SPACE-BASED POSITIONING
NAVIGATION & TIMING
NATIONAL ADVISORY BOARD

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

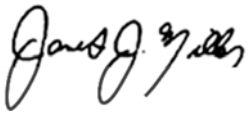
## Twenty-Third Meeting

## June 6-7, 2019

**The Westin Old Town Alexandria**

**Alexandria, VA**

ADM Thad Allen, *Chair*



Mr. James J. Miller, *Executive Director*

SPACE-BASED POSITIONING NAVIGATION & TIMING
NATIONAL ADVISORY BOARD

# 23rd Meeting
# June 6-7, 2019

The Westin Alexandria Old Town, Edison D Room
400 Courthouse Square, Alexandria, VA 22314

## Agenda

**THURSDAY, JUNE 6, 2019**

| | | |
|---|---|---|
| 8:30 - 8:40 | **BOARD CONVENES**<br>*Call to Order, Logistics, & Announcements* | Mr. James J. Miller, Executive Director, *PNT Advisory Board, NASA Headquarters* |
| 8:40 - 9:00 | Welcome & Kick-Off of 23rd PNTAB Meeting:<br>*Intro of New Chair & Members for 2019-2021* | ADM Allen, *Chair,* Dr. Bradford Parkinson, *1st Vice-Chair,* Gov Jim Geringer, *2nd Vice-Chair* |
| 9:00 - 9:25 | 23rd PNTAB Focus and Priorities:<br>*Update on Protect, Toughen, Augment (PTA) Initiatives*<br>***VIEW PDF (2 MB)*** | ADM Allen, *Chair,* Dr. Bradford Parkinson, *1st Vice-Chair,* Gov Jim Geringer, *2nd Vice-Chair* |
| 9:25 - 9:40 | Opening Remarks: National Space Council (NSpC) Perspective *- PNT Policy Update Plans*<br>***VIEW PDF (712 KB)*** | Col Curtis 'Scraps' Hernandez, *Director, National Security Space Policy, NSpC* |
| 9:40 - 10:05 | GPS Program Status & Modernization Milestones: *IIIF, OCX, & Emerging Capabilities for Users*<br>***VIEW PDF (2 MB)*** | Maj Dave Sampayan, *GPS Directorate (GPS-D), Space & Missile Systems Center (SMC)* |
| 10:05 - 10:25 | Initial Approach on the GPS Space Service Volume (SSV)<br>***VIEW PDF (952 KB)*** | Mr. Robert Wright, *Principal Engineer, Lockheed Martin* |
| 10:25 - 10:50 | Global Navigation Satellite Systems - *What's Up?*<br>***VIEW PDF (1 MB)*** | Dr. Oliver Montenbruck, *Head, GNSS Tech & Nav Group, German Aerospace Center (DLR)* |
| 10:50 - 11:00 | **BREAK** | |
| 11:00 - 11:15 | Update on Dept. of Transportation (DOT) Equities:<br>*Ensuring Safety for all Modes of Transportation & Civil PNT*<br>***VIEW PDF (962 KB)*** | Ms. Karen Van Dyke, *Director, Positioning, Navigation, and Timing (PNT) & Spectrum, DOT* |
| 11:15 - 11:40 | Economic Studies of GPS and the National Geodetic Survey (NGS) Gravity Program: *Spectrum Regulatory Stability Needed*<br>***VIEW PDF (773 KB)*** | Dr. Irving Leveson, *Founder, Leveson Consulting* |

