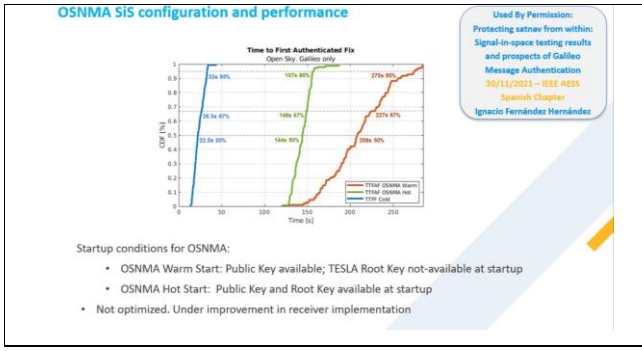


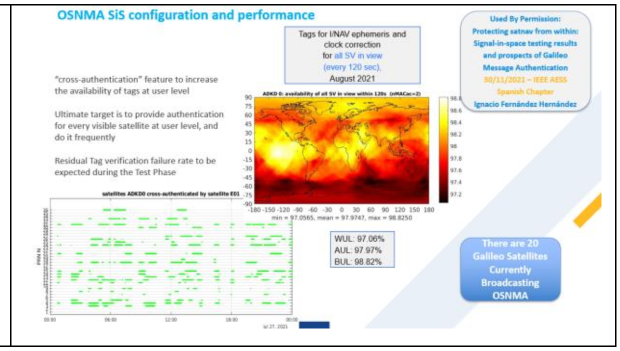
Slides 17-18

The Galileo data authentication will be transmitted on the E1B signal component and ranging authentication will be on the E6 frequency band (Slide 19). E6 is currently not authorized by the FCC for use in the U.S., so it will be an interesting policy question how to deal with that. This is a critical capability that GPS does not have. Galileo is publishing its keys, and you basically have to touch the receiver once to get some key material, and then you are set for life (Slide 20). The reason for that is that you have an Over the Air Rekeying (OTAR) mechanisms that allow you to constantly update the keying material as needed. It's not like you have to go in there every few months to update the keys. Also, they authenticate satellites that are not transmitting the keys by using the data retrieved from the Galileo satellites that do transmit the keys. This is referred to as cross-authentication. With cooperation with the U.S. State Department, they could also authenticate GPS signals.

Slides 19-20

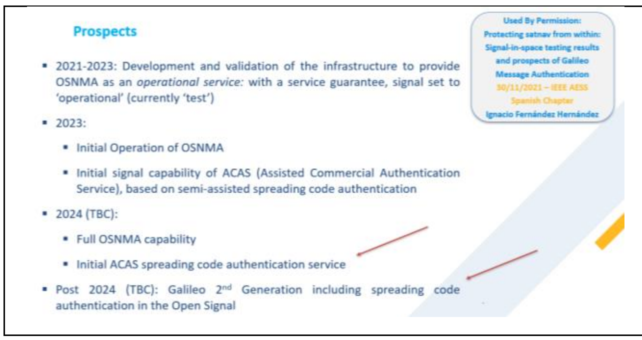
How long does it take to authenticate? In slide 21, the blue line is the time to first fix, the green line assumes the receiver was on recently, and the red line is when the receiver has been turned on for the first time or hasn't been on for a while. The time to first authentication is 3 min 95% of the time, though it is possible this may get pushed down to 100 seconds. In terms of current coverage, 98% of the world is covered right now (Slide 22). Currently there are 20 Galileo satellites broadcasting OSNMA. European receiver manufacturers are very active in developing this capability.





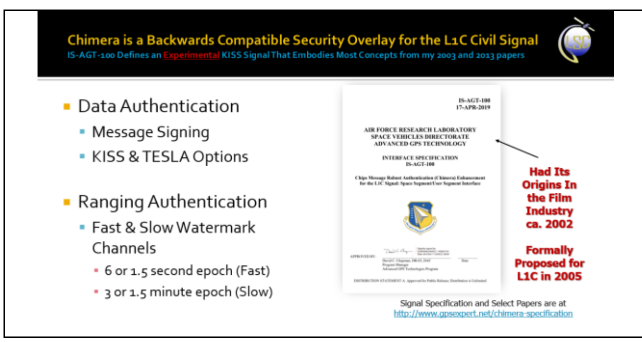
Slides 21-22

In terms of prospects, Galileo is talking about having full OSNMA and initial Assisted Commercial Authentication Service (ACAS) in the 2024 timeframe (Slide 23). Galileo is also looking to put spread code authentication in the Open Signal as part of its 2nd generation of satellites. This will open themselves to something I call 'fast channel authentication". In his view, Galileo has done a superb job in engineering to field the world's first civil satnav authentication capability (Slide 24). Galileo has shown strong vision and leadership support to go off and do it. He wishes he were talking about GPS.



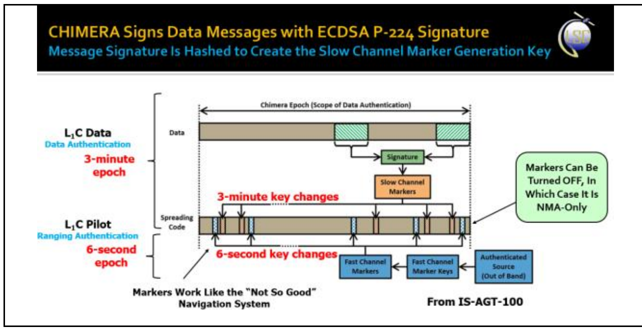
Slides 23-24

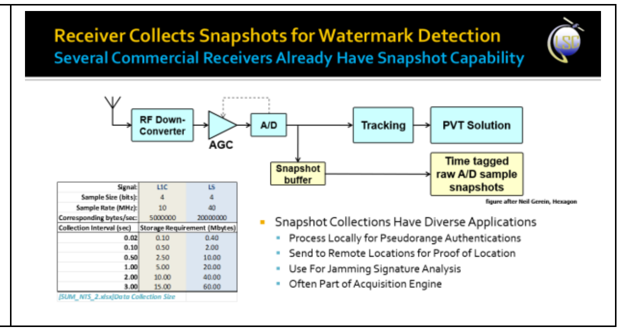
With regards to Chimera, the U.S. system we're working on, it has its origins back in 2002 (Slide 25). The signal characteristics is that it basically has data authentication (with two forms of message signing that are possible) and ranging authentication (with two channels, one that is fast [every six seconds] and another that is slow [every three minutes]). Chimera is going to be broadcast experimentally by the AFRL Navigation Technology Satellite 3 (NTS-3), for launch in 2023 (Slide 26).



Slides 25-26

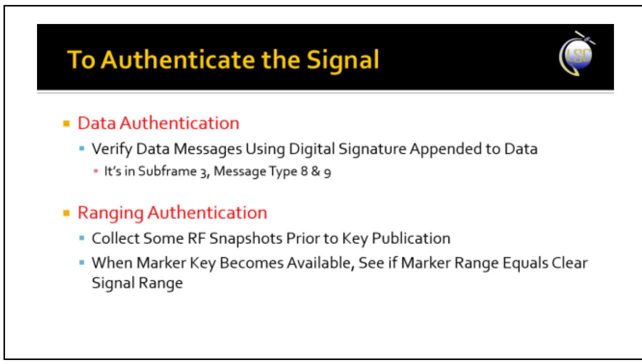
As far as Chimera's signal structure, in Slide 27 the top part shows the data signing process where you get a signature every 3 min, and then that signature is used to drive the slow channel marker keys. Mostly, the signal is just an L1C signals with these markers stuck in there. Then we have the six second marker keys which you must get from out of band (we don't have the data rate in L1C to support this). We had a serious offer from a Chief Executive Officer (CEO) of a company that provides worldwide authentication to 'transport' those keys and provide the six-second authentication signal. As far as the receivers go, it turns out there are some commercial receivers that have the requisite part (Slide 28). The blue part on the slide is basically a regular GPS receiver and the yellow part is the 'snapshot' component. The reason a lot of receivers already have this is because they use them for jamming signature analysis and as part of their acquisition engine. So, a lot of receivers already have the requisite hardware in there.

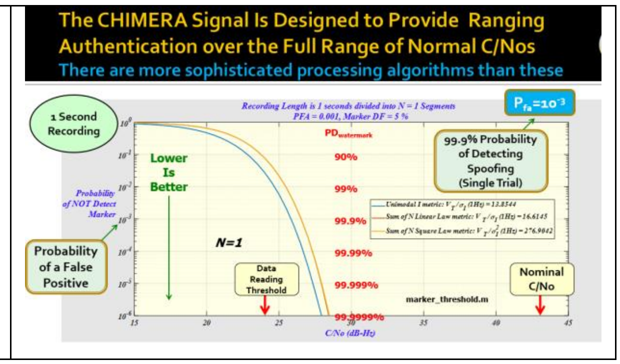




Slides 27-28

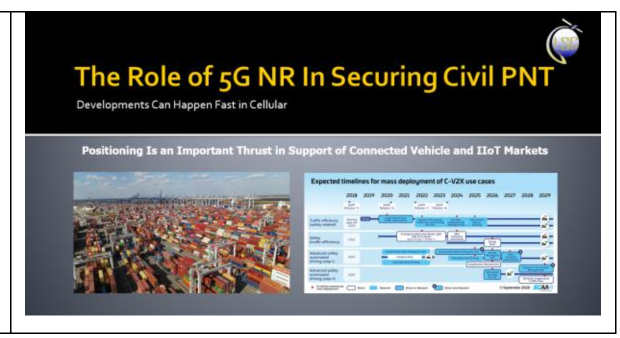
To authenticate the signal, there are basically two parts (Slide 29). You verify the data using the digital signature, and then for ranging authentication you collect RF snapshots before every key is published and then you look and see if the marker range equals the signal range. The Chimera signal is designed to operate "in the mud". In other words, the nominal C/N$_0$ you get are quite high (Slide 30). This signal is designed so that if you can track it, then you can also authenticate it. There are more sophisticated processing algorithms in it than the three algorithms shown on Slide 30.





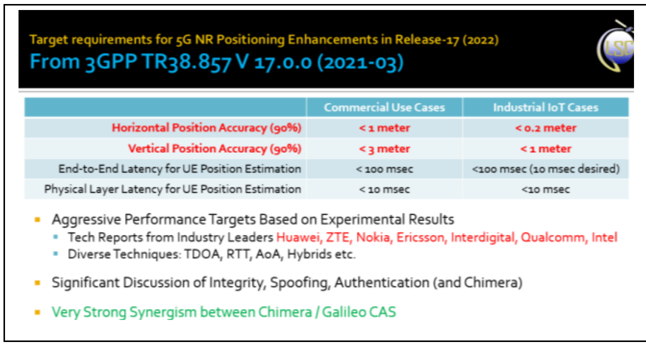
Slides 29-30

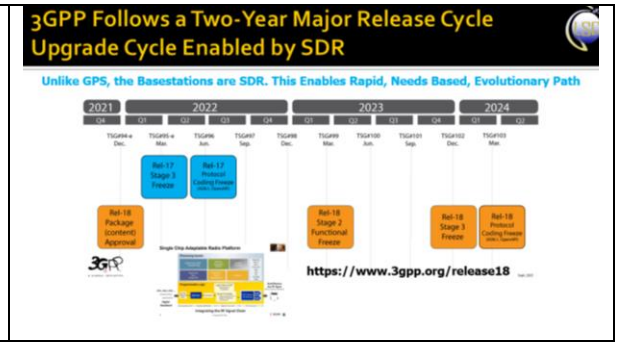
Navigation Message Authentication (NMA) is a step in the right direction, but it's not sufficient (Slide 31). You need the watermarks too. There are a lot of civil receivers that never read the data so they're going to have to use some other method, preferably watermarks to verify their location. Also, NMA does not provide a basis for proving location to a remote user. Positioning is an important thrust in support of connecting vehicles and Internet of Things (IoT) markets (Slide 32). In China there are 11 government ministries working on this.



Slides 31-32

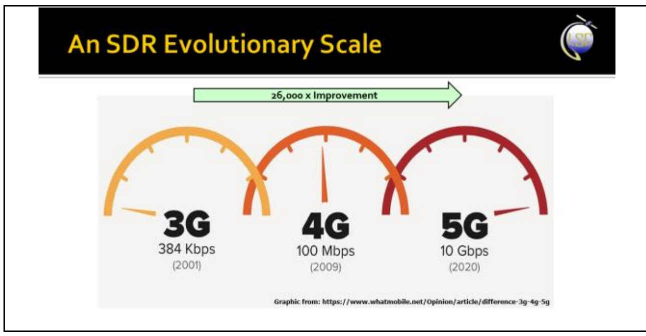
If you look at TR38.857, you can see what their objectives are in terms of accuracy (Slide 33). This is not signal of opportunity stuff but, rather, where you are basically doing two-way ranging, angle of arrival, and other techniques. There is very significant discussion of integrity, spoofing, authentication, and even Chimera. There is also a very strong synergisms between 5G and Chimera range authentication. When looking at 5G, another thing to understand is that in 3GPP the base stations are SDRs and, as such, you can do major modifications to the systems without having to build new infrastructure (Slide 34). You just have to the new software. 3GPP for the cellular industry has developed procedures to manage, and incorporate, innovation over the years. It is basically a two-year major release cycle.

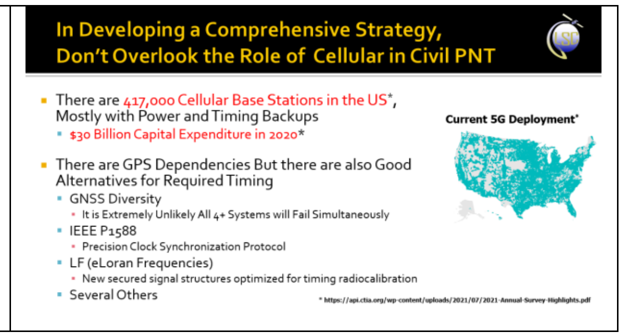




Slides 33-34

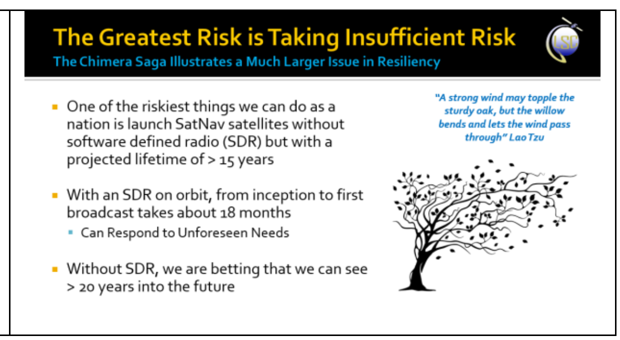
Slide 35 shows SDRs on an evolutionary scale. When talking about 5G, it is a factor of 26,000 in improvement over 3G. Much of this is done through software deployment. As the PNT Advisory Board is thinking about how one builds a comprehensive strategy with regards to PNT, it is important to take into account the role of cellular infrastructure to support civil PNT (Slide 36). There is a \$30B/year capital expenditure. Yes, there are GPS dependencies, but there are good alternatives for timing at the 1 microsecond level. You can get that from diverse GNSS sources, IEEE 1588, Loran Frequencies, and others. So, don't discount 5G as a possible way to improve security.





Slides 35-36

Mr. Scott's parting recommendation is that the greatest risk is taking insufficient risk (Slides 37-38). He would argue that as a nation, the biggest risk we can take right now is to continue to launch satnav satellites with over 15-year lifetimes but no SDR. With an SDR in orbit (GPS), something like Chimera would take 18 months to first broadcast. An SDR also allows us to respond to unforeseen needs.



Slides 37-38

Q&A / Discussion:

Dr. Parkinson asked which GPS satellite we could conceivably put this on first.

Mr. Scott replied, probably one of the Block III. He recommends a fundamental policy change. If we don't do this, we'll be in a situation we need 20+ years to deploy a new capability.

Dr. Parkinson responded that let's say we all agree, and even the EXCOM agrees, and asked how it can be implemented with any speed at all short of pulling the III's offline to modify them.

Mr. Scott said we would probably have to put this in Low Earth Orbit (LEO) satellites.

Dr. Parkinson commented that this relates to the governance issue we discussed earlier. To him, this is very discouraging.

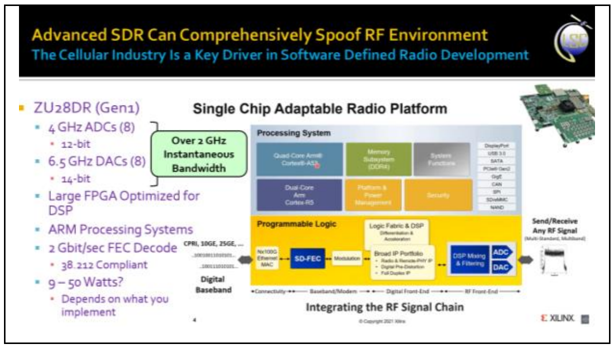
Mr. Scott agreed that it's discouraging, and it's been many years coming.

Dr. Parkinson reiterated that this is just one example of things we should consider looking at.

Mr. Shields added that as a software guy, his recommendation would be to hold the current GPS III satellites and rework them. He doesn't understand why we are putting things in space that we can't modify once they are deployed.

Dr. Betz noted there are different definitions of SDR. He asked what Mr. Scott means by SDR.

Mr. Scott replied that his example of an SDR is along the lines of what he describes in one of the backup slides (Slide 45, see below).



Slide 45 (Backup Slides)

Dr. Betz responded that Mr. Scott hasn't motivated the need for that kind of flexibility. If we are talking about changing the content of the signal for Chimera, that would take only a small subset of the work power you are talking about here.

Mr. Scott agreed. He is not just talking about Chimera. He is talking about a lot of things.

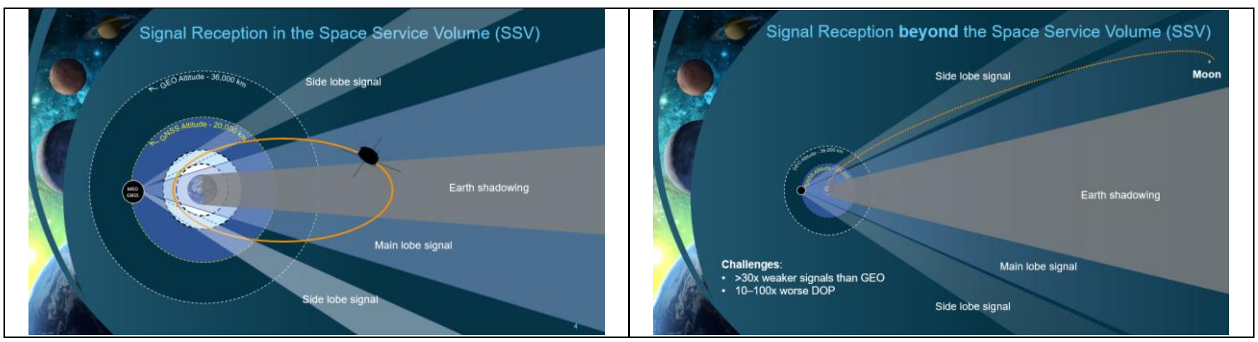
* * *

Lunar GNSS Utilization: From Vision to Reality
A NASA PNT Update
Dr. Joel J. K. Parker *PNT Policy Lead, GSFC, NASA*

Mr. Parker thanked ADM Allen and the PNTAB for the opportunity to speak. He hoped to share an encouraging presentation about GNSS use in space, specifically as we return to the Moon. Two years ago, Dr. Ben Ashman (NASA) shared the vision for lunar GNSS with the PNTAB, and now there is opportunity to take that to a measure of reality. For those that are new to this topic, NASA uses GNSS across the portfolio of use cases. The most straightforward case is using GNSS for real-time on-board PNT to support space missions. NASA also has launch vehicle range operations like the Autonomous Flight Termination System (AFTS), which uses GNSS to track the launch vehicle and make decisions based on whether it is on course or off course. GNSS may also be used for attitude determination, or how to determine the orientation of a spacecraft (where it's pointing). Time synchronization is self-explanatory. For Earth Sciences, L-band signals provide raw measurements for in many applications, such as radio occultation techniques used in for atmospheric measurements. Finally, applications such as precision orbit determination usually involve post-processing on the ground but can get to cm level accuracy for missions like the Gravity Recovery and Climate Experiment Follow-On (GRACE-FO).

For those new to this topic, GNSS signal geometry enables its use within the SSV, which is currently defined as the region of space between 3000 km altitude in LEO and Geosynchronous (GEO) altitude 36,000 km (Slide 4). This is the classic SSV, where many spacecraft operate. Spacecraft operating in the SSV above the GPS constellation can see portions of the main beam of the GPS that spills past the limb of the Earth from GPS satellites on the other side of Earth, and they also see the side lobe signals that are broadcast at a much wider angle at a little bit less power. These signals have proven very useful for operational navigation.

As we move beyond GEO altitude towards the Moon, there is a much lonelier picture in terms of visible GPS signals within the SSV (Slide 5). Those signals are much broader, but much weaker, 30 times weaker at a minimum than they would be at GEO. In addition, as seen by a spacecraft, GNSS satellites are within approximate 5-degree disc in the field of view, and so that leads to geometric diversity that is very poor, 10-100 times worse Dilution of Precision (DOP).

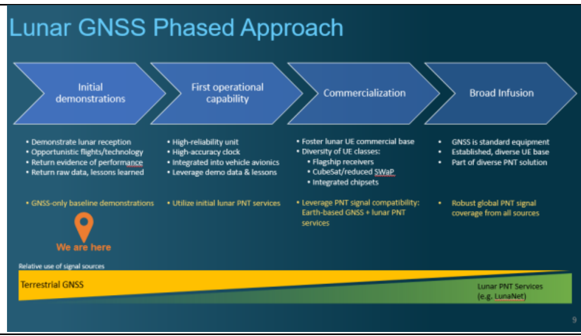


Slides 4-5

This leads to having to take on new techniques and methods for doing this. A little less than 10 years ago, Frank Bauer and Mike Moreau, in the context of the original SSV definition, had a vision of current and future customers including lunar exploration. The vast majority of these have already come to fruition, and now we are talking about lunar exploration at this time. The ongoing work is parallel to the original definition of the SSV where we're exploring what's possible, implementing it, and codifying it. In terms of roles for GNSS in lunar exploration, it runs the gamut for everything from receivers on surface operations, rovers, space suits, orbital vehicles with crew or robotics aboard, using signals for Earth or ionospheric observations, satellite servicing, or lunar exploration infrastructure. Typically, when talking about GNSS at the moon, there are questions about the feasibility and possibility of using it at lunar distances. There have been studies over the past 20 years looking into this in various degrees of fidelity. The most recent that NASA has done looked at the Lunar Gateway vehicle, which is the human-tended vehicle that will orbit the moon and will provide a launching pad for human sorties to the lunar surface. In September 2020, NASA completed a high-fidelity study of this, where we observed that GPS van provide greatly improved performance compared to the Deep Space Network (DSN) alone, and that GPS is a real-time, on-board system without reliance on ground-based assets. This study envisions a combined solution of DSN for ranging and using the available signals and existing technology of GPS to continue real-time on-board navigation.

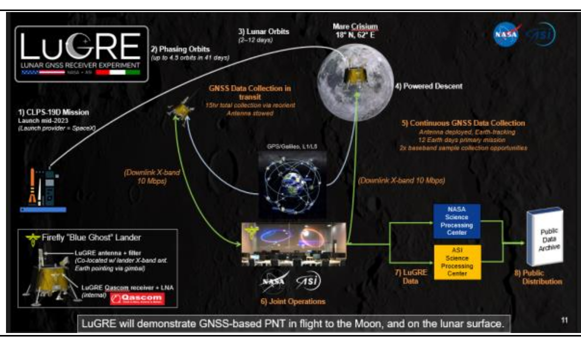
A phased approach that can be taken to make Lunar GNSS a reality (Slide 9). NASA is starting with initial demonstrations on opportunity flights where we launch an available GNSS receiver on an available flight and see what works. Next, we can go into a first operational capability, building that first receiver using the collected data to target the specific use case. After that it would be up to industry, taking the lessons learned from that first unit, to build a broad user equipment base. These could be flagship receivers, CubeSat receivers, or integrated chipsets on space suits. Finally, we arrive at broad infusion, where GNSS and other signals are simply standard equipment on lunar exploration activities. This kind of activity is in parallel with the service side of the equation. In the first instance, there is total full use of terrestrial GNSS because that is what exists. As time goes on, perhaps there might be lunar-focused PNT services, which would grow over time so that reliance on terrestrial GNSS would diminish, but it would never go away. There is always a use case for using terrestrial GNSS as a link between the Earth portion of the orbit and the lunar portion of the orbit where we could rely on eventual local services. Currently, we are focused on the initial demonstration portion of the roadmap.

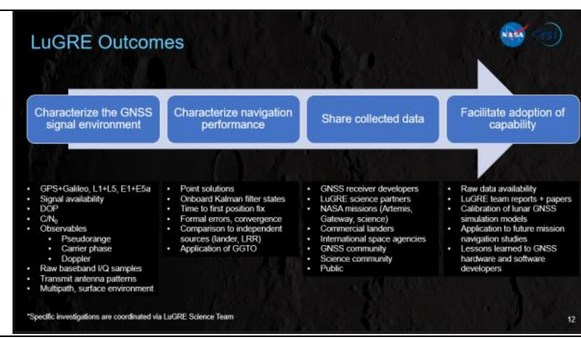
There are several pieces coming in the very near term (Slide 10). As Dep Melroy mentioned this morning, Artemis I will launch in early 2022, and it will be the first mission that will fly a GPS receiver in lunar vicinity. However, that is a LEO receiver, so they will keep it on to collect signals, but it is an item of interest to see how far it collects signal. The first experiment that falls into the category of being designed to study GNSS signal capability is the Lunar GNSS Receiver Experiment (LuGRE), a payload on the Firefly Aerospace Blue Ghost-1 lunar lander, planned for launch in 2023. The 2024 Lunar Pathfinder is an ESA mission that will fly a GNSS receiver and a companion NASA-furnished laser retro-reflector payload. Looking beyond, we get into payloads on Gateway as that system gets built up, where we can fly demonstrations and certain classes of operational payloads. Then we can focus on providing lunar-focused PNT services through LunaNet.



Slides 9-10

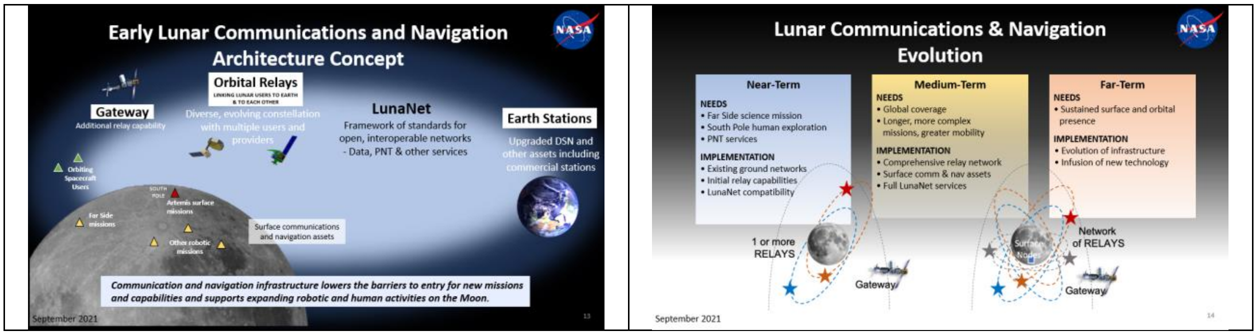
As mentioned earlier, LuGRE is a payload on the Firefly Blue Ghost-1 lander as part of the NASA Commercial Lunar Payload Services (CLPS) program, where NASA purchases space to fly scientific and technology demonstration payloads on commercial landers to go to the moon. This payload is a collaboration between NASA and the Italian Space Agency (ASI), and it will fly a receiver that was built and provided by Qascom. It is a relatively simple mission Concept of Operations (CONOPS), where a GNSS receiver is flown to the moon and we see what we get in terms of signal during transit and on the lunar surface (Slide 11). The difference is that this is a receiver and antenna specifically designed for this purpose. It will launch in mid-2023 on a SpaceX Falcon-9 from Kennedy Space Center. It will go into two months of transit phase from Earth to moon with about 15-20 opportunities to point the vehicle back at the Earth and observe the GPS and Galileo signals, dual constellation, dual frequency, L1 and L5. We will collect as much data as we can going up and into lunar orbit. The system will be turned off for powered descent and turned back on once landed. There will be nearly continuous 12 days of observations collecting as much data as possible while watching the GNSS satellites and doing various tuning and calibration experiments on the receiver. All that data will come down to a joint operations center where it will be processed for the technology results we hope to achieve, then it will be broadcast for public dissemination. The purpose of this is to demonstrate the feasibility for the broader GNSS space user community. In terms of the specific outcomes, LuGRE aims to characterize the GNSS signal environment, to characterize navigation performance to see how accurate we can get with the equipment we have, to share the data publicly, and to facilitate adoption of the capability and apply to future missions like Artemis (Slide 12).





Slide 11-12

Switching from the user side to the service provision side, LunaNet is a new concept that NASA has been developing for a few years now, which is a broad vision for PNT and communication service around the moon (Slide 13). It is a lunar comm and nav architecture concept, not a particular constellation, rather a framework of interoperable standards, such that any provider, domestically or internationally, could provide a node to the LunaNet, and it would act sort of as the internet does on Earth. The components of this would be stations on the Earth like the DSN, orbital relays, existing assets that are provided with relay equipment like Gateway, and the users of it include the whole range of activities happening on and around the moon, particularly those on the far side or south pole. In terms of the evolution of this, right now there are draft interoperability standards that are undergoing a comment and coordination period. Near-term, we will establish an initial constellation with one or more relays focusing specifically on the near-term needs like lunar far side science missions and south pole human missions (Slide 14). In the medium term, we would build that out to be more of a global constellation, focusing on a broader range of activities. Far-term, this would be a sustained network that would service the broad range of activities and evolve as the infrastructure and new technology develops.



Slides 13-14

There is a broader set of PNT activity occurring internationally as well. The ICG was established in 1999 to bring together all GNSS and regional systems into one space at least once a year to talk about GNSS interoperability, compatibility, performance, and all the issues that go along with the utilization of multi-GNSS rather than just individual constellations. The ICG is split into four working groups, and most of the work on GNSS for space use is within WG-B focused on Enhancement of GNSS, specifically the Space Use Sub-Group (SUSG) which was established in 2018. NASA is one of three co-chairs for this group. It was created specifically to provide a focal point for representing the needs of space users within this international framework. There were two major products out of the ICG-15 meeting in 2021, including the second edition of Interoperable GNSS SSV booklet and a companion SSV outreach video. The SSV booklet (Slide 18) series is intended to be a "one stop shop" for SSV data for all GNSS providers. The booklet can be accessed online and includes tables listing all the SSV parameters in one spot, a set of analyses that share the benefits of using multi-constellation data over individual constellations on their own, and a whole range of technical information. The booklet update also includes profiles of real-world SSV and multi-GNSS missions. The video is a companion to the booklet intended as an outreach tool for all users broadly (Slide 19). It conveys what the SSV is, the benefits of it, and why it is important for the international community to continue this development. Both NASA and the NCO sponsored the video. The video is available on YouTube and GPS.gov. Looking ahead to future work of the SUSG, there work plans including public availability of technical date, building space user mission profiles, and establishing timing standards and space user standards. Notably, the US is leading the work plan item on the expansion of the GNSS SSV to support lunar operations. The plan has several steps, but essentially involves coordinating with existing bodies that are involved in this effort, assess user needs, augment any analysis that needs to be done, and provide a formal definition and recommendations.

Slides 18-19

The genesis of all lunar GNSS activity began with the original SSV work, which has been hugely successful. In 2017, there was a Memorandum of Understanding (MOU) established between NASA and the USAF for cooperation GPS capabilities to support space users. The MOU also provided for the release of GPS antenna data and includes a NASA representative in the GPS IIIF procurement cycle. Late last year there were a couple of good accomplishments in data availability. In late 2020, there was a re-release of the GPS IIR/IIR-M antenna gain pattern thanks to Rick Hamilton (Navigation Center, USCG). Also, in late 2020, the first four GPS III service vehicle phase center, group delay, and inter-signal bias data was released and is available on the USCG website[2]. There is a remaining need for the release of the GPS III antenna gain pattern data, which was last discussed in the context of the 2019 PNTAB. This is the last remaining piece before there is a full and complete picture of what the signal environment is going to be around the moon as GPS III is deployed.

[2] L Band Antenna Panel Patterns and Performance (uscg.gov)

It is important that we fully characterize the space user base. The PNTAB has heard this week about the growth of the space user base, especially commercially with mega-constellations going up. Previous US studies, such as, "The Economic Value of GPS," in 2019 did not look at the space user segment. Europe recently tried to fill this gap with its EU Agency for the Space Programme (EUSPA) Report on Space User Needs and Requirements published in summer 2021. They have a process in Europe with conferences and meetings to collect user needs and bring the user base together, at least in their area, to assess needs and requirements. A similar process in the US would be highly valuable as well. We recommendation a comprehensive study to characterize the PNT space user segment and needs for US government, commercial, and university customers.

In conclusion, the moon is the next frontier in space use of GNSS. NASA is pursuing multiple open, collaborative activities, and the first demonstrations are just around the corner. NASA is working within the ICG to enhance the benefits of space use of GNSS through multi-GNSS interoperability to improve PNT performance and resilience. The burgeoning space commercial market requires a comprehensive PNT space use study to ensure the US is strategically positioned to support the myriad of missions and capabilities. Finally, NASA is proud to work with GPS and the international GNSS providers to ensure GNSS services are accessible, interoperable, robust, and precise for all users for the benefit of humanity.

Q&A: Discussion:

> Dr. van Diggelen thanked Mr. Parker for the presentation, saying the only thing cooler than GPS is GPS on the moon. When NASA shares the data from LuGRE, that data will likely include measurements like pseudoranges and so on. Dr. van Diggelen asked if NASA will share ground truth data to show where the receiver really was. He asked how that ground truth data will be determined and what coordinate system will it be specified in.
>
> Mr. Parker thanked Dr. van Diggelen for the questions. The short answer is that the LuGRE team is still working out the details. They are looking to provide as much data as possible to maximize the development of receivers that are capable of doing this. They want to make this a broad infusion of GNSS for lunar activities and sharing the data as broadly as possible is NASA's way of doing that. The data will include the raw telemetry, such as pseudorange, carrier phase, C/N_0, for the constellations. There is also a laser retro-reflector on LuGRE, but that is mainly associated with the surface campaign, not transit, but that is another way measurements could be made. Another way is to compare ranging data from the host vehicle with LuGRE's data for validation. As much as that is possible will released publicly. Once the analysis is done and results are assessed for accuracy, those analysis products will come out as well. The exact list of products is being undertaken by the LuGRE science team, and there is a paper coming out at the Institute of Navigation (ION) International Technical Meeting at the end of January. There is also structure in place where LuGRE would accept science partners into the LuGRE science team to help look at the data and perform investigations.
>
> Dr. Powell noted that there is a cool display in the lobby that shows the globe of the moon and all the Apollo landing sites, some of which have laser retro-reflectors. What is the value in having them on the Moon, including the ones left by the Apollo program?
>
> Mr. Parker replied that laser ranging is part of building a complete picture of lunar reference frame, and how it is tied to Earth's reference frame. That is going to become a key part of the future lunar PNT services previously mentioned. One of the aspects of the standardization and coordination going on for LunaNet are core reference frame and time system in the lunar environment.
>
> Dr. Axelrad asked what antenna gain LuGRE plans to use.
>
> Mr. Parker explained that there is a 15 dB peak antenna gain. In the NASA Magnetospheric Multiscale (MMS) mission the peak gain is 7 dB, so at twice the distance we need twice the gain.
>
> Dr. Axelrad noted that the Gateway showed about 200 m in lateral instantaneous position, which is surprising.
>
> Mr. Parker replied that the RSS (root sum squared) lateral result was very good, settling at a little over 100 m. The paper is available, which includes all the assumptions that went into it. It was a very high-fidelity study. What wasn't mentioned in the presentation is that the assumptions included the crew, so it isn't a quiescent vehicle because the crew is moving around, things are being vented out the spacecraft, and there are all kinds of perturbations involved. Even with those perturbations, there was still a 100 m class lateral instantaneous position performance.
>
> Mr. Shane shared that he was interested in the ICG. The PNTAB has spent some time talking about the advance capabilities of BeiDou and Galileo and comparisons between GPS and other systems. He asked if there was transparency and collaboration in the international GNSS community.
>
> Mr. Parker responded that from his perspective as the co-chair for the SUSG, it is an extremely collaborative group. There are about 10 people from all the different GNSS providers, including China, Europe, India, Japan, and Russia. The SUSG produced the SSV booklet and conducted joint analyses. There is not a lot of geopolitics that comes into that level of technical discussion. There is also a lot of excitement there. When NASA first brought in the idea of the SSV and more recently the lunar aspect of it, you could see year-to-year starting from about 2017 that India, Japan, and in particular China have brought forward their lunar plans, what they would like to do to support lunar exploration, and what their SSV and side lobes look like. Technically, it has been a very beneficial group to be a part of.