| | | |
|---|---|---|
| 11:40 - 12:05 | General Motors use of Precise GNSS and V2X for Automated Vehicles<br>*VIEW PDF (798 KB)* ➡ | Mr. Curtis Hay, *Technical Fellow, GNSS, V2X and Maps, General Motors* |
| 12:05 - 12:30 | Use of GPS in Positive Train Control (PTC) Implementation: *Federal Railroad Administration (FRA) Perspective*<br>*VIEW PDF (2 MB)* ➡ | Ms. Carolyn Hayward-Williams, *Director of Technical Oversight, Office of Safety, FRA* |
| 12:30 - 1:45 | **LUNCH** - (working - Annual Ethics Briefing) | Mr. Adam F. Greenstone, *NASA Ethics Counsel* |
| 1:45 - 2:00 | Concise Update on Dept. of Homeland (DHS) Security Priorities: *PNT Resilience — Identify & Mitigate Vulnerabilities*<br>*VIEW PDF (1 MB)* ➡ | Mr. James (Jim) Platt, *Director, PNT Office, DHS* |
| 2:00 - 2:25 | Proposed PNT Threat Environment Model for Military and Civilian Use<br>*VIEW PDF (1 MB)* ➡ | Mr. Mark Johnson, *Assured PNT Campaign Lead, Collins Aerospace* |
| 2:25 - 2:50 | GNSS Radio Frequency Interference Detection from LEO *Results & Lessons Learned for Future Deployments*<br>*VIEW PDF (3 MB)* ➡ | Dr. Todd Humphreys, *Associate Professor, Aerospace Engineering, Univ. of Texas at Austin* |
| 2:50 - 3:15 | The Role of Civil Signal Authentication in Trustable Systems<br>*VIEW PDF (6 MB)* ➡ | Mr. Logan Scott, *Logan Scott Consulting* |
| 3:15 - 3:40 | Proposed Guidelines for Resilient PNT Receivers<br>*VIEW PDF (2 MB)* ➡ | Mr. William Woodward, *Chairman, SAE PNT Technical Committee* |
| 3:40 - 3:55 | **BREAK** | |
| 3:55 - 4:20 | DARPA Positioning, Navigation, and Timing Technology and their Impacts on GPS users<br>*VIEW PDF (3 MB)* ➡ | Dr. John Burke, *Program Manager, Microsystems Technology Office, DARPA* |
| 4:20 - 4:55 | Non-Inertial Navigation in the 21st Century and Beyond<br>*VIEW PDF (2 MB)* ➡ | Dr. Val Parker, *President, Non-Inertial Navigation Technology, LLC* |
| 4:55 - 5:20 | Research on GPS Resiliency and Spoofing Mitigation Techniques across Applications<br>*VIEW PDF (5 MB)* ➡ | Mr. Yoav Zangvil, *Co-Founder and Chief Technology Officer, Regulus Cyber* |
| 5:20 - 5:30 | Brief Update on Newly Launched Congressional GPS Caucus and Other Educational Efforts<br>*VIEW PDF (761 KB)* ➡ | Mr. J. David Grossman, *Executive Director, GPS Innovation Alliance* |
| 5:30 | **ADJOURNMENT** | |

*RETURN TO TOP OF PAGE*

**FRIDAY, JUNE 7, 2019**

| | | |
|---|---|---|
| 9:00 - 9:05 | **BOARD CONVENES**<br>*Call to Order* | Mr. James J. Miller, *Executive Director, PNT Advisory Board, NASA Headquarters* |
| 9:05 - 9:45 | **Concise Observations from New Members:** | |
| | ▪ Dr. Pat Diamond<br>▪ Dr. Frank van Diggelen<br>▪ Dr. Dorota A. Grejner-Brzezinska<br>▪ Dr. Terry Moore | ADM Allen, *Chair,* Dr. Bradford Parkinson, *1st Vice-Chair,* Gov Jim Geringer, *2nd Vice-Chair* |