Mr. Miller thanked Mr. Parker for the presentation. Mr. Miller added in response to Mr. Shane's question that SPD-7 explicitly calls out NASA to develop requirements civil space users, everything that NASA is doing will translate into benefits for the commercial space sector as well. SPD-7 also explicitly highlights the use of allied GNSS systems, so LuGRE's partnership with ASI will use GPS & Galileo for greater availability. There are many technical and geopolitical reasons to do that. The PNTAB has been extremely supportive and made a big difference. NASA holds the world record for GPS reception halfway to the moon, and if LuGRE is successful in 2023, it will be historic. It will set the stage for use of GNSS in the lunar domain. Additional contributors to this effort include Steve McKim, Frank Bauer, Lisa Valencia, and Gen David Thompson, who ensured NASA representation on the GPS III procurement team.

* * *

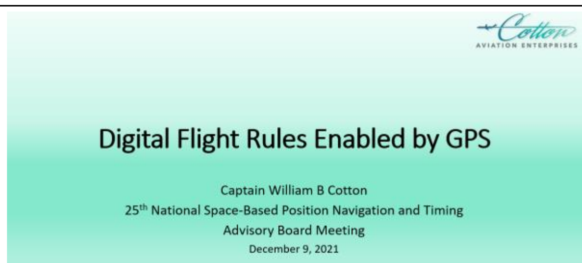
Digital Flight Rules Enabled by GPS

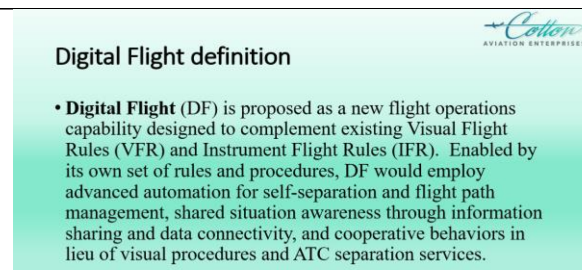
Modernization of the National Airspace System

Capt. William Cotton, *Founder & President, Cotton Aviation Enterprises, Inc.*

Back in 1975, Capt. Cotton represented the Airline Pilots Association (APA) and made a trip to Los Angeles to visit the Air Force Base (AFB), where he learned about this thing they were developing called GPS. At the time, they just had an upside-down constellation out in the desert making measurements, and Capt. Cotton was immediately taken with the idea especially when they said that there would be a civil frequency that can be used by anyone. Transponders were common at the time, so if users had a receiver, an unlimited number of people could use it. Capt. Cotton then wrote an article for a magazine called Commercial and Business Aviation about GPS and what it would mean for aviation. It took a long time because aviation needs to make sure things are safe before they can be used in an operational way, but it opened up a world of possibility. At that time, GPS was framed in terms of 10 m accuracy, which is smaller than most airplanes. In terms of navigation systems, we used to talk in terms of miles, not feet. He remarked how incredible that was to consider.

Capt. Cotton then turned to his presentation about Digital Flight Rules (DFR) (Slides 1-2). This is not GPS, but an application of GPS that is very important. Digital Flight (DF) is a flight operations capability designed to complement existing Visual Flight Rules (VFR) and Instrument Flight Rules (IFR). Any flight taking off today must operate under one of those two sets of rules. DFR represents a new additional set of rules as a way of operating in the air space. It would be enabled by its own set of rules and procedures, employing automation for self-separation and flight path management through shared situational awareness, data connectivity, and cooperative behaviors in lieu of visual procedures and Air Traffic Control (ATC) separation services. This is talking about a new paradigm here.





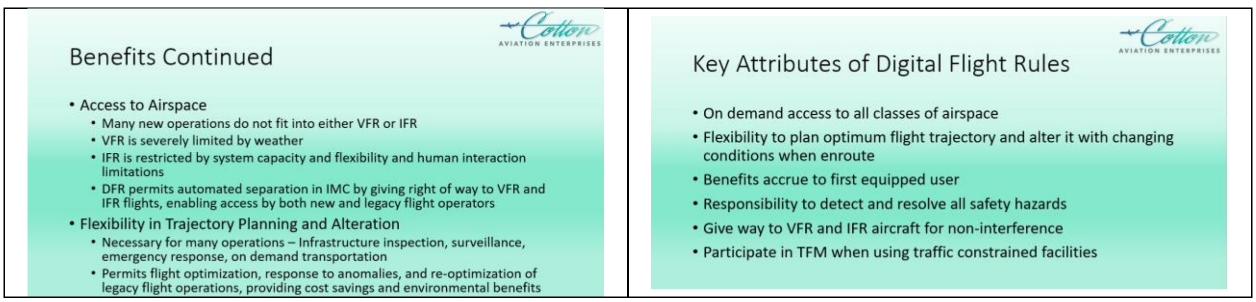
Slides 1-2

This was explored in a paper written last year by David Wayne and Ian Levitt at the NASA Langley Research Center (LaRC). "New Flight Rules to Enable the Era of Aerial Mobility in the National Airspace System." This wasn't a brand-new thing in 2020; it has a long history of similar proposals, which Capt. Cotton has been fortunate enough to participate in. In 2011, Capt. Cotton and David Wayne co-wrote a paper on what were then called Autonomous Flight Rules. In 1995, the FAA entertained an idea called Free Flight (Slide 3). Twenty years before that, Lincoln Labs proposed a concept called Electronic Flight Rules. In Capt. Cotton's own graduate studies, he and two other students called it the Airborne Traffic Situation Display. There was a long history to this concept, and now it is finally possible to implement it. Digital Flight Rules were not possible without a robust air to air digital surveillance system and good communications among the aircraft. GPS, Automatic Dependent Surveillance-Broadcast (ADS-B), DataComm and computing power have enabled an environment of technologies that can realistically support automation of the separation function in new flight operations integrated with existing VFR and IFR flights.

Who would benefit from this? Everyone (Slide 4). There has been a lot of information in the press about new entrants to airspace, including UAVs, drones, and airplanes that are flown remotely without pilots on board. If you look out the window, you won't see many planes out there. It's not a question of if there's enough airspace for all these vehicles, but rather how to manage the thousands that could be there. DFR has scalability as its primary focus. Other benefits include access and flexibility, elements which are denied under VFR and IFR today (Slide 5). Many new entrants do not fit into either VFR or IFR. VFR is severely limited by weather. IFR is restricted by system capacity and human interaction limitations between the pilot and controller. DFR permits automated separation in Instrument Meteorological Conditions (IMC) by giving right of way to VFR and IFR flights, enabling access by both new and legacy flight operators. The second major benefit is flexibility, both in trajectory planning and the ability to alter the flight plan once in route. This is necessary for many of these new entrants, including infrastructure inspection, surveillance, emergency response, and on-demand transportation. It also permits for flight optimization, response to anomalies, and re-optimization of legacy flight operations, providing cost savings and environmental benefits.

Slides 3-4

Some of the key attributes of DFR include on demand access to all classes of airspace, the flexibility to plan the optimum flight trajectory and alter it with changing conditions when on route (Slide 6). Importantly, the benefits accrue to the first equipped user, rather than needing a critical mass of users to gain the benefits of the system. Anyone operating under DFR has a responsibility to detect and resolve all safety hazards, including weather and terrain. DFR can also make it into the airspace by giving right of way to VFR and IFR aircraft to avoid interference. While that sounds like a tremendous penalty to be paid by a DFR operator, there is plenty of airspace. This is talking about separation standards, which are quite different from what you may be used to today at 3 to 5 miles between airplanes when it could be more like 500 feet. That makes a significant difference in how much airspace is available to use by both the new and the old operators. If anyone using DFR is using the same constrained runways that have led to ground-delay programs or other forms of traffic flow management (TFM), they would still participate in TFM when using traffic-constrained facilities. Many of the new entrants have no intention of using any of those runways, so they would be exempt from those kinds of TFM processes anyway.



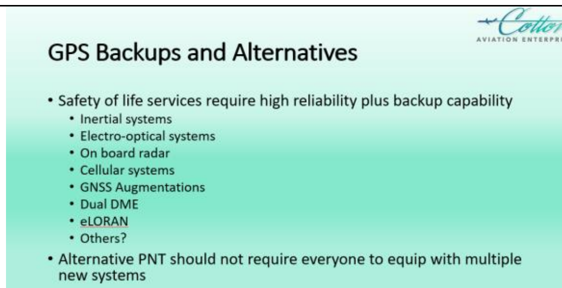
Slides 5-6

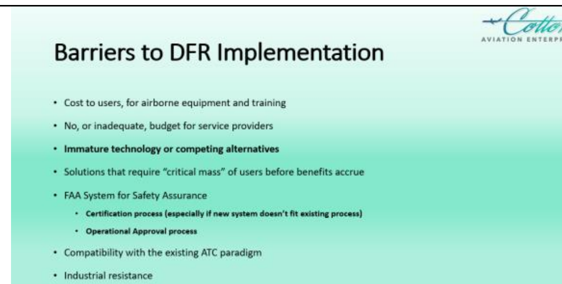
There is a major reliance for both navigation and surveillance within DFR (Slide 7). Navigation assumes reliable GPS signal coverage, but in urban areas and remote areas, which typically isn't an issue for GPS unless inside a parking garage. Airborne surveillance begins with Position, Velocity, and Time (PVT). The safety of digital flight is dependent on GPS system reliability. We all know that GPS is vulnerable, and we have seen many presentations today about what those vulnerabilities are and how we can address them (Slide 8). Capt. Cotton shared a map from Airbus showing radio frequency interference (RFI) measured by 150,000 flights around the world, where 19% of flights experienced jamming and spoofing between 2017 and 2020. Capt. Cotton shared that on a flight a few days before, his colleague noticed the GPS-denied environment for 150 miles around El Paso, Texas around the White Sands environment. What was interesting was that while GPS wasn't available on the airplane, it was still working on his cellphone. Capt. Cotton also remarked on the FAA notice prohibiting the use the automatic landing systems, which rely on the radio altimeters, because of the potential interference in the C-band.

Slides 7-8

If DFR cannot rely on GPS exclusively, it must consider GPS backups and alternatives (Slide 9). Safety-of-life services require high reliability and backup capabilities. As proposed alternatives, Capt. Cotton suggested inertial systems, electro-optical systems, on-board radar, cellular systems, GNSS augmentations, dual Distance Measuring Equipment (DME), Enhanced Loran (eLoran), or others. It is widely expected that standards required for digital flight, both for airborne surveillance and navigation would be performance-based standards. Any alternative PNT shouldn't require everyone to equip with multiple new systems, because the added cost would no longer be economical. Robustness is important, and toughening GPS is certainly the right way to go.

There are many potential barriers to DFR implementation (Slide 10). NASA held a Technical Interchange Meeting (TIM) with members of the aviation community to present this concept and get their feedback on the benefits and potential barriers, both technical and economic. The first barrier is cost. If it costs too much, and the business case isn't there, it doesn't make sense to implement. The savings would be tremendous, but some operators may not have the budget to implement currently. In putting together this list, Capt. Cotton went back through the last 60 years of transformational technologies in the industry, trying to understand what allowed technologies to succeed. Many in the audience may remember the Microwave Landing System (MLS), which suffered from competing alternatives in the US Time Reference system and the European Doppler MLS. By the time a decision was made on the standard, the need had come and gone with the advent of GPS. If it's not possible to come to agreement on what technology should be used, that may be a significant barrier to implementation. Any solutions that require a critical mass of users before the benefits accrue would be challenging. One of the hardest things to overcome is the FAA System for Safety Assurance. The certification process is extremely important and especially hard to do when what is being certified has never been certified before. This is a new function for hardware and software based on the airplane, and someone has to figure out how to propose it to the FAA. Operational approval is another hurdle to be overcome. There needs to be compatibility with the existing ATC paradigm. Finally, there may be industrial resistance. Pilots and controllers don't like change, but there are now airplanes without pilots, and it is possible to separate planes without air traffic controllers. It would be impossible for the existing IFR system to handle putting 1000 small planes in the Washington, DC area right now, but DFR could do it.

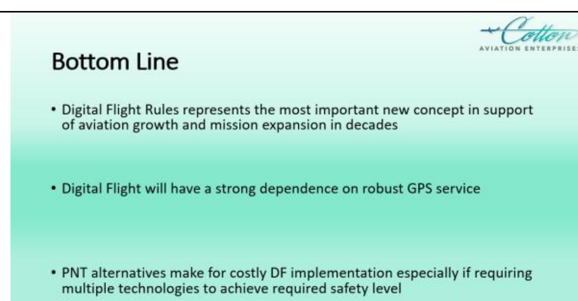




Slides 9-10

He then outlined success factors for DFR (Slide 11). If there is a strong business case and strong advocacy by industry or government champions, it could be successful. Through this process that NASA LaRC has undertaken bringing in different airspace user segments, it is likely that a strong industry base will emerge. There needs to be a clear, proven technical solution, which now should be possible to do. International cooperation and commitment would be helpful as well. While this is being talked about at NASA LaRC, it is also being considered in other parts of the world as well. The International Air Transport Association (IATA) wrote a paper recently on the inadequacy of VFR and IFR for future operations. FAA mandates would certainly help, but we don't expect it in this case. It is meant as an alternative option available to an operator. Congressional action would support this. He noted a previous circumstance where Congress passed a law before the FAA mandated the service, encouraging progress. Finally, investment by the proponents would be required.

In conclusion, DFR represents the most important new concept in support of aviation growth and mission expansion in decades (Slide 12). It will have a strong dependence on a robust GPS service. PNT alternatives will make for costly DF implementation, especially if requiring multiple technologies to achieve the required safety level. Capt. Cotton opened the floor for questions.



Slides 11-12

Q&A / Discussion:

Capt. Burns thanked Capt. Cotton for the presentation. A lot of small general aviation aircraft have single threat systems, one for GPS and that's it, for their instrument rules. How does that apply for DFR? Are they going to be able to get by with just a single GPS system or is there outfitting that's going to be required?

Capt. Cotton replied that he doesn't think the safety case could be made with a single threat system, so it would likely have to be dual equipment. The software for this would probably go into the navigator, and the output for the surveillance system would go into this for the software to act upon it. The conflict detection resolution algorithms would be approved by the FAA so that they would cooperate and work all together. But Capt. Cotton doesn't see a way to do it without dual systems.

Dr. Parkinson remarked that the presentation was inspirational in terms of where the industry is going. Capt. Cotton mentioned the dependency on GPS. In 1992, some of Dr. Parkinson's students put together a series of blind landings of a Boeing 737 loaned by the FAA. The GPS dependency bothered him then and now. All the airlines resist putting large phase array antennas on their airplanes, but the popularity of Wi-Fi has seen a change in tune because of the money coming in. Dr. Parkinson asked Capt. Cotton what would be persuasive to airlines to put a tough GPS set on commercial airplanes.

Capt. Cotton responded that it is all about the business case. Back in 1995, Capt. Cotton had to make the case for a new system at United Airlines. He had to show that the system would save enough money to pay for itself within 18 months. This included an upgrade to the system and putting GPS on the airplane. They were able to make the case based on the savings that would result from operations. The most expensive part of that system was satellite communications because it was primarily being used over the Pacific Ocean. Fortunately, that very expensive high-gain satellite antenna was paid for by telephone service to the back of the airplane. The rest of the equipment was paid for by the savings in fuel by the efficiencies that were gained through using the new system. The same must be demonstrated with DFR. Capt. Cotton believes the savings for DFR are much larger, and it might be able to cover the cost of a more robust system like Dr. Parkinson is talking about.

Dr. Parkinson referred to the map that showed near-continuous jamming over the Middle East for the past 3-4 years. We know how to toughen receivers, but he was unsure how to justify that to a tough Chief Financial Officer (CFO) at an airline.

Capt. Cotton replied that PNT alternatives will always be sought out, and in the final analysis, it is the performance of the total system that is going to matter. GPS is going to be a major part of it, but not the only part of it, and that may make a better business case than trying to rely solely on one system.

Mr. Murphy thanked Capt. Cotton for the interesting briefing. He summarized that any move towards DFR would require being totally transparent with any current VFR and IFR traffic by putting the onus on new DFR people to get out of their way. Mr. Murphy noted that there's some potential in changing the basic environment for VFR and IFR by having more people. Even if they aren't supposed to interact, they may have unintentional interactions like setting of Traffic Collision Avoidance Systems (TCAS) on other airplanes. He asked if there is any work going on to look at those elements to ensure that DFR wouldn't create some subtle change in the environment that might impact IFR and VFR. Is it practical to put the total onus for safety on the new DFR?

Capt. Cotton replied that based on initial analysis, it is in fact okay to put the onus on DFR but noted that it is certainly an area that is ripe for additional research. In the feedback for the initial TIM, that very question was asked. Capt. Cotton believes it can be proved, but it hasn't yet been by any sort of robust simulation. Capt. Cotton would like to put the system in his own airplane and fly around and show how little interaction there really is. He has flown VFR for over 60 years, and in all that time, he had three close calls, fortunately never hitting anybody. VFR is not very robust. He would much rather have DFR where there is an automated system helping to maintain separation from everybody out there.

* * *

Using UAVs in GPS-Denied Environments
Mr. Pramod Raheja, CEO, Airgility

Mr. Raheja introduced himself as the CEO and Co-founder of Airgility, a company based in Washington, D.C. that focuses on Artificial Intelligence (AI) and autonomy for aerial robotics. Many of those in the audience probably remember the television show called The Jetsons, which featured flying cars. As a precursor to flying cars, there are now small UAVs flying around, and Airgility is focused on how to build resilience to GPS dependency and have a robust system onboard these vehicles so that they can avoid conflicts. Airgility only uses parts built in the US. Airgility is a dual-use company servicing both government and the commercial sector and has received a lot of recognition despite only having been around for four years.

To build upon what Capt. Cotton said earlier, with manned aviation there are redundancies and multiple points of failure, including GPS, Inertial Navigation Systems (INS), and VHF Omni-directional Range (VOR) receivers. To this day, if using GPS, VOR functions as a backup. However, as has been talked about all day, GPS can be a single point of failure. Mr. Raheja then shared a video clip of a drone light show in China where, at one point, drones start falling out of the sky. It turns out rival company jammed the drones because they were unhappy that they didn't get the contract for the light show. A simple Google search shows all kinds of ways to jam GPS, some for as little as $20. In response to this issue, Airgility focuses on augmenting and toughening through a robotics-based approach. Each aircraft has its own eyes and ears. Airgility combines sensors that provide both redundancy and confidence in concert with algorithms that allow for navigational and situational awareness prioritization. An example of that would be obstacle and collision avoidance, and once that is achieved, anyone can become an expert pilot or operator.

Airgility, at its heart, is built of aerospace engineers, so they took the best attributes of fixed wing, helicopter, and quad-copter Unmanned Aircraft Systems (UAS) and combined them into a design philosophy that results in beneficial characteristics. With an exoskeleton, the payload can be put inside of the UAV. Sometimes payloads are more expensive than the actual vehicle, so that becomes very important. Aerodynamic qualities that make up the lifting bodies are modular so they can have swappable payloads, which are serviceable in the field. The patented designs are scalable. When getting into environments where GPS is not available, like indoors, underground, or in urban canyons within cities, most drones right now more or less fall out of the sky. When flying around tight areas in a room like this, it takes a lot of skill to fly that manually. Airgility does on-board edge processing, both navigation as well as mission specific. There is a combination of optics (cameras) and LIDAR (light detection and ranging), which provide situational awareness. Airgility began flying in GPS-denied environments with DHS, particularly within disaster scenarios. The drone itself has a thrust vector that allows it to take many different orientations. Airgility then layers in AI-powered autonomy, which makes it easy to operate with object and collision avoidance. Data sets can be added in to include object detection, facial recognition, anomaly event detection, and GPS-denied confined space navigation.

Looking at the development of AI, this becomes relevant for situational awareness on a vehicle. AI development can be very computationally heavy, so prioritization is key. Airgility does both Machine Learning (ML) and non-ML. AI is not necessary in every single situation. Airgility focuses on using AI when needed and prioritizing to switch to other algorithms when not. DHS S&T started a Smart Cities Technologies initiative, and Airgility was selected in 2018 to develop their technology and deploy autonomy demonstrations in the largest SAR demo activity ever held on US soil in 2019. Airgility now focuses on enterprise, public safety, and defense. Mr. Raheja then showed a video of how these drones function, including examples of a demo cell tower inspection, aircraft inspection, flying in a tunnel, and flying in a silo. One of the areas they have also begun to look at is counter-drone and perimeter defense, where a small drone uses on-board vision-based tracking to follow a target.

This is still early stage of UAS development. There are a lot of regulatory hurdles that still need to be addressed, but from a product perspective, they will be adding in thrust vectoring and improving communications. Current operations are optimized for indoor environments but looking forward to true UAS navigation reliability in GNSS denied environments may require incorporating Inertial Navigation Systems or radar-based velocity systems.

Q&A / Discussion:

> Dr. Filjar thanked Mr. Raheja for the presentation. Dr. Filjar recently had a student who completed a master's thesis on a similar topic of guiding UAVs along a predetermined trajectory, so this was particularly interesting to him as far as the GNSS applications go. Dr. Filjar noted that Airgility is using ML, very likely for the feature extraction in order to roll over the demand for computation, and also to utilize some of the simultaneous localization mapping if you are discovering an unknown area. Dr. Filjar asked what platform Airgilitiy uses for computation, whether it was on-board the UAV or shared via communication with a server.
>
> Mr. Raheja responded that the computation is completely onboard. Essentially, Airgility stacks their boards. One board focuses on lower-level navigation autonomy then another for the higher-level learning and thinking.
>
> Dr. Filjar asked how they manage the power-related issues.
>
> Mr. Raheja referred back to what he mentioned about prioritizing ML versus non-ML, as there is no getting around the power constraints, but those can be optimized.
>
> Dr. Filjar then asked about gaining knowledge from previous flights. He asked if Airgility has any algorithms that repeat previous trajectories.

Mr. Raheja responded yes, a lot of what Airgility does is autonomy, so one of their capabilities is to set parameters. If a mission has started and the battery happens to need to be changed mid-flight, the flight can be paused to replace the battery and then resume where it left off.

Dr. Filjar joked that United pilots may lose their jobs before his flight home the next day. He thanked Mr. Raheja again.

Capt. Burns thanked Mr. Raheja and his co-founder for the good work. This takes drones to the next level. He asked how much this technology would add to the cost compared to basic GNSS capabilities?

Mr. Raheja referred to the initial work with DHS where an off-the-shelf solution doesn't work. Challenging missions need better equipment, so the cost goes up. Over time, when the volume of technology and machines being used more ubiquitously, the cost will lower. In conversations with current DoD or enterprise customers, this is something they have already budgeted for and isn't as much of an issue.

Dr. Winfree commented on the onboard sensor suite. As the product development is scoped out over time, does Airgility anticipate continuing to use off-the-shelf components or to build in more onboard capabilities?

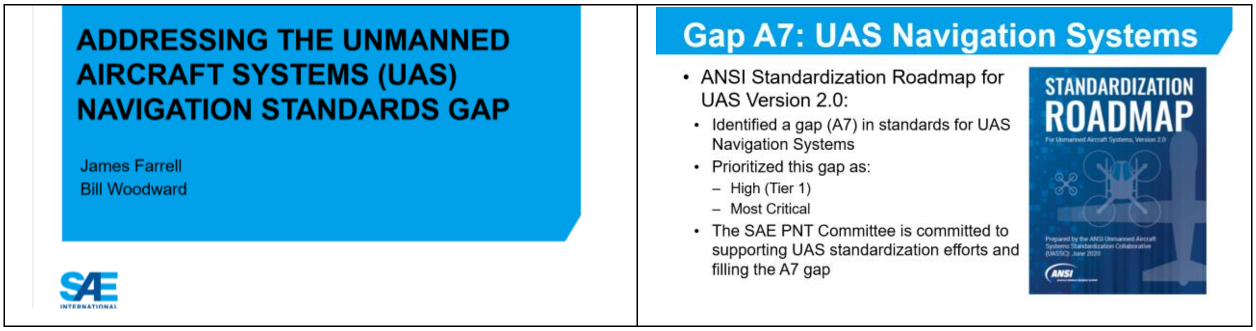
Mr. Raheja responded that over time, Airgility is looking at miniaturization, particularly for the variety of possible sensors they could use such as laser-based optics or stereo cameras. Complete situational awareness requires a combination of technology, and product development is working hard to increase their capabilities. Some things can be done in house, but other things must be integrated. He thanked the group for the opportunity to speak.

* * *

UAV Roadmap Follow-Up from 2015 / 2018
Dr. Jim Farrell, *Owner, VIGIL* & Mr. Bill Woodward, *PNT Committee Chair, SAE International*

Part 1: Dr. Jim Farrell

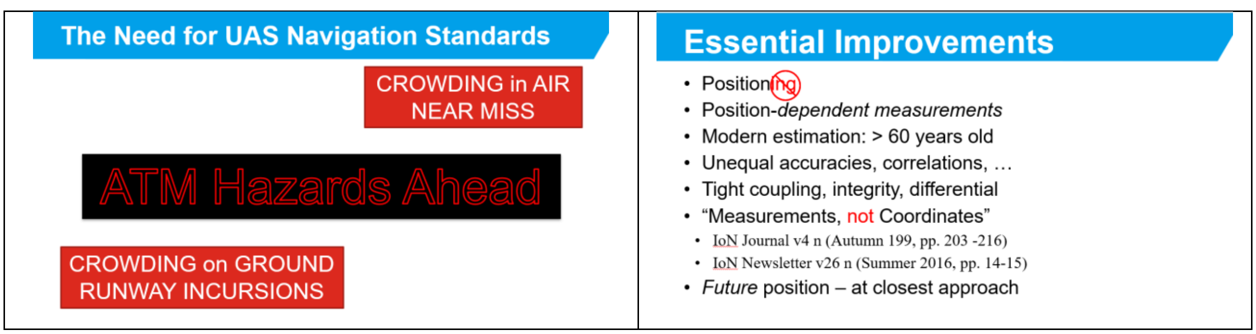
A good way to begin is by citing the American National Standards Institute (ANSI) roadmap (Slides 1-2). This document has been around for a couple of years and hits the nail on the head. Three is a gap which is most critical and leaves no choice but to address it.



Slides 1-2

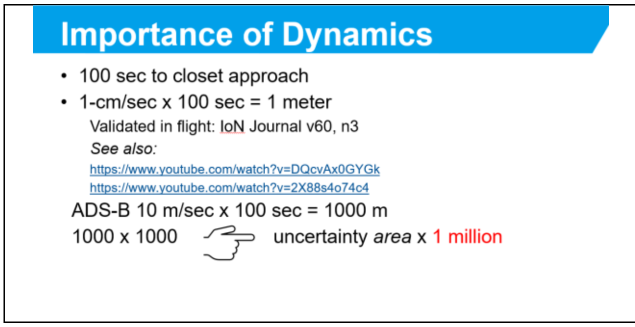
The way we are going to address this gap is shown in slide 3. The reasons include air traffic management hazards, a lot of which are due to the mass introduction of UAS. There have been reports on the internet of collisions and near-misses in mid-air. While many of these were not official, they should not be ignored. Also, on the ground we've also crossed the threshold of 1000 incursions each year. We have no choice but to do something about it. We have to add something to air traffic control.

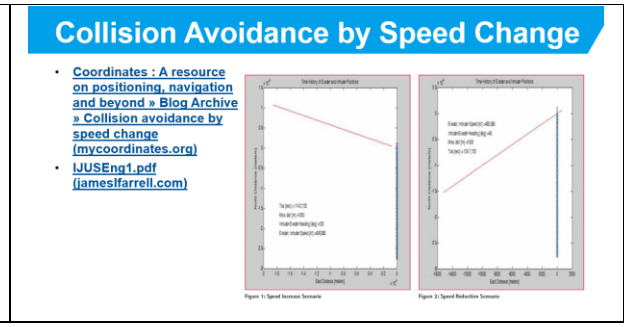
Slide 4 describes a straightforward way to do this, and it centers on the crucial difference between 'positioning' versus position-dependent measurements. The difference is more than just semantics. In 1959 Kalman showed how to take full advantage that there is much more position information available. Position is like a trail of crumbs, but some of those positions are more accurate than others depending on how they've been collected. Some of these measurements have radically different sensitivity in terms of direction. Some are sensitive to latitude, others to longitude, and there are correlations all over the place. A specific measurement error may be correlated with another measurement. There are correlations in the axes being used, and also in time. We care about correlations in time because of dynamics. This is crucial. It's not just about where the aircraft is right now, but also where it will be in the future and the time of closest approach to every other object in the air. We need to address all of them because we can't collide with any of them. The way to take advantage of this is to do what Kalman said in 1959 and look at all these things. If we don't do this then we can't do tight coupling, integrity testing, or differential operations. Therefore, we need to focus on the measurements themselves and not just the coordinates. We need to take advantage of all that we've learned over the past 60 years.



Slides 3-4

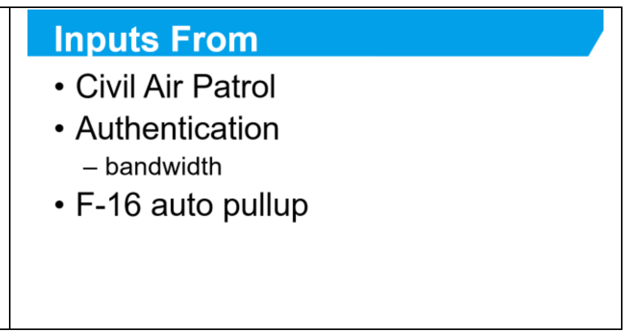
Slide 5 goes into the importance of dynamics. Suppose you have 100 s to closest approach to another aircraft, and you are sharing information. Then 100 s at 1 cm/s rate of change is equivalent to a 1 m cross-range and 1 m long-range uncertainty area. If we use 10 m/s over 100 seconds, then we have 1000 m uncertainty and an uncertainty area of 1000 long-range x 1000 cross-range, which gives you a product of 1 million. You can find this parameter in some of the ADS-B errors. Slide 6 is about what we used to do with collision prevention. There was only one direction: long-range. Cross-range was too inaccurate. However, if we had vector information then you can avoid the collision by changing your speed. As shown in the figure, a small velocity change ahead of time results in a big separation a few minutes later.





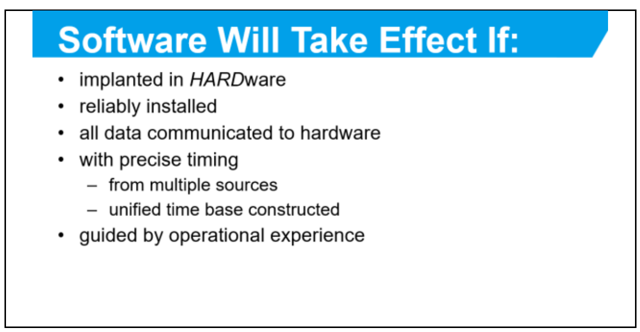
Slides 5-6

Slide 7 shows what he did with the SAE EDGE report, “Unsettled Topics in the Application of Satellite Navigation to Air Traffic Management.” More than half of the people in the development team are also present today. Slide 8 highlights inputs for authentication and the bandwidth needed to add measurements instead of just coordinates. You can do pretty much what ADS-B was doing, with the same hardware, same messages, and just taking the coordinates out and replace them with measurements. The automated ground collision avoidance system is credited with saving the lives of F-16 pilots. If you are constantly monitoring the velocity, altitude, and dive angle, and you know the characteristics of your flight control, then if the pilot is not going to do a pull-up then you take the controls away from the pilot and save his life by performing the auto pullup.



Slides 7-8

For software to take effect, it must happen in the hardware and the operational environment (Slide 9). A lot of things must happen, such as cabling, synchronization, among others.

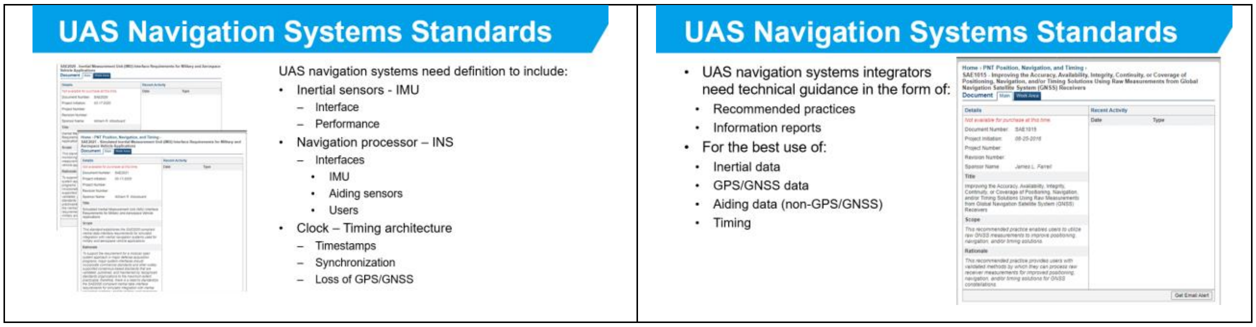


Slide 9

Part 2: Mr. Bill Woodward

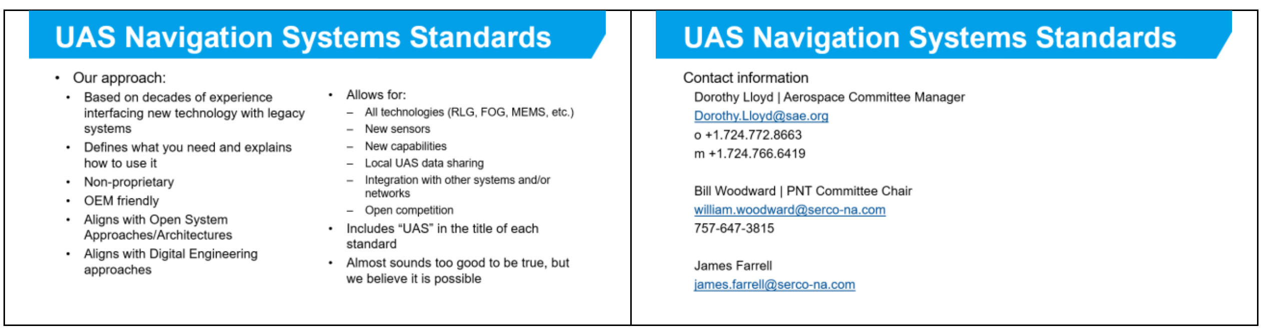
Mr. Woodward noted he’s chair of SAE’s PNT committee (Slide 10). We recently learned about the gaps in the navigation of UAS. Today we are going to talk about ‘A7’. He is going to describe how we think we are going to fill those gaps and how we think that will help with navigation performance. Standards are meant to be used as tools, either when developing a system, when you are sustaining things, or when you are designing something new. We are going to focus on the specifications, but we also have information reports and recommended practices. We’re not only developing a standard, but also showing you how to use it. As shown on slide 10, for UAS standards we are focusing on three areas: inertial sensors, navigation processors, and clock. What we are working on is on the interface of the Inertial Measurement Unit (IMU) and defining the performance of the inertial. We also want interface standards for the inertial sensors, aiding sensors, and the user. For the clock, you need to develop the timing architecture, where you will need timestamps, synchronization, and what you’re going to do if you lose GPS or GNSS.

For UAS navigation system integrators, or managers, to be successful, we are going to need technical guidance in the form of recommended practices and information reports so that we have a source we can send people to learn how to use this (Slide 11). This is also needed in schools. SAE has been doing this for years. We can make these for the best use of inertial data, GPS/GNSS data, non-GPS/GNSS aiding data, and timing.



Slides 10-11

Our approach is based on lots of experience (Slide 12). My job for decades has been integrated new equipment into old planes, old ships, and old submarines. There are a lot of things one doesn't think about when getting into things like that, and not everything is backwards compatible. The systems we have out here today are not going to go away. We must be able to interface with everything that's legacy, and we want to bring new capabilities and still maintain all those legacy interfaces. With the information reports and the recommended practices, we need to define what you need and then to explain how to use it. Everything we do need to be non-proprietary and original equipment manufacturer (OEM) -friendly, that is, you want to develop standards that those manufacturers will want to use. We need standards that are friendly to their business model and know what they'll do and won't do. You also want to align with open systems. This push has been going on for a while, and we're now starting to see open systems in the PNT world. Therefore, we can't change things out easily. You also want to align with digital engineering approaches, because all this stuff is going into models. We want to work with all the technologies, and we need to be able to interface all their capabilities. We want to be able to share this data, integrate with other networks, and we want open competition. This may seem like a lot, but we think it is possible to do. Let's take the IMU, for example. IMUs have been around for a long time, but the IMUs being flown on UAS today are very different from those flying on aircraft. Some may be providing updates 10,000x per second, whereas aircraft IMUs are getting updates 200x per second. We're not trying to create a new interface from scratch. We are working with the OEMs of these devices, and they are sharing their information with us. We are extracting this so we can create ICDs that work with these new IMUs and that will work with the old IMUs. Hopefully in a few years we can have all these standards out there so that folks can put them into contract. Slide 13 is our contact information. If you want to be part of the SAE PNT committee, just let me know.



Slides 12-13

Q&A / Discussion:

Dr. Parkinson remarked on his concerns about the integration of inertials with GPS. There are ways to do it with two black boxes, and interface, and they deal with each other. There's another way that gets a lot deeper in what is happening in the signal. It's called the filter-vector-receiver. If you start getting into that, you get into a total Kalman filter wrap. If successful, it would give you the best estimate of the probability of collision. But when it relates to what you're talking about, he ends up worried that you are going to constrained in, for example, the implementation of a vector receiver in which he is taking the raw measurements, he brings them into the IMU, and then go back and maintain tracking on the system or airplane he is working on. This could result in the loss of some advantages.