| | | |
|---|---|---|
| | ▪ Hon. Jeffrey N. Shane<br>▪ Mr. Gary W. Thompson<br>▪ Dr. Todd Walter | |
| 9:45 - 10:00 | Concise Update on Dept. of State (DOS) International Engagements: *Bilats & International Committee on GNSS (ICG)*<br>***VIEW PDF (715 KB)*** | Mr. David Turner, *Deputy Director, Office of Space & Advanced Technology (SAT), DOS* |
| 10:00 - 10:15 | Radio Equipment Directive (RED) Implementation Update<br>***VIEW PDF (726 KB)*** | Ms. Ann Ciganer, *GPS Innovation Alliance* |
| 10:15 - 11:05 | **Additional Representatives / International Perspectives:** | |
| | ▪ Dr. Gerhard Beutler *(Switzerland)*<br>***VIEW PDF (3 MB)***<br>▪ Dr. Sergio Camacho-Lara *(Mexico)*<br>***VIEW PDF (806 KB)***<br>▪ Mr. Matt Higgins *(Australia)*<br>▪ Dr. Refaat M. Rashad *(Egypt)*<br>▪ Mr. Dana Goward *(Resilient Navigation and Timing Foundation)*<br>***VIEW PDF (806 KB)*** | ADM Allen, *Chair,* Dr. Bradford Parkinson, *1st Vice-Chair,* Gov Jim Geringer, *2nd Vice-Chair* |
| 11:05 - 12:00 | **Roundtable Discussion -- Recommendation Formulation** | |
| | ▪ Working Group Organization -- 2019-2021 Work Plan Schedule<br>▪ Next Meeting Nov 20-21, Cocoa Beach, FL, with site visit to Kennedy Space Center (KSC) | All members, led by Chairs |
| 12:00 - 1:00 | **LUNCH** — *Working as needed* | |
| 1:00 | **ADJOURNMENT** | |

*RETURN TO TOP OF PAGE*

Dates and times are as originally scheduled and do not reflect actual presentation times. The Advisory Board also heard the following presentation that was not on the agenda:

- **Drone Dependence on GPS**
  Captain Joe Burns, *CEO, Airo Group*
  ***VIEW PDF (772 KB)***

# Table of Contents

# Executive Summary

The 23rd session of the National Space-Based Positioning, Navigation, and Timing (PNT) Advisory Board met on June 6-7, 2019, in Alexandria, Virginia. The main objectives of this session were to hear and discuss expert reports and to plan the Advisory Board's future actions. This document summarizes the key briefing points and discussions at the meeting.

**High-Level Action Items:**

- ADM Allen said the Advisory Board had been preoccupied with the "tyranny of the present." The board needs to look to the larger world circumstance. He presented a tentative list of topics that comprised the Advisory Board's immediate work. This list includes: What is meant by the Gold Standard? L5 signal availability, Space Service Volume, and the Global Positioning System (GPS) launch schedule. This list will be emailed to Advisory Board members for comments and additions, who should reply to Mr. Miller to consolidate the responses. A telecon may be held prior to the next Advisory Board session.
- On the topic of 5G, ADM Allen hoped that White Papers that have been prepared will evolve into a permanent government structure to help identify in which areas subject matter experts need to be brought in.
- Mr. Pat Diamond volunteered for the telecom and finance segments as a matter of record.
- Mr. Goward volunteered to present a short report on what is meant by Gold Standard.
- Mr. Murphy volunteered to present a short report on issues that make it more difficult to toughen receivers, such as export controls.
- Dr. Moore noted the lack of diversity on the Advisory Board and urged this to be addressed. Mr. Miller urged that member agencies be pressed to make diversity a much higher priority in future nominations. ADM Allen noted that this could be directed as well to any subgroups that support the Advisory Council.
- Mr. Shane said clarity was needed on what policy issues the Advisory Board currently faces and needs to address for the Executive Committee (EXCOM).
- Multiple Advisory Board members sought an earlier delivery of the presentation charts and/or a reduced number of presentations with more time available for discussion.
- ADM Allen urged the Advisory Board to proceed with the topic of threat assessment, as no single government agency appears to be tasked with the matter.
- [Post-Meeting: Mr. Shane volunteered to produce white paper from International Air Transport Association (IATA) on the importance of stable and reliable GNSS to the commercial aviation sector.]