Dr. Farrell responded that in air-to-air tracking we don't have access to what the other guy is going to do. We only have access to aiding information. Regardless, we do also want the raw measurements.

Mr. Woodward added that we want to give the option to have all the data, and the highest data rate possible, to allow people to do everything they may want to do.

* * *

Recap of Presentation Highlights & Closing
All members, led by ADM Thad Allen

ADM Allen expressed thanks to the days presenters and reiterated his enthusiasm for Mr. Shane's presentation, which would be moved to the next morning's agenda. ADM Allen asked the board to consider the committee structure and work plan for discussion. All the new PNTAB members will have the chance to address the board tomorrow as well.

Mr. Miller referred the group to the recommendation templates that had been sent out previously. He asked anyone who would like to make a recommendation to prepare it to be shared the next day.

ADM Allen thanked those who dialed in remotely for their patience and participation.

Mr. Higgins added that the presentations all went well remotely and that he may not be able to participate fully in Friday's meetings due to the time difference.

* * *

ADM Allen adjourned the Thursday, December 9 session at 6:08pm.

* * *

Session of Friday, December 10, 2021

Board Reconvenes
Call to Order
Mr. James J. Miller, *Executive Director, National Space-Based PNT Advisory Board, NASA*

* * *

PNTAB Leadership Observations from Day 1:
Prioritization of Opportunities and risks
Protect, Toughen, Augment Focus Areas
Establish Subcommittees to Develop Recommendations
ADM Allen, *Chair, PNTAB*
Dr. Bradford Parkinson, *1st Vice Chair, PNTAB*

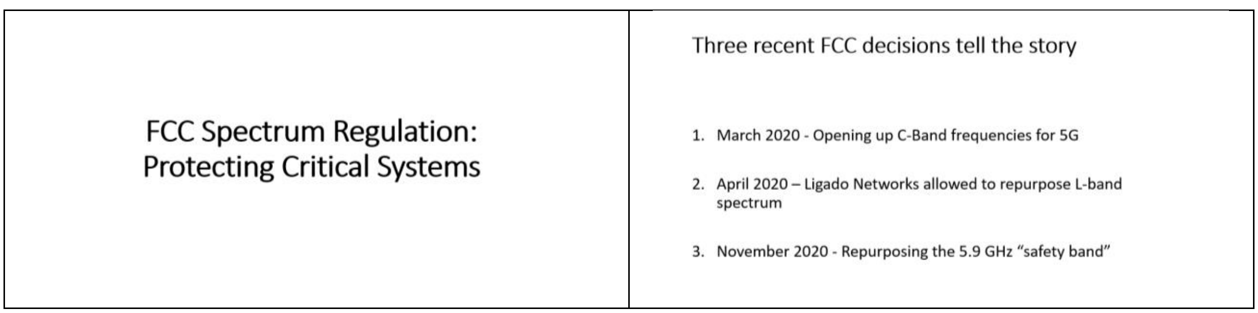
ADM Allen opened Day 2 of the PNTAB 25th meeting by identifying key priorities for the day. He discussed the PNTAB topic list from the NCO, which the board will review offline in the new year. He emphasized the need for identifying a governance structure for the board moving forward. Traditionally, the PNTAB has held two meetings a year, with one meeting in the DC area in the summer and a meeting in Redondo Beach or El Segundo in the winter. He proposed a spring meeting in the May timeframe and asked the board to consider their schedules for upcoming meetings. Mr. Miller and Dr. Parkinson concurred with those suggestions.

* * *

FCC Spectrum Regulation
Addressing Perceived Conflicts with Safety & National Security Systems
Hon. Jeff Shane, *IATA Representative & PNTAB Member*

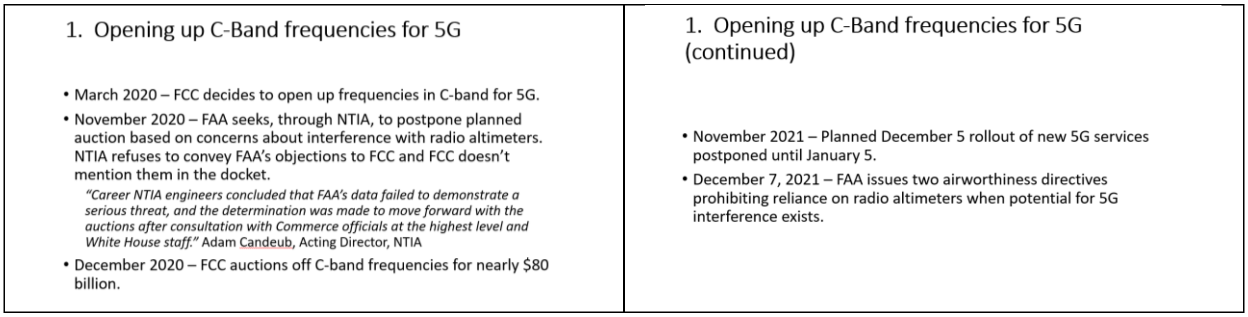
Mr. Shane thanked ADM Allen and welcomed in person and online attendees to the presentation (Slide 1). He began by stating that he is not an enemy of the FCC, nor does he encourage any of the board members to be. The FCC does what it does because of the motivations built into a law that it does its best to carry out. He referenced the recommendation to develop an effective narrative to ensure peaceful coexistence between the affairs the PNTAB cares about and the innovations the world wants to bring online.

Mr. Shane reviewed three recent decisions made by the FCC (Slide 2): (1) In March 2020, the FCC opened C-band frequencies for 5G that led to an auction in December 2020; (2) In April 2020, the FCC allowed the Ligado Network to repurpose L-band spectrum; and (3) In November 2020, the FCC repurposed the 5.9 GHz safety band.



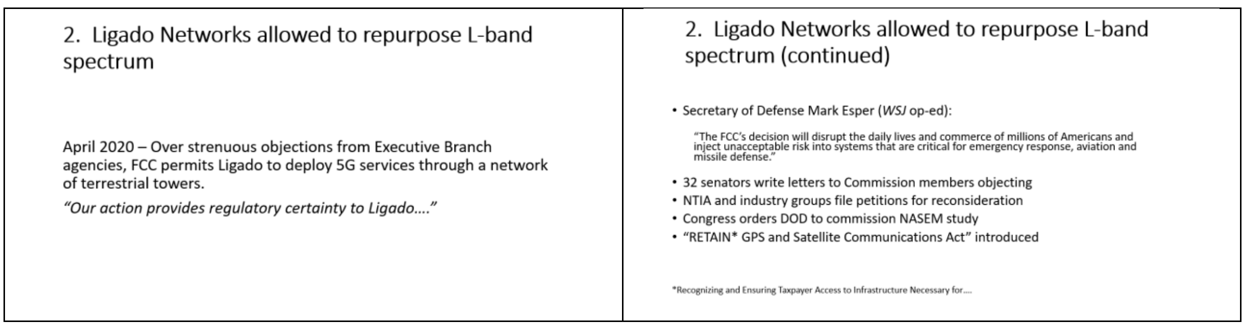
Slides 1-2:

In November 2020, the FAA tried through the National Telecommunications and Information Administration (NTIA) to postpone the proposed auction of the C-band frequencies for 5G due to concerns about potential interference with radio altimeters (Slides 3-4). The NTIA did not convey those objections to the FCC. When asked about why NTIA refused to convey to the FCC concerns the FAA expressed concerns about potential interference, NTIA Acting Director Adam Candeub responded that "FAA's data failed to demonstrate a serious threat, and the determination was made to move forward with the auctions after consultation with Commerce officials at the highest level and White House staff." Mr. Shane noted that the higher you get in government, the less expertise those individuals tend to have in spectrum matters. As a result, the FCC did not mention anything about radio altimeters in its docket and in December 2020, the FCC auctioned off C-band frequencies for nearly $80 billion dollars. As a result of the controversy that followed, the planned December 5, 2021 rollout of new 5G services was postponed until January 5, 2022. On December 7, 2021, the FAA issued two airworthiness directives prohibiting reliance on radio altimeters when potential for 5G interference exists. As a result, many flights are going to be cancelled, and it is highly likely that many of you sitting in this room will be on an aircraft in the new year where a flight where be cancelled after boarding due to 5G interference in the air. This is the consequence of NTIA engineers deciding that there was no serious threat to radio altimeters.



Slides 3-4

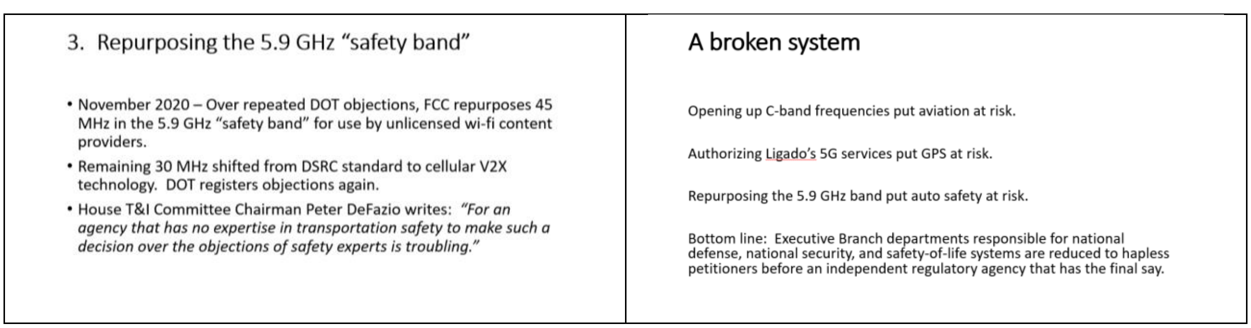
In April 2020, despite the objections of thirteen executive branch agencies through the NTIA, the FCC permitted Ligado to deploy 5G services through a network of terrestrial towers (Slides 5-6). In the opening paragraph of the FCC decision, it states "our action provides regulatory certainty to Ligado." Secretary of Defense Mark Esper wrote a Wall Street Journal op-ed objecting to the decision, 32 senators wrote letters to FCC members in objection, and NTIA and industry groups filed petitions for reconsideration, most of which are still pending. Congress ordered the DoD to commission the National Academies of Science, Engineering, and Medicine (NASEM) to study the decision. The "RETAIN[3] GPS and Satellite Communications Act" was introduced in the Senate. If you were an investor in Ligado, you were likely unhappy with this set of circumstances, which were all triggered by the FCC's decision.



Slides 5-6

In November 2020, over repeated DOT objections, the FCC repurposed 45 MHz in the 5.9 GHz "safety band" for use by unlicensed wi-fi content providers (Slide 7). The remaining 30 MHz were shifted from Dedicated Short-Range Communications (eLoran) standard to cellular vehicle-to-everything (V2X) technology. DOT registered objections again. The House Transportation & Infrastructure Committee Chairman Peter DeFazio wrote, "For an agency that has no expertise in transportation safety to make such a decision over the objections of safety experts is troubling."

In summary, these three decisions indicate a broken system (Slide 8). Opening up the C-band frequencies put aviation at risk. Authorizing Ligado's 5G services put GPS at risk. Repurposing the 5.9 GHz band put auto safety at risk. The bottom line is that Executive Branch departments responsible for national defense, national security, and safety-of-life systems are reduced to hapless petitioners before an independent regulatory agency that has the final say. That is strange as a matter of national policy. Don't blame the FCC, blame the structure.



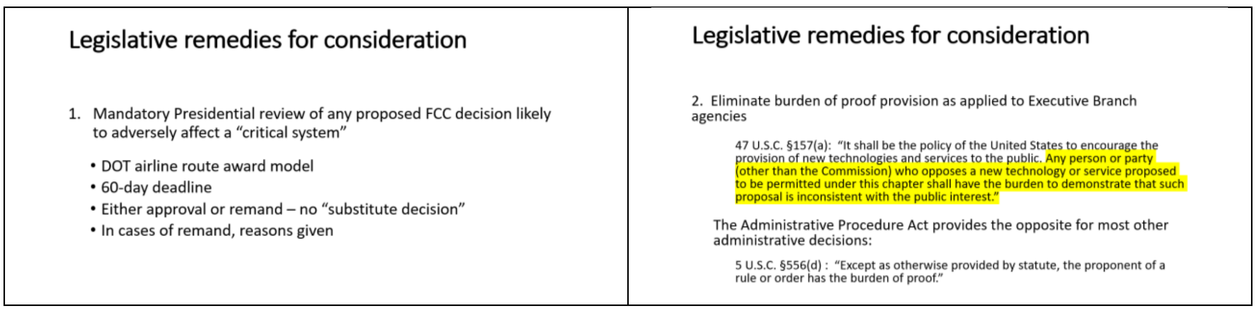
Slides 7-8

[3] Recognizing and Ensuring Taxpayer Access to Infrastructure Necessary

Mr. Shane presented legislative remedies for consideration due to his belief, as a lawyer, for change to be effective, there must be changes in the law. However, it has been suggested to him that Executive Orders might be a better route. He was unsure whether the PNTAB could make legislative recommendations even through committee but proposed the review of these ideas for consideration and discussion.

The first recommendation is to implement mandatory Presidential review of any proposed FCC decision likely to adversely affect a critical system (Slide 9). In the past, there was a Civil Aeronautics Board (CAB), an independent regulatory agency like the FCC, where one of its responsibilities was to award international routes to airlines, whether domestic or foreign, and once proposed, that decision needed to go to the White House for review. This review is limited to very narrow circumstances and only allows the President to veto the decision to send it back for more work. Even though the CAB went away in 1984, DOT inherited that function, and when licenses are granted, they are sent to the WH for review. Mr. Shane proposes a similar system for FCC decisions that could potentially adversely affect critical systems. There would be a 60-day deadline for approval or remand, and in cases of remand, reasons are provided.

The second proposal is to eliminate the burden of proof provision as applied to Executive Branch agencies in communications law today (Slide 10). Current US communications law puts priority on innovation but requires any party who opposes the new technology or service to demonstrate that such proposal is inconsistent with the public interest. In all other decisions, the proponent of innovation bears the burden of proof. Everyone understands burden of proof, that you are innocent until proven guilty, and that prosecutors must provide evidence for conviction to an independent third party. Currently, Executive Branch agencies bear the burden of proof before an agency encouraged by law to provide access for new technologies. Mr. Shane recommends removing provision as it applies to Executive Branch agencies and the owners of critical systems.

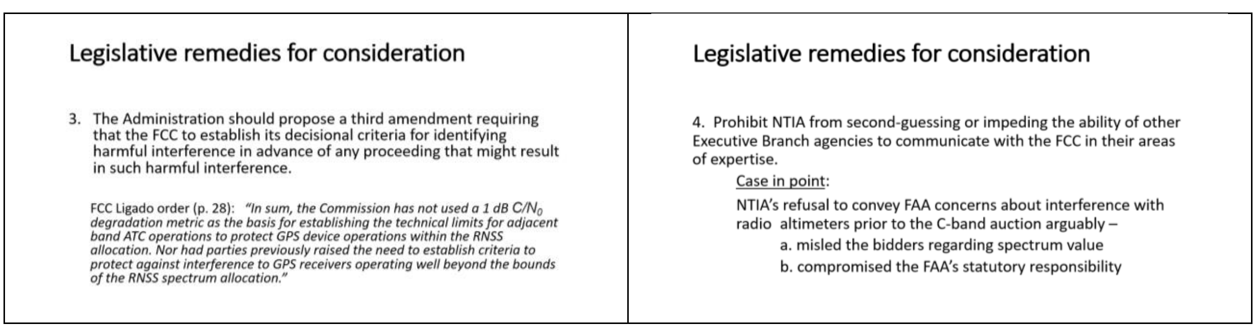


Slides 9-10

The third recommendation is for the Administration to propose an amendment requiring that the FCC establish its decisional criteria for identifying harmful interference in advance of any proceeding that might result in such harmful interference (Slide 11). All parties in a competitive proceeding need to understand what the criteria are. In the Ligado order, DOT ran government tests using standard carrier signals and noise ratio. Everyone assumed that was the testing standard, but it turned out it wasn't. On page 28 of the FCC Ligado Order, the FCC stated that it had not used a 1 dB C/N_0 degradation metric, nor had parties previously raised the need to establish criteria to protect against GPS interference. In Mr. Shane's opinion, this was one of the biggest flaws in the ways in which the Ligado case was decided.

Finally, Mr. Shane proposed prohibiting NTIA from second-guessing executive branch agencies. NTIA's refusal to convey FAA concerns about interference with radio altimeters prior to C-band auction misled bidders regarding spectrum value and compromised FAA's statutory responsibility (Slide 12). The FAA is responsible for aviation safety, not for others in government. Its concerns were walled off from the decision makers at the FCC.

Mr. Shane acknowledged that the ways and means of implementation would be an entirely separate conversation, and he opened the floor for discussion among PNTAB members.



Slides 11-12

Discussion:

ADM Allen thanked Mr. Shane for the presentation.

Dr. Parkinson remarked that the presentation dazzled him with the clarity of thought. He wondered how a group of reasonable, unbiased people came to those decisions. In the matter of critical systems, who decides what those are?

Mr. Shane responded that the agencies that owns or is responsible for the system should decide. In the case of 5.9 GHz, DOT would have authority. For GPS, it would be DoD.

Dr. Parkinson added that both DoD and DOT have shared ownership of GPS.

Mr. Shane confirmed that if DoD or DOT raised concerns in his proposed system, that would trigger White House review.

ADM Allen suggested that one way to approach this would be under the domain of "critical infrastructure." Whoever owns, from a regulatory standpoint, the safety and responsibility for that infrastructure, would then decide.

Dr. Parkinson added that some interference concerns may be classified. He hopes that the structure proposed by Mr. Shane would accommodate that.

Mr. Shane responded that such an approach would make it more consistent with what goes on in the airline context.

Capt. Burns thanked Mr. Shane for the briefing and noted that the recent airways directives will impact over 6800 major aircraft. The added uncertainty will impact takeoff as well as flights in route, increasing costs dramatically for operators. This takes effect as of January 7, 2022 and will likely cause delays moving forward until a better solution comes out.

Dr. Axelrad made a comment regarding the fundamental issue that rules about use of spectrum are only concerned with communications primarily, rather than navigation or environmental sensing in those same frequencies are used for.

Mr. Shane responded that there's a general feeling that the problem is our reliance on a law written during the golden age of broadcasting. However, the laws have been updated to encourage and promote innovation in the uses of spectrum beyond traditional broadcasting. The question is who has responsibility for potential conflicts that arise as the spectrum gets increasingly crowded.

Dr. Parkinson followed up to emphasize the importance of bringing navigation experts to the FCC.

Mr. Shane proposed adding resources to the FCC to take full account of all the issues at stake in these cases. The FCC has not done a lot of research. They were referees to different tests that were done according to different standards and criteria. Mr. Shane asked why the FCC doesn't do its own independent research. This could be addressed through the budget or the hiring process.

Gov. Geringer shared the adage that the best way to change a bad law is to enforce it. Ligado currently has regulatory certainty to proceed and has shed as much risk as possible. The only way to change anything like the Ligado decision is to come up with a remedy that las legal liabilities. They currently view the situation as very well protected under the cover of the FCC order. Ligado is not in the business of operating 5G networks and will likely sell the spectrum elsewhere, or they may start network with towers with minimal interference to sell to someone else. Gov. Geringer referred to public service commissions who must review and evaluate the impact of decisions with an independent eye focused on public interest. He asked Mr. Shane if he could comment on the value of independent staff within the FCC that could act like state public service commissions do.

Mr. Shane referred to experience earlier in his career with the CAB and the Interstate Commerce Commission (ICC), which all had independent consumer advocates within the staff. He was unsure whether the FCC had independent consumer advocates, but if it does, they would suffer the same issues of burden of proof.

Mr. Goward added that the FCC has an office of economic analysis that was instituted because of criticisms around lack of transparency, but it is up to the chairman's discretion whether it gets involved in a particular decision. It was not involved in the Ligado decision and likely was not involved in the other decisions as well.

Dr. Winfree asked to what extent the chaos referenced reflects the tension between the legislative branch and the executive branch. He observed that the turf fights between all three branches of government might make it difficult to find any accord in implementing executive oversight into legislative activity.

Mr. Shane responded that it seems to be tension specifically within the legislative branch. The Armed Services Committees in both houses have proposed the RETAIN act, which will impose a liability on Ligado for the cost of repairing everyone's receiver, not only DoD receivers. The law is intended to be a business killer. Whether or not it passes is dependent on the Armed Services Committee generating support among other members of Congress and will likely be an uphill battle.

Dr. Powell asked whether the order of proposed recommendations refers to order of priority or likelihood of success.

Mr. Shane responded that the first proposal is the highest priority, and that if implemented, it would change the conversation entirely.

Mr. Shields thanked Mr. Shane for his effort and took to heart the comment that attacking the FCC doesn't do us any good. Looking at the three decisions, each decision provided spectrum for internet, largely operating under the Obama-era internet priorities from 2011 encouraging connectivity. There is nothing to counter that. Mr. Shields proposed the addition of a recommendation on the priority of safety-of-life (SOL) so that the FCC must consider SOL in addition to internet connectivity.

Mr. Miller encouraged Mr. Shane to draft a recommendation and referred to their work on the President's Spectrum Policy Initiative for the 21st Century.

Mr. Shane thanked the board for listening.

ADM Allen thanked Mr. Shane for his presentation and invited the new members to begin their observations.

* * *

Concise Observations from New Members:

1) Lt Gen Michael Hamel (USAF, ret.)

Lt Gen Hamel thanked ADM Allen and expressed how pleased and excited he was to be a part of the reinvigorated PNTAB. He remarked that he had been away from most of the specifics for 10-20 years and that things are now enormously more complex and consequential. He praised Dr. Scott Pace's presentation (at the non-FACA fact-finding meeting held Wednesday Dec. 8) for highlighting the space domain perspective and the development of policies within the previous iteration of the NSpC that have allowed for the continuity and consistency in the change of administration. One of the most important things lacking around PNT and GNSS is a coherent narrative around the importance of PNT in an information age, and likewise, the values, imperatives, and geostrategic consequences to US and allies and partners overall. We need a story that can be told, but we don't currently see where it's being told. There are different stovepipes at different agencies, and we don't have a national narrative about it overall. Lt Gen Hamel had a conversation with Dr. Pace on how there have been four to five decades of consistent space policy that has not become self-actualizing. With so many agencies and stakeholders, the question remains, "who is going to pay for something?" We lack a strategy about ways and means to achieve policy ends. Even if we cannot agree on everything, we must get buy in and collaborate across various agencies and the private sector. Rather than a whole of government approach, try a whole of nation strategy overall. Many issues are the same now as they were ten years ago – what are the core GPS services that we as a nation and government intend to provide? Good ideas pop up and linger, but there seems to be no coherent narrative about what those core services and augmentations are and what opportunities for innovation are present. Absent such roadmap, we will continue to get caught in arguments about who pays for what. Referencing the GDGPS Task Force study led by Dr. Betz, Lt Gen Hamel emphasized the importance of clarifying what GPS delivers to preserve its status as the gold standard for the world. The discussion on the SSV, and GPS use throughout Cislunar space, is a great example of an issue that could force action or consensus, as there are technical solutions that can be implemented with limited resources, potentially allowing for participation from civil, defense, and international participation moving forward. Lt Gen Hamel also requested more input from the user community in future meetings, including people like marines and sailors, who can highlight the importance of GPS and where they may be disappointed by it, so that the PNT community may respond.

2) Dr. Jade Morton

Dr. Morton thanked the group for the opportunity to participate in the board. She enjoyed the breadth of discussions over the last few days, from the need and means to toughen GPS to international politics and national policies, from signal authentication to timing infrastructure and system updates to all the various applications. Most importantly, the group talked about Wi-Fi interferences on automobiles, aircraft, UAVs, and timing applications. These are very broad topics and they have been very educational, but she noticed that there were not any specific discussions on scientific applications, which are deeply connected to all the concerns discussed throughout the meeting. Ten years ago, there was a survey that recorded GPS measurements from radio occultation systems. GPS was found to be among the top four most important data contributors for weather and climate modeling. For ionospheric and space weather modeling, GPS data is the most dominant source. GPS data is relied upon in those areas, not to mention traditional applications like geodesy and survey. There are new applications like reflection signals from the Earth's surface that are measured by LEO satellites with antennas mounted on the bottom side of the satellites, which monitor ocean wind speed, soil moisture, etc. All these applications will be impacted by radio frequency interferences, causing data to be misinterpreted or making data unavailable, leading to a high economic impact worldwide. Most of the applications rely on high accuracy carrier phase measurements, which are even more susceptible to RF interferences because user spacecraft antennas are pointing to Earth. The impact of interference has already been seen in data products like soil moisture. RF interference coming from Africa and the Middle East have already impacted data collected over the last two years. Toughening receivers is one thing, but also enabling accurate interpretation of the data is an even harder challenge. That's why Dr. Morton volunteered to join Dr. Parkinson's proposal to toughen the receivers and develop better technologies at the same time, hopefully persuading people to avoid interference so scientists can do their work.

3) Dr. Gregory Winfree

Dr. Winfree expressed his appreciation of the opportunity to participate in such an august assemblage. His last formal engagement with these issues and this community was in November 2016 when he closed his tenure at the ESG with a rather poignant observation, as many folks remember. Despite the passage of five years, Dr. Winfree was concerned but unsurprised that vexing issues of that day, such as incompatible activities adjacent to GPS primary frequency bands, remains a vexing issue. But upon reflection of a day and a half of world-class presentations, the bookends for Dr. Winfree were Mr. George Beebe's sober historic recitation of the circumstances potentially underlying the Ukraine crisis, and Mr. Jeff Shane's clear advocacy for the fundamental rebuild of the governance structure underlying RF spectrum allocation. Dr. Winfree has a lot to consider and is eager to contribute to an area in which he has developed a tremendous passion.

4) Ms. Eileen Reilly

Ms. Reilly appreciated the opportunity to learn so much from colleagues and wanted to share about the rail industry. The rail industry relies on a toughening of the system, but also need more spectrum and spatial diversity so there is better coverage across the country. In 2008, after a horrific accident in California, a Metrolink and a United Parcel Service (UPS) train collided, the rail industry was mandated to implement Positive Train Control (PTC) across the US, which is a communication-based train control system that to date has cost $15 billion. One of the big issues with it is the impact that it has had to the velocity of this critical infrastructure. Railroads are part of the strategic network or deploying fuel, troops, equipment, and goods during a crisis. A particular area the rail industry is concerned with is getting spatial and spectrum diversity that would enable tightening the braking systems and, in turn, allow trains to increase velocity and get the trains across the country in an expedient way. In addition to the use of PTC, the rail industry relies on the use of GPS for timing in its communications, Geographic Information Systems (GIS), and unmanned surveillance to monitor tracks. Ms. Reilly reiterated that as her mission and primary contribution to the board and looked forward to achieving spectrum diversity and toughening GPS systems by getting approval for use of other GNSS in the US, in particular GLONASS.

ADM Allen commented that he would like a briefing on PTC, as there is an ongoing issue as whether can use GLONASS.

Ms. Van Dyke added that a presentation on the issues the rail industry faces, particularly in Alaska, would be valuable. Setting the stage with the problems that they face with PTC at high latitude and understanding potential solutions without much infrastructure available. It may be valuable to consider analysis of other PNT alternatives and other GNSS systems.

Ms. Reilly added that this issue not only affects the Alaska Railroad, but also the southbound trains that travel through mountains and tight corridors where GPS visibility is obstructed and, thus, prevents accurate location services. Over the last five years, there have been many US-wide studies that Ms. Reilly would like to share at the next meeting.

5) Dr. Tom Powell

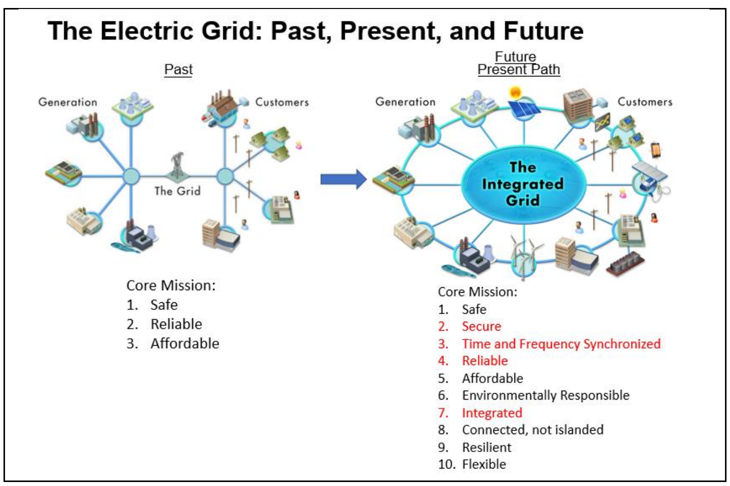
Dr. Powell strongly supported the effort to reinvigorate the PNT EXCOM process so that recommendations receive the review and attention they deserve. He also added that he would be willing to support Dr. Parkinson's proposal to review ITAR considerations for multi-element antenna. As Mr. Shane mentioned, the NASEM study is ongoing, and it would be wise for the PNTAB to stay up to date on their progress. Dr. Powell seconded the notion of having a strategic communications effort and would be willing to support with that.

6) Dr. Sonia Alves-Costa

Focusing on the science and practical benefits of GPS for society, Dr. Costa discussed land ownership and disaster warning prevention. Nowadays, most national geodetic reference frames rely on space technology, and the most popular is GPS. However, lots of national efforts towards network modernization rely on acquisition of GNSS receivers. GNSS has been indispensable for Earth and atmospheric science, for monitoring Earth's ionosphere and troposphere, and for time frequency transfer. To maintain and ensure long-term stability of the national geodetic reference frames for general geodetic network identification, global reference frames, precise orbits, tropospheric measurements, and all products must be coordinated by the International GNSS Service (IGS). Even online geodetic applications or services like PPP use IGS ultra-rapid products. For example, from Canada and Brazil, online PPP services use IGS products, so any survey can be coordinated and computed in two hours, which is a great advancement for many institutions. With the advances of mobile internet, real-time applications are increasingly used all over the world, and precise real-time IGS combined products are nowadays provided through entry protocol. For example, the presentation on Galileo HAS was well done, and IGS products are provided in hourly, daily, and weekly basis through the internet. Dr. Costa recommended strengthening the cooperation between GPS and Galileo to improve the performance for end users, for example by amplifying the area for high accuracy service across the globe. To ensure the scientific and practical high accuracy multi-GNSS applications, Dr. Costa proposed bringing an IGS representative to PNTAB as a member, considering the importance of all activities developed by this group. She also recommended supporting all monitoring and coordination for science GNSS applications of IGS. She recommended strengthening the cooperation with other GNSS services and providing real-time service over the internet. Finally, she recommended intensifying and improving communication and outreach all over the world with national and regional entities, promoting workshops and discussion groups related to GNSS applications.

7) Dr. Vahid Madani

Dr. Madani represents the energy sector and in particular electric energy. Dependency on GPS goes well beyond aviation, and much of his presentation focused on the commercial and industrial aspects of GPS dependency, as well as concerns about jamming, spoofing, physical attacks, and integrity monitoring. The purpose of the PNTAB is PTA, and many of the presentations this week discussed innovation. Interference and resiliency are major concerns, sequential event recording is something to be discussed when considering advanced applications. He remarked on the similarities between commercial avionics and the auto industry, specifically autonomous vehicles. Autonomous electric grid operations are soon to take place, and Dr. Madani recommended arranging a presentation on that for the next meeting. One of the other PNTAB members mentioned the word “roadmap,” and to Dr. Madani’s knowledge, of the 16 critical infrastructures in the US, 15 use GPS timing, and 13 sectors have identified it as mission critical. This broad impact may be leveraged towards initiatives of issues that need to be highlighted. The impact of interference mentioned today is vital if it’s going to cause disruptions on the power system. For situational awareness, starting with the 2003 Northeast outage, Federal Energy Regulatory Commission (FERC) Orders were mandated, and carried out by the North American Electric Reliability Corporation (NERC). During the 2003 disturbance in the Northeast, where roughly 51 million people lost power for over 24 hours, it took roughly six months to put that sequence of events together. In 2011, there was a disturbance between Arizona, California, and part of Mexico, and the information was available in less than two hours. Quite a bit of that innovation is credited to the Department of Energy (DOE) and the American Recovery and Reinvestment Act. The $1 billion in investment from 2010-2018 is only in technology, and utility upgrades were likely over $20 billion. If these investments are going to be impacted in any shape or form from a grid reliability, resiliency, or monitoring perspective, this is going to be a major issue for the energy sector. Green energy proliferation is going to have a significant effect on how the grid is being operated. The new administration’s Infrastructure Bill is going to have significant reliance on GPS. The energy sector continues to explore the possibilities presented by Advanced Control Systems and big data analytics. Outside of the US, some countries are experimenting with controlled operation or substation monitoring robotics, so it’s not a question of if, but when this technology will be implemented in the US. In the past, the electric grid was only responsible for the core mission of being safe, reliable, and affordable. The integrated grid of today and moving forward is safe, secure, time and frequency synchronized, reliable, affordable, environmentally responsible, integrated, connected vs. islanded, resilient, and flexible. Those highlighted in red (see chart below) are all timing sequence requirements of GPS.



Integrated Electric Grid

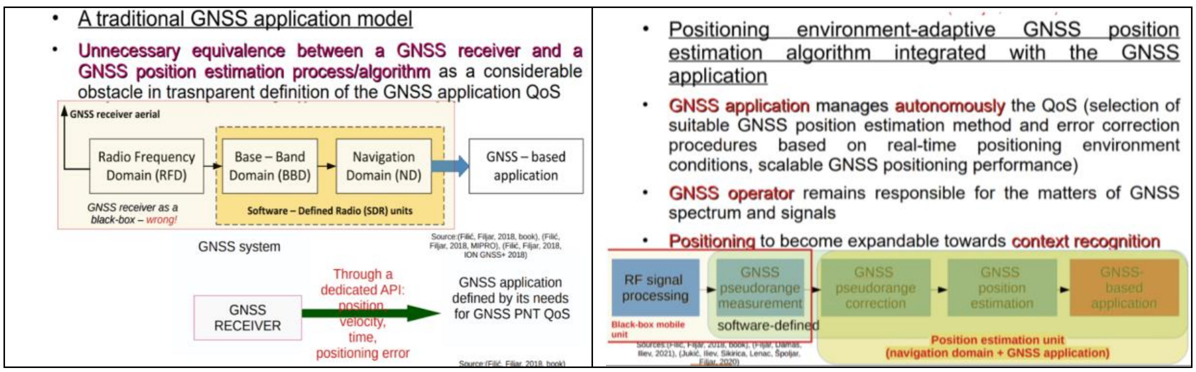
ADM Allen thanked Dr. Madani and added that there had been many discussions over the past few days about his previous experience as a senior mentor for the GridEx exercise that NERC operates every few years. This project goes to the highest levels of government with the NSC, Northcomm, and others. This topic is a candidate down the line in addition to the railroad to take a closer look at moving forward.

8) Dr. Renato Filjar

Dr. Filjar proposed focusing on the information perspective and the need for enforcement for GNSS receivers. It’s easy to explain why GPS is the gold standard and will remain as such, for its simplicity, efficiency, and the elegance of the infrastructure developed to provide everyone the opportunity to identify position, velocity, and time. It was devised in the mid-1970s thanks to Dr. Parkinson and his team. As an infrastructure, GPS should provide the framework for the services, systems, and application development. It is important to hear from the application developers, operators, and users so that the infrastructure can serve as the foundation for applications development. This means that the infrastructure should be robust and resilient to many potential adversarial effects from both natural and artificial sources, protecting the radio frequency domain, the base-band domain, and the navigation domain. Most concerns are raised about the signals and spectrum, but somehow the information / navigation domain has not been considered, particularly for the process of position estimation.

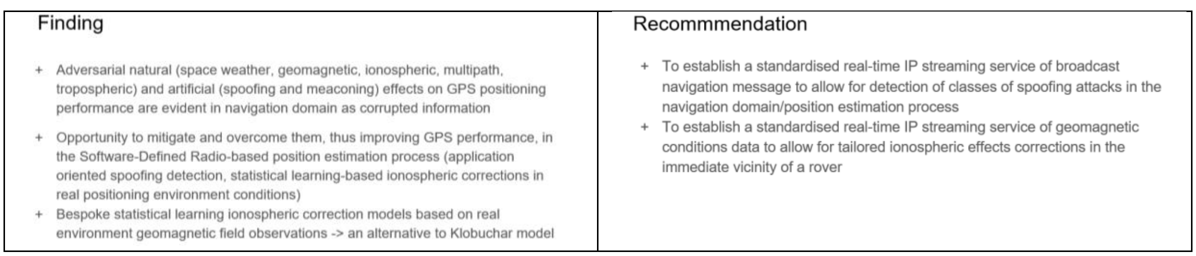
This process is usually seen as a method to provide the application with what is considered important, e.g., PVT and position error estimates (Slide 1). There are concerns with position accuracy for that reason. But from the application side, many applications are not interested in positioning accuracy. They are interested to see if the system can provide the position with the sufficient level of quality to be utilized for certain applications. For example, simple location-based services can point you towards the nearest petrol station. Centimeter level accuracy for that is not necessary, and the best GNSS receiver is not required. All that is needed is a receiver estimation process that will derive position with sufficient accuracy. Dr. Filjar asked why there is not greater consideration of how to allow the application itself to decide the level of accuracy it needs. As an electrical engineer by training, his background was in statistical learning and signal processing, and his team developed this idea.

In the light of new technologies like 5G and IoT, this idea is even important. Small devices may take care of signal processing while communicating with the rest of the position estimation process to provide the sealed range measurements and other details that will enter into a statistical estimation process. His team believes that GNSS-based applications should make decisions on the corrections they need and how GNSS position estimation will be conducted. The provision of GPS as an infrastructure should be concerned with the functionalities and features that will allow for application development. Dr. Filjar's team has worked extensively on the means to overcome adversarial natural and artificial effects on GPS positioning performance and developed statistical learning-based methods that can allow for personalized receiver-agnostic position estimation process that take into account the real and immediate conditions in which the GNSS positioning takes place (Slide 2).



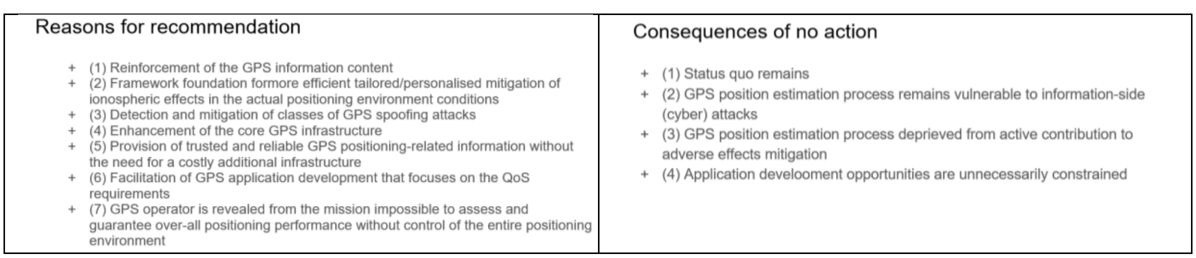
Slides 1-2

Dr. Fijlar presented some findings (Slide 3) and formulated several recommendations that he believes will drive GPS and GNSS into the future- (Slide 4).



Slides 3-4

From these recommendations, it is possible to better detect spoofing, increase performance of GPS positioning, and relieve GPS operators of the concerns about accuracy, because the application itself will drive those decisions. GPS operators can then focus on robustness and signal and spectrum protection (Slide 5). If no action is taken, GPS position estimation process remains vulnerable to cyber-attacks and application development opportunities are unnecessarily constrained (Slide 6).



Slides 5-6

GPS should be successfully integrated with other GNSS, and this also raises the importance of international collaboration during conversation with those involved with ICG WG-S (Systems, Signals, and Services). As an external contributor to this group, Dr. Filjar spoke on the benefits of the open and transparent collaboration of international partners on GNSS standardization. He complimented the booklet from WG-B (Enhancement of GNSS Performance, New Services, and Capabilities) and shared that WG-S is also working on an information booklet related to GNSS and GPS interference detection and mitigation. Dr. Filjar thanked the group for the opportunity to participate among such an exceptional group of individuals.

9) Mr. David Grossman

While not a military expert, Mr. Grossman hoped to bring the background from having worked with the FCC on Capitol Hill from the perspective of the GPS Innovation Alliance and now representing the Consumer Technology Association (CTA). The CTA brings the perspective of a wide variety of players, form those who manufacture chips to smartphone makers, drones, self-driving vehicles, and software-based apps that rely on GPS like rideshare services and major retailers. As the group talks about whether the PNTAB would put forward legislative proposals, Mr. Grossman highlighted the work of the Congressional GPS Caucus, which gave a presentation to the board in 2019. This bipartisan, bicameral group of representatives and senators understands the importance of GPS and can be the Board's champions on these issues. In the House, it is led by Rep. Don Bacon, an Air Force veteran, and Rep. Mikie Cheryl from New Jersey. In the Senate, it is led by Sen. Duckworth and Sen. Ernst. The Caucus has hosted briefings over the years ranging from a GPS-101 to the role GPS plays in drones, firefighting, and 911 services. He brought up the GPS Caucus because of the recommendation that ADM Allen put forward regarding a Communications and External Affairs committee, and Mr. Grossman volunteered to participate in that effort. He mentioned that there had been an effort to bring a member of the GPS Caucus to present at PNTAB-25 and they were unable to attend, but they would be available to host a special meeting or webinar for this group to hear the perspectives of those in Congress.

Mr. Grossman expressed particular interest in the conversation around spectrum policy and how federal agencies work together and coordinate activities. He mentioned that CTA would be opposed to proposals that regulate receiver performance and would want to provide their perspective to those issues. Lt Gen Hamel spoke to the importance of hearing from the user community, and Mr. Grossman agreed with that suggestion. The CTA also represents major consumer technology retailers and Mr. Grossman believes that industry could do more to combat the prevalence of jammers, encourage more robust FCC enforcement, and address the sale and manufacturing of illegal jammers. There was another comment made yesterday that 99% of engineers at the FCC come from a cellular background, and Mr. Grossman confirmed that is true. When talking to congressional staff on the commerce committee, they will say they are not engineers and their bosses are not engineers, so they defer to the expertise of the expert agency, being the FCC, but that this does not differentiate between those with expertise in communications vs. navigation. He noted that this is something the group can continue to work on.

Turning to Mr. Shane's presentation, he is concerned about the notion of a presidential review of decisions made by the FCC, noting the political perspective of the FCC as an independent agency. Focusing on eliminating the burden of proof by federal agencies, he noted that would impact innovation not only for GPS but other technology as well. As some alternative recommendations, Mr. Grossman proposed updating the MOU between the FCC and NTIA, as the last update was made in 2003 and much has changed in how we think about spectrum over the last 20 years. The Spectrum Coordination Act has already passed through the House Energy and Commerce Committee with strong interest on both sides of the aisle and industries as diverse as the GPS and wireless industries who recognize the ways we can improve the spectrum process. He also suggested that the PNTAB could make a recommendation to the FCC Committee of Technology to retain a detailee from the GPS program from DOT or DoD. The FCC commissioner's office typically has 4-5 advisers and attorneys who may not have engineering expertise, and the PNTAB could recommend bringing engineers to each commissioner's office who understand communications, navigation, and safety of life applications to advice each office. He again expressed his gratitude for being included in the group and looked forward to continued discussions.

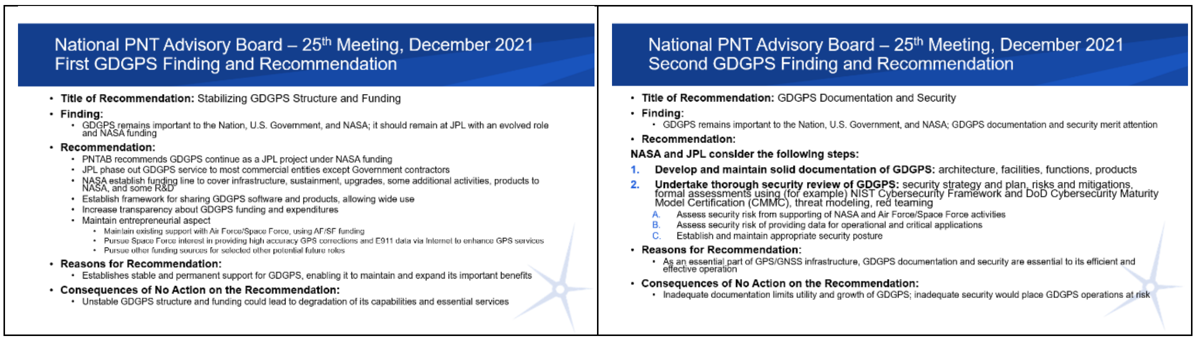
* * *

Roundtable Discussion – Recommendation Formulation
Organization of Work for 2021-2023 (Subcommittees, Task Forces, etc.)
Developing Findings & Recommendations
All members, led by Chairs

Mr. Miller thanked the new members for their remarks and emphasized the importance of hearing objective feedback and perspectives from a diverse group. He noted that new members would benefit from staying in touch with the EXCOM agencies and departments who nominated them to the board. He also highlighted the commemorative coins created in honor of the 25th meeting.

1) GDGPS Task Force Recommendation

ADM Allen asked for any additional comments on the GDGPS report and recommendation.



GDGPS Task Force Recommendations

<Dr. Axelrad and Lt Gen James recused themselves from discussion on GDGPS>

ADM Allen asked for approval of the first GDGPS recommendation by unanimous consent.

<A vote was carried, and the first recommendation was formally approved by the board>

ADM Allen asked for approval of the second GDGPS recommendation by unanimous consent.

<A vote was carried, and the second recommendation was formally approved by the board>

ADM Allen noted that the findings and recommendations from the GDGPS report will be compiled and shared with the NASA Administrator.

2) PTA Objectives

Dr. Parkinson remarked on adding "Innovate" to the PTA acronym.

Lt Gen James emphasized the value of involving innovation into PTA without necessarily creating it as a separate area.

Dr. Parkinson noted that the development and incorporation of new technologies deserves explicit recognition within the board's structure and that it may require further consideration.

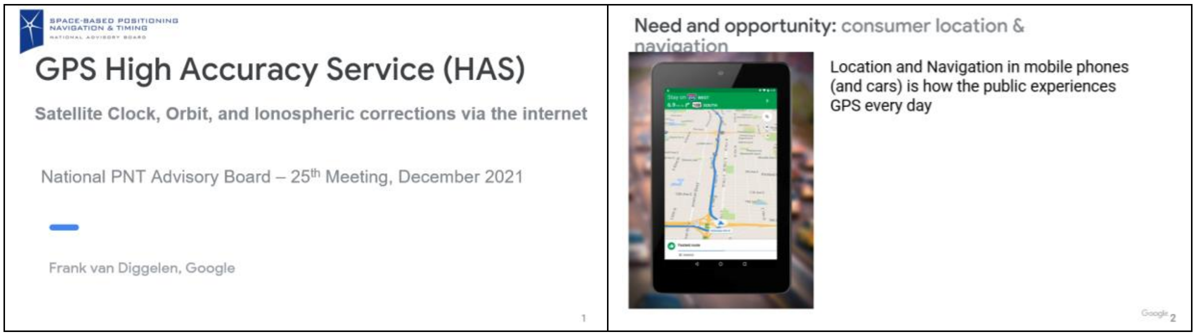
Gov. Geringer spoke to the value of taking initiative with GPS innovations rather than always being on the defensive and recalled Ms. Durkovich's comment that we cannot tolerate GPS as a single point of failure. He noted opposition to GPS from the FCC, the former Dep Sec of Defense, and Ligado. He referred to the video shared by Airgility on the previous day where a swarm of drones lost GPS and fell into instant failure mode rather than failing to safety. He recommended consideration of alternatives to GPS and ways to toughen and augment GPS services.

ADM Allen noted that this approach aligns with PTA objectives.

3) Proposal for a GPS High Accuracy Service Task Force

Dr. van Diggelen shared a brief presentation (Slide 1) on a proposed GPS HAS task force as a follow up to the GDGPS task force and yesterday's Galileo HAS discussions.

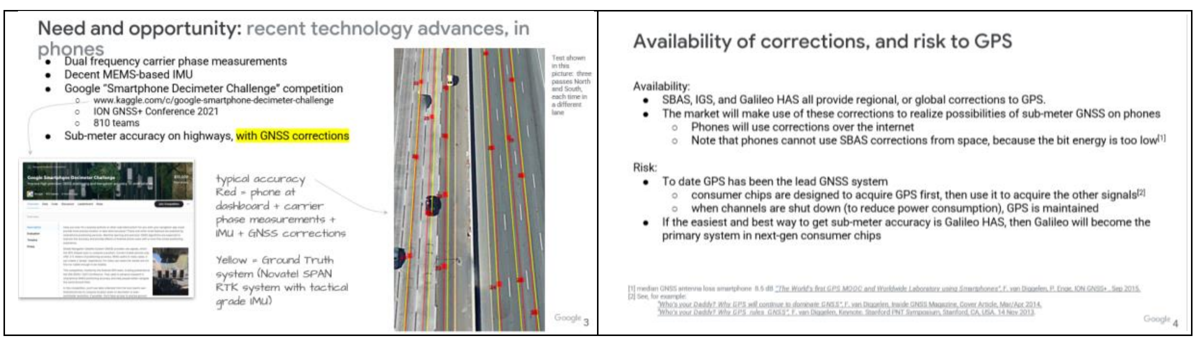
The primary use of GPS by consumers involves navigation and traffic monitoring on mobile phones (Slide 2).



Slides 1-2

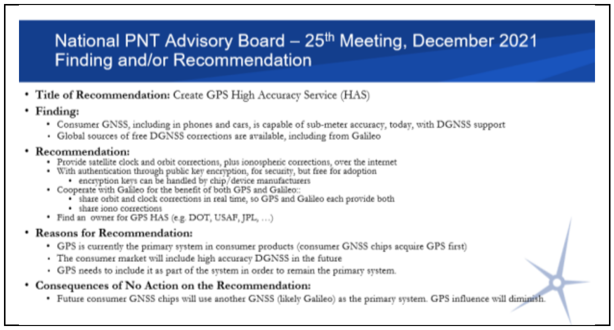
However, current traffic monitoring has limitations as it does not differentiate between lanes because smartphones and cars do not track GPS signals with sufficient accuracy (Slide 3). Recent technological advances in smartphones include dual frequency carrier phase measurements and better performing micro-electromechanical system (MEMS)-based IMU, which holds accurate location over a few seconds, allowing carrier phase positions to be stitched together even if obstructions like highway overpasses are encountered. Google recently hosted a "Smartphone Decimeter Challenge" with other 800 teams participating worldwide. Competing teams demonstrated sub-meter accuracy on highways using smartphones with GNSS corrections, as opposed to the more expensive real-time kinematic (RTK) systems. This technology would enable users to understand the traffic patterns in their immediate lanes within the next few years rather than waiting decades for new GPS satellites to be launched.

Dr. van Diggelen then reviewed potential objections to providing corrections, including the traditional argument that government should avoid competing with commercial companies (Slide 4). There is no private sector corrections service available globally, and current public sector corrections services include Satellite Based Augmentation System (SBAS), IGS, and Galileo HAS, as seen in the earlier presentation by Mr. Fernandez-Hernandez. The question is whether GPS will be at the forefront of these innovations or fade into obscurity as other systems take the lead. As an additional note, phones cannot use SBAS corrections from space because the bit energy is too low. If in the future, the easiest and best way to get sub-meter accuracy in phones is through using Galileo HAS, then Galileo will become the primary system in next generation consumer chips.



Slides 3-4

Dr. van Diggelen proposed a draft recommendation on the creation of a GPS High Accuracy Service, noting that Consumer GNSS, including in phones and cars, is capable of sub-meter accuracy today, with Differential GNSS (DGNSS) support. Global sources of free DGNSS corrections are available, including from Galileo (Slide 5). The recommendation is to provide a similar service through GPS with public key encryption for security, and to cooperate with Galileo for the benefit of both systems. The reasons for the recommendation are to keep GPS as the leading system and to maintain capabilities offered by other GNSS systems.



Slide 5

ADM Allen thanked Dr. van Diggelen for the presentation and emphasized its connections to conversations with Ms. Durkovich on GPS as the gold standard for GNSS and noted that this proposal may conflict with the recommendation going to the NASA Administrator regarding GDGPS.

Dr. Betz added that NASA and GDGPS are not the only way to provide differential corrections and proposed developing an independent task force to look at alternative implementations to guide discussions.

Dr. Parkinson added that this discussion is an example of the "I" of innovation spanning all three aspects of Position, Navigation, and Timing, and advocated for the development of a task force.

Dr. Axelrad asked whether this would look at global GNSS or GPS alone.

Dr. van Diggelen clarified that he was proposing High Accuracy Service as part of the GPS system itself. He noted that the primary use case would be consumers with devices like phones, cars, and watches that are already connected to the internet, and that this is an opportunity to enhance GPS without waiting 20 years for new satellites to be developed.

Gov. Geringer asked what the data rate would be for this service.

Dr. van Diggelen responded that the service would use very low data rates on top of existing internet connections.

Mr. Goward proposed developing a high-level recommendation for consideration and feedback from the government in conjunction with the creation of a task force.

ADM Allen asked the board to support the creation of a new task force on GPS High Accuracy Service and Dr. Parkinson concurred. ADM Allen appointed Dr. van Diggelen as chair of a task force on the GPS High Accuracy Service.

ADM Allen recommended a separate solicitation period for task force membership to balance participation following the conclusion of the meeting.

ADM Allen summarized that there will be an ad hoc GPS HAS committee, a PTA committee, and a Communications & External Affairs committee.

4) Other Recommendations

Mr. Miller opened the floor to members to review other recommendations before the board.

ADM Allen asked for a count of additional recommendations before deciding how to proceed.

Mr. Goward proposed the endorsement and recommendation of a resilient national timing architecture within the US, referring to two white papers from the RNT Foundation[4],[5] and a recommendation on timing in the 2018 PNTAB Topic Papers[6].

Mr. Shane had submitted a recommendation based on his earlier presentation, but suggested further time be taken to examine the issue before proceeding.

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[4] Dr. Marc Weiss, Dr. Patrick Diamond, Mr. Dana A. Goward. "A Resilient National Timing Architecture: Securing Today's Systems, Enabling Tomorrows." RNT Foundation. 16 October 2020. https://rntfnd.org/wp-content/uploads/Resilient-National-Timing-Architecture-16-Oct-2020.pdf

[5] Dr. Marc Weiss, Dr. Patrick Diamond, Mr. Dana A. Goward. "A Resilient National Timing Architecture – Now for an RFP." RNT Foundation. 12 October 2021. https://rntfnd.org/wp-content/uploads/A-Resilient-National-Timing-Architecture-Now-for-an-RFP.pdf

[6] National Space-Based Positioning, Navigation, and Timing (PNT) Advisory Board Topic Papers. September 2018. https://www.gps.gov/governance/advisory/recommendations/2018-09-topic-papers.pdf

ADM Allen proposed reviewing Mr. Shane's recommendation within a Communications & External Affairs subcommittee.

Mr. Goward added that he and Dr. Costa had put together a recommendation encouraging a formal partnership between GPS and Galileo, along the lines of what GLONASS and BeiDou are doing.

ADM Allen proposed incorporating recommendations into the follow-on sub-committee structure to address in that way.

Mr. Higgins added that there is already a high level of cooperation between the EU and the US on Galileo and GPS.

Dr. Betz concurred, adding that there was a 2004 agreement establishing working groups that meet regularly. He encouraged the group to consider that any future recommendation should propose additional levels of cooperation than what is being done already.

ADM Allen proposed a briefing by the State Department at the next PNTAB meeting.

Dr. Filjar added that there has been ongoing collaboration within the IGS and bilateral working groups. Dr. Filjar noted he also submitted a recommendation on the provision of a navigation message as a backup during the Internet Protocol (IP) streaming and suggested this also be considered by the GPS HAS task force.

ADM Allen concurred.

Mr. Murphy discussed his draft recommendation on eliminating export control barriers to toughening GNSS receivers. He suggested discussion within at subcommittee level and the creation of a small ad hoc group to develop a roadmap that could be shared with the EXCOM on how to proceed.

Mr. Miller noted that the board at this time was not in a position to vote and formalize these other recommendations, but rather develop groups that are interested in pursuing the topics further and set up a series of fact-finding meetings in preparation for the next EXCOM.

ADM Allen reviewed the process undertaken by the GDGPS task force, which included the development of a statement of work, instructions to partake in a series of fact-finding meetings, and the development of briefings which were shared with the full board for review and formal recommendation. He indicated this replicable process could be reused for the new groups under deliberation at the meeting.

Dr. Parkinson recommended Mr. Murphy to lead the group that will review export control barriers.

Mr. Higgins asked for clarification regarding study topics from the PNT EXCOM.

ADM Allen confirmed that the list of study topics is still under deliberation by PNT EXCOM departments/ agencies and will be sent to the board for review via email.

* * *

Wrap-Up
ADM Allen, *Chair, PNTAB* and Dr. Bradford Parkinson, *1st Vice Chair, PNTAB*

Gov. Geringer thanked Mr. Miller for putting together an excellent meeting and series of presentations, and he praised the contributions of the new members to the board. He suggested developing a timeline to consider how to be best prepared to brief the ESG and the PNT EXCOM. He acknowledged that the board may not have resources to accomplish all the topics suggested by the EXCOM and encouraged the board to consider what might be possible if resources did become available. He reiterated the importance of defining a timeline between the committees, the EXCOM and ESG meetings, and the next meeting of the PNT advisory board.

ADM Allen thanked Gov. Geringer for his comments. He confirmed that the board will proceed with the development of subcommittees and formulate a plan for how to engage the ESG and EXCOM moving forward.

Mr. Miller thanked Gov. Geringer for his comments. He added that it would be possible to hire contract support just as the board had done previously with the 2015 economic assessment of GPS[7,8], and that the NCO, DOT, and NASA would work together to ensure that the board has appropriate resources in place. He thanked Ms. Lesha Zvosec, Dr. A.J. Oria, and Ms. Ginny Randall for their support in organizing the PNTAB meeting. He proposed the next board meeting tentatively for the first week of June.

Dr. Powell added that the Joint Navigation Conference (JNC) may conflict with that date.

Dr. Filjar confirmed that the ICG will be held during the same time frame.

ADM Allen recommended offline deliberation of future meeting dates. He also asked the additional support staff to be recognized, and Amanda Allen and Kenyatta Haygood were also recognized for their contributions.

Mr. Miller thanked the board for their participation and affirmed the goal to commit to a regular meeting schedule moving forward.

ADM Allen ended by acknowledging the additional work to be done offline and thanked everyone for their participation.

* * *

ADM Allen adjourned the 25th session of the PNT Advisory Board at 11:49 a.m.

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7 Irv Leveson. The Economic Value of GPS: Preliminary Assessment. Briefing to National Positioning, Navigation, and Timing (PNT) Advisory Board on June 11, 2015: https://www.gps.gov/governance/advisory/meetings/2015-06/leveson.pdf

8 Irv Leveson. Value of GPS: Furthering the Analysis. Briefing to National Positioning, Navigation, and Timing (PNT) Advisory Board on Oct. 30, 2015: https://www.gps.gov/governance/advisory/meetings/2015-10/leveson.pdf

Appendix A: National Space-Based PNT Advisory Board Membership

Special Government Employees

SGE's are experts from industry or academia who temporarily receive federal employee status during Advisory Board meetings.

- Thad Allen (Chairman), former Commandant, U.S. Coast Guard
- John Stenbit (Deputy Chairman), former Assistant Secretary of Defense
- Bradford Parkinson (1st Vice Chair), Stanford University
- James E. Geringer (2nd Vice Chair), Environmental Systems Research Institute (ESRI)
- Penina Axelrad, University of Colorado
- John Betz, MITRE
- Scott Burgett, Garmin International
- Joseph D. Burns, The Airo Group
- Patrick Diamond, Diamond Consulting
- Dorota A. Grejner-Brzezinska, The Ohio State University
- Michael Hamel, Former Commander, Space and Missile Systems Center
- Larry James, Jet Propulsion Laboratory
- Vahid Madani, GridTology
- Jade Morton, University of Colorado
- Timothy A. Murphy, The Boeing Company
- Tom Powell, Aerospace Corporation
- Eileen Reilly, Global Train Services
- T. Russell Shields, RoadDB
- Gary Thompson, North Carolina Geodetic Survey
- Frank van Diggelen, Google
- Todd Walter, Stanford University
- Gregory D. Winfree, Texas A&M Technology Institute

Representatives:

Representatives are individuals designated to speak on behalf of particular interest groups.

- Sonia Maria Alves Costa, Brazilian Institute of Geography and Statistics (Brazil)
- Renato Filjar, University of Rijeka (Croatia)
- Dana Goward, Resilient Navigation and Timing Foundation
- J. David Grossman, Consumer Technology Association
- Matt Higgins, International GNSS Society (Australia)
- Terry Moore, University of Nottingham (UK)
- Jeffrey N. Shane, International Air Transportation Association

Executive Director

The membership of the Advisory Board is administered by a designated federal officer appointed by the NASA Administrator:

- James J. Miller, Executive Director

Subject Matter Experts

- Martin Faga, former CEO, The MITRE Corporation
- Kirk Lewis, Institute for Defense Analyses (IDA)

Appendix B: Sign-In Sheets

Note: In addition to the in-person attendees, there was a public livestream.

Thursday, December 9, 2021

Advisory Board Members – In Person:
Thad Allen
Penina Axelrad
John Betz
Scott Burgett
Joe Burns
Sonia Maria Alves Costa
Marty Faga
Renato Filjar
Dana Goward
J. David Grossman
Dorota Grejner-Brzezinska
Michael Hamel
Larry James
Vahid Madani
Terry Moore
Jade Morton
Tim Murphy
Brad Parkinson
Tom Powell
Eileen Reilly
Jeffrey Shane
Russ Shields
Greg Winfree

Advisory Board Members – Online:
Patrick Diamond
Frank van Diggelen
Jim Geringer
Matt Higgins
John Stenbit
Gary Thompson
Todd Walter

Invited Speakers/ Guests:
George Beebe, CFTNI
Bill Cotton, Cotton Aviation Enterprises
Bryan Chan, Xona
Caitlin Durkovich, NSC
Jim Farrell, SAE Int'l
Harold "Stormy" Martin, NCO
Pramod Raheja, Airgility
Logan Scott, LSC
Karen Van Dyke, DOT
Bill Woodward, SAE

NASA Personnel:
Barbara Adde, NASA SCaN
Frank Bauer, NASA
Chris Bonniksen, NASA
Al Feinberg, NASA SCaN
Stephen McKim, NASA GSFC
Pam Melroy, NASA
A.J. Oria, NASA
Joel Parker, NASA GSFC
Benjamin Phillips, NASA
Lisa Valencia, NASA SCaN
Badri Younes, NASA SCaN

Other Attendees:
Zeschram Ahmed, VIP Global Net
Huascar Ascarrunt, Frequency Electronics
Jeffrey Auerbach, State Department
Bing Blair, Bosch
Duke Buckner, Microchip
Steve Bradford, FAA
Jim Burton, NCO
Scott Calhoun, USCG NAVCEN
Kevin Cammie, USCG
Chris Cannazzaro, NSC
Dale Dalesio, CEC
Vince Dalessandro, L3Harris
Dee Ann Divis, Navigation Outlook
Jessica Du, GAO
TJ Eller, NCO
Rich Foster, Microchip
Yuka Gomi, Ygomi
Sarah Green, GAO
Valerie Green, Ligado
Rick Hamilton, US Coast Guard
Mark Hite, Echo Ridge/ Parsons
David Hillierd, Wiley Rein LLP
Charlene King, Satelles
Ajay Kothari, Astrox
Parateek Kumar, VIP Global Net
Rick Lee, iPosi Inc.
Bridge Littleton, Hellen Systems
Stephen Mackey, DOT/ Volpe Center
Jules McNeff, DoD CIO
Ed Powers, Aerospace
Sabrina Riddick, GAO
Joe Rolli, L3Harris
Jason Tama, NSC
Evandro Valente, Airgility Inc.
Ajay Vemuru, Spirent
Michael Vilaby, L3Harris
Hadi Wassaf, DOT/ Volpe
Susan Zimmerman, GAO

Friday, December 10, 2021

Attendees – Friday, December 10, 2021

Advisory Board Members
John Betz, PNTAB
Tom Powell, Aerospace
Sonia Costa, IBGE
Dana Goward, RNTF
Renato Filjar, Krapina University of Applied Sciences, Croatia
David Grossman, CTA
Penina Axelrad, CU Boulder

NASA Personnel
Chris Bonniksen, NASA
Al Feinberg, NASA ScaN
Lisa Valencia, NASA ScaN

Other Attendees:
Bing Blair, Bosch
Jim Burton, NCO
Charles Chue, UrsaNav
DeeAnn Divis, Navigation Outlook
TJ Eller, NCO
Jim Farrell, VIGIL
Yuka Gomi, Ygomi
David Hilliard, Wiley Rein
Charlene King, Satelles
Stephen Mackey, DOT/ Volpe
Sabrina Riddick, GAO
Karen Van Dyke, DOT
Ajay Vemuru, Spirent
Hadi Wassaf, DOT/ Volpe
Kirk Montgomery, Microchip

Appendix C: Acronyms & Definitions

$	U.S. Dollar Currency
2 SOPS	2nd Space Operations Squadron
4G	4th Generation Mobile Communications Standard
5G	5th Generation Mobile Communications Standard
911	Emergency telephone number in the U.S.
A/J	Anti-Jamming
AB	Advisory Board
ACAS	Assisted Commercial Authentication Service
ADM	Admiral
ADS-B	Automatic Dependent Surveillance-Broadcast
AFAL	Air Force Astronautics Laboratory
AFB	Air Force Base
AFRL	Air Force Research Lab
AFTS	Autonomous Flight Termination System
AI	Artificial Intelligence
AIS	Automated Information Systems
ANSI	American National Standards Institute
APA	Airline Pilots Association
ARAIM	Advanced Receiver Autonomous Integrity Monitoring
ASAT	Anti-Satellite
ASI	Italian Space Agency (Agenzia Spaziale Italiana)
ASIC	Application-Specific Integrated Circuit
ATC	Air Traffic Control
ATIS	Alliance for Telecommunications Industry Solutions
BeiDou	China's GNSS
bps	Bits per second
C/A	GPS Coarse Acquisition
C/N_0	Carrier to noise floor ratio
C-band	Operating frequency range 4-8 GHz in the radio spectrum
C3	Command Control Center
CAB	Civil Aeronautics Board
CDDIS	Coastal Dynamics Data Information system
CDR	Critical Design Review
CEO	Chief Executive Officer
CFO	Chief Financial Officer
CIA	Central Intelligence Agency
CIO	Chief Information Officer
CISA	Cybersecurity & Infrastructure Security Agency
CLPS	Commercial Lunar Payload Services
cm	Centimeter
CONOPS	Concept of Operations
COTS	Commercial Off the Shelf
COVID-19	Coronavirus Disease 2019
CRPA	Controlled Reception Pattern Antennas
CTA	Consumer Technology Association

dB	Decibel
dBW	Decibel-Watt
DEFIS	European Commission Defense Industry and Space
DF	Digital Flight
DFR	Digital Flight Rules
DFW	Dallas Fort Worth Airport
DGNSS	Differential GNSS
DHS	Department of Homeland Security
DME	Distance Measuring Equipment
DOC	Department of Commerce
DoD	Department of Defense
DoD CIO	Department of Defense Chief Information Officer
DOP	Dilution of Precision
DOS	Department of State
DOT	Department of Transportation
DSN	NASA Deep Space Network
E1	Galileo Open Service
E5	Galileo Safety-of-Life Service
E6	Galileo High Accuracy Service (formerly Commercial Service)
EC	European Commission
E.O.	Executive Order
eLoran	Enhanced Loran
EOP	Executive Office of the President
ESA	European Space Agency
ESG	National Space-Based PNT Executive Steering Group
EU	European Union
EUSPA	EU Agency for the Space Programme
EXCOM	National Space-Based PNT Executive Committee
FAA	Federal Aviation Administration
FACA	Federal Advisory Committee Act
FCC	Federal Communications Commission
FERC	Federal Energy Regulatory Commission
ft	Feet
FY	Fiscal Year (Oct.1 – Sep. 30)
g	Acceleration of gravity at sea level (9.81 m/s^2)
G2G	Galileo 2nd Generation
Galileo	European GNSS
GAO	Government Accountability Office
GDGPS	Global Differential GPS System
GEO	Geosynchronous Orbit
GGN	NASA’s Global GNSS Network
GHz	Gigahertz
GIS	Geographic Information Systems
GLONASS	Russian GNSS
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GPS III	Typically refers to GPS Block III SVs 1-10
GPS IIIF	GPS III Follow-On, which refers to GPS Block III SVs 11-32

GRACE-FO	Gravity Recovery and Climate Experiment Follow-On mission
GSS	Galileo Sensor Stations
HAS	High Accuracy Service
hr	Hour
HPE	Horizontal Position Error
Hz	Hertz
IATA	International Air Transport Association
ICD	Interface Control Document
IEEE	Institute of Electrical and Electronics Engineers
ICG	International Committee on GNSS
IGS	International GNSS Service
IFR	Instrument Flight Rules
IMC	Instrument Meteorological Conditions
IMU	Inertial Measurement Unit
INS	Inertial Navigation System
ION	Institute of Navigation
IoT	Internet of Things
IP	Internet Protocol
ISS	International Space Station
ITAR	U.S. International Traffic in Arms Regulations
ITRF	International Terrestrial Reference Frame
J/S	Jamming to Signal Ratio
JPL	Jet Propulsion Laboratory
JPO	GPS Joint Program Office
km	Kilometer
kW	Kilowatt
L1 C/A	1st GPS Civil Signal (C/A = coarse acquisition)
L1C	4th GPS Civil Signal (interoperable with Galileo)
L2C	2nd GPS Civil Signal (commercial)
L5	3rd GPS Civil Signal (safety-of-life / aviation)
L-band	Operating frequency range of 1–2 GHz in the radio spectrum
LaRC	NASA Langley Research Center
LCS	Launch and Checkout System
LEO	Low Earth Orbit
LIDAR	Light Detection and Ranging
LORAN	Long-Range Aid to Navigation
LRA	Laser Retro-reflector Array
LRR	Laser Retro-reflector
LunaNet	Lunar Internet (concept for Lunar Communications and Navigation Services on/ around the moon)
LuGRE	Lunar GNSS Receiver Experiment
m	Meter
M-Code	GPS encrypted signal
MEMS	Micro-electromechanical Systems
MEO	Medium Earth Orbit
MGUE	Military GPS User Equipment
MHz	Megahertz
min	Minute
ML	Machine Learning

MLS	Microwave Landing System
MMS	NASA's Magnetospheric Multi-Scale mission
MOPS	Minimum Operational Performance Standards
MOSA	Modular Open System Approach
MOU	Memorandum of Understanding
NASA	National Aeronautics and Space Administration
NASEM	National Academies of Science, Engineering, and Medicine
NATO	North Atlantic Treaty Organization
NAVWAR	Navigation Warfare
NCO	National Coordination Office for Space-Based PNT (hosted at Dept. of Commerce, Washington, D.C.)
NDAA	National Defense Authorization Act
NEC	National Economic Council
NERC	North American Electric Reliability Corporation
NIST	National Institute of Standards and Technology
NMA	Navigation Message Authentication
NSC	National Security Council
NSF	National Science Foundation
NSpC	National Space Council
NSTAC	National Security Telecommunications and Information Administration
NTIA	National Telecommunications and Information Administration
NTS-3	AFRL Navigation Technology Satellite 3
NYC	New York City
OCX	Next Generation Operational Control System
OEM	Original Equipment Manufacturer
OMB	Office of Management and Budget
OS	Open Service
OSNMA	Open Service Navigation Message Authentication
OTAR	Over-the-Air Rekeying
PNT	Positioning, Navigation, and Timing
PNTAB	PNT Advisory Board
PPP	Precise Point Positioning
PTA	Protect, Toughen, and Augment
PTC	Positive Train Control
PVT	Position, Velocity, and Timing
R	Radius
R&D	Research and Development
RETAIN	Recognizing and Ensuring Taxpayer Access to Infrastructure Necessary
RF	Radio Frequency
RFI	Radio Frequency Interference
RFP	Request for Proposals
RMS	Root Mean Squared
RNP	Required Navigation Performance
RNT	Resilient Navigation and Timing
RSS	Root sum squared
RTCA	RTCA, Inc., formerly named the Radio Technical Commission for Aeronautics.
RTCM	Radio Technical Commission for Maritime Services
RTK	Real-Time Kinematic
S&T	Science and Technology

SAE	SAE International, formerly named the Society of Automotive Engineers
SAR	Search and Rescue
SBAS	Satellite-Based Augmentation System
SCaN	Space Communications and Navigation Program (NASA)
SDR	Software Defined Radios
SGE	Special Government Employee
SLR	Satellite Laser Ranging
SMC	Space & Missile Systems Center
SME	Subject Matter Expert
SOL	Safety-of-Life
SPD-7	Space Policy Directive 7 for U.S. Space-Based PNT
SSC	USSF Space Systems Command
SSV	Space Service Volume
SUSG	ICG WG-B Space Use Sub-Group
SV	Space Vehicle (formerly referred to as Satellite Vehicles)
TCAS	Traffic Collision Avoidance Systems
TF	Task Force
TFM	Traffic Flow Management
TIM	Technical Interchange Meeting
TTI	Texas A&M Transportation Institute
UAG	Users' Advisory Group (National Space Council)
UAS	Unmanned Aircraft System
UAV	Unmanned Aerial Vehicle
ULS	Uplink Stations
UN	United Nations
UPS	United Parcel Service
URE	User Range Error
US	United States of America
USAF	U.S. Air Force
USCG	U.S. Coast Guard
USSF	U.S. Space Force
UTC	Coordinated Universal Time
V2X	Vehicle-to-Everything
VFR	Visual Flight Rules
VLBA	Very Long Baseline Array
VOR	VHF Omni-directional Range
VPE	Vertical Position Error
W	Watt
WG	Working Group
WH	White House
WWI	World War I
WWII	World War II