**Other Action Items:**

- ADM Allen suggested a demonstration on the timing project be presented at the next Advisory Board meeting. He suggested that Mr. Platt and Ms. Van Dyke collaborate.
- ADM Allen suggested an update on the Space Service Volume be made at some future meeting.
- ADM Allen urged the Advisory Board to receive an update on the key points of geodesy at each meeting.
- Dr. van Diggelen urged that, regarding backup studies, user robustness should balance both the system and user devices.
- Dr. Parkinson urged placing on a forthcoming agenda the question of how the isolex requirement might act as a constraint on the ability to expand the bandwidth that served the earth.
- Lt Gen Thompson said he would report back on whether the Department of Defense (DoD) has any plans to expedite the incorporation of the Wide Area Augmentation System (WAAS).
- Dr. Grejner-Brzezinska urged that as "smart" technologies are developing rapidly, the Advisory Board might wish to devote more attention to such efforts.
- Dr. Grejner-Brzezinska noted that U.S. education programs in geodetic science are weakening and the Advisory Board might wish to make recommendations.
- Mr. Thompson urged the Advisory Board to have a presentation on the 2022 change of data that would affect all geodetic equipment users.
- Dr. Camacho-Lara urged the Advisory Board to receive a regular update on GNSS issues at the United Nations (UN).

- Mr. Goward suggested Advisory Board members arrive at each meeting with a list of the outcomes they would like to see, with this discussed at the session. This could lead to decisions on what matters are to go forward as action items.
- Dr. Rashad urged Advisory Board support for undergraduate PNT programs.
- Mr. Hatch suggested a list be created on spoofing and jamming, including what the difficult and simple problems are to address, how they could be addressed and by whom.

# Session of Thursday, June 6, 2019

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

**Welcome & Kick-Off of 23rd PNTAB Meeting**
Introduction of New Chair & Members for 2019-2021
ADM Allen, *Chair*, Dr. Bradford Parkinson, *1st Vice-Chair*; Gov. Jim Geringer, *2nd Vice-Chair*

ADM Thad Allen, Chair, welcomed everybody to the 23rd meeting of the National Space-Based PNT Advisory Board. He particularly thanked those who traveled a significant distance. ADM Allen also called attention to the commemorative proceedings taking place on this day, June 6, for the 75th anniversary of the allied landings in Normandy, France, in 1944.

James J. Miller, Executive Director, stated his pleasure at having ADM Allen as the new chair. He noted the Advisory Board's charter for 2019-2021 was signed on May 3. Mr. John Stenbit, who remains as Deputy Chair, is unable to attend this meeting. Mr. Miller also expressed his appreciation that Lt Gen David Thompson (Commander, U.S. Air Force Space Command) is attending.

Mr. Phil Liebrecht, Assistant Deputy Associate Administrator for Space Communications and Navigation (SCaN), noted that tasks throughout National Aeronautics and Space Administration (NASA) are typically accomplished through partnerships, in particular with the U.S. Air Force. He then presented Lt Gen Thompson with a montage commemorating his support for NASA's efforts to improve GPS.

Lt Gen Thompson appreciated the gesture and noted it should be shared with thousands of Air Force personnel also engaged in the effort.

Mr. Miller reminded all present that the Advisory Board was established by Presidential policy with the intent to provide independent counsel and advice to the PNT EXCOM. Meetings are governed by the Federal Advisory Committee Act (FACA). The meeting is open to the public, comments are on the record, and formal minutes will be posted on https://www.gps.gov/governance/advisory/ within 90 days. Members are nominated by the PNT EXCOM member agencies and appointed by the NASA Administrator. All members serve as volunteers. Special Government Employee members must abide by established ethics laws. If any member feels there is a conflict of interest then at that point they should recuse themselves from the discussion and the recusal noted in the minutes.

Dr. Brad Parkinson, 1st Vice-Chair noted that the Advisory Board is unique in that while it was established by the U.S. government it also includes a significant complement of international members. He commended Mr. Miller for his efforts in getting the new charter approved. He added that the Advisory Board's basic purpose is to preserve GPS for both current and all possible future uses. This effort has focused on the Protect, Toughen, and Augment (PTA) program: Protect the radio spectrum, Toughen GPS receivers, and Augment with additional resources and techniques. These objectives are supported through transparency, written performance commitments, and monitoring to ensure users are aware of the system's reliability. The Advisory Board urges other Global Navigation Satellite Systems (GNSS) to do likewise. At present, GNSS has 3 billion users worldwide. The economic value of GNSS has been estimated from $60 billion to $2 trillion, annually. However, as the GPS signal is inherently weak, its protection is paramount. Dr. Parkinson also expressed a deep regard for former members, the late Dr. Per Enge and for Ms. Ruth Neilan and other departing members. He noted the Advisory Board's new members for 2019-2021:

- Dr. Pat Diamond, Principal, Diamond Consulting
- Dr. Frank van Diggelen, Principal software engineer, Google
- Dr. Dorota A. Grejner-Brzezinska, Associate Dean for Research, The Ohio State University
- Dr. Terry Moore, Director, Nottingham Geospatial Institute, United Kingdom
- Mr. Jeffrey N. Shane, general counsel, IATA
- Mr. Gary W. Thompson, Chief, North Carolina Geodetic Survey
- Dr. Todd Walter, Director, Wide-Area Differential GNSS Lab, Stanford University

Dr. Parkinson added that the new members spanned the world of GPS applications. The Advisory Board's charter also allows the appointment of subject matter experts, of which two have been newly appointed: Mr. Martin Faga and Mr. Brian Ramsey, both of which have for many years worked with the Advisory Board.

* * *

**Discussion on GPS Adjacent Band Compatibility**
Dr. Bradford Parkinson, *1st Vice-Chair*

*[Advisory Board member recusals from this topic: Capt. Joe Burns, Ms. Ann Ciganer, Mr. Tim Murphy, Dr. John Betz, Mr. Ronald Hatch, and Mr. Scott Burgett].*

Dr. Parkinson restated the vital status of the GPS system. He presented background on an eight-year old issue, where a private operator licensed for satellite-to-ground communications and ancillary terrestrial communications saw an opportunity to modify its license to primarily high power terrestrial transmissions for broadband. This would, of course, significantly raise its value. The Advisory Board learned of this action, realized it would greatly threaten the GPS signal, and took steps to slow such approval. More recently, a successor to the company is proposing using transmitters at lower power level (9.8 W) with unknown tower spacing, but probably very close spacing (100 to 300 meters). As shown by extensive Department of Transportation (DOT) testing, even at this lower power over half of high precision GPS receivers would still be degraded over more than 10% of their operating region. Such high precision uses includes aviation, precision agriculture, robotics, weather probes, survey and mapping, and others. This puts rapidly expanding uses, such as Remotely Piloted Vehicles (RPV) and Unmanned Aerial Vehicles (UAV) at risk. The Advisory Board remains in strong disapproval of the proposal for modifying the license. Such power level also violates the 1 dB noise floor limit international standard. To avoid even a 10% signal degradation tower spacing would have to be six times the degradation radius. High precision receivers begin to degrade at 3,400 meters from a 10 W transmitter and typically lose accuracy at 500 meters distance (complete loss of the GPS signal can occur at 170 meters). If one assumes a 10 W transmitter, then a 12 mile spacing is needed to ensure high-performance receivers remain unaffected. Therefore, such transmitters are clearly incompatible with high precision receivers. Moreover, wireless radiation from a 5G network would be 30 times stronger compared to 4G. Therefore, unless the proposed power level is reduced tremendously, valuable high precision receivers are seriously affected. Dr. Parkinson presented information on how other classes of GPS receivers would be affected.

Dr. Parkinson noted that the Federal Communications Commission (FCC) in November 2018 approved use of the Galileo E1 and E5 signals (but not the E6 signal) in the U.S. Users of these signals would also be affected by the strong terrestrial broadband transmissions.

Dr. Parkinson closed by presenting a partial list of organizations that have gone on record as being opposed to the proposal for license modification. Further analysis of the implications from 5G has strengthened the Advisory Board's opposition. The proposal conflicts with the January 2012 PNT EXCOM goal to protect "existing and evolving uses of space-based PNT services."

Dr. Parkinson expressed his wish that this topic is finally closed.

* * *

**Opening Remarks: National Space (NSpC) Perspective**
*PNT Policy Update Plans*
Col Curtis Hernandez, *Director*
*National Space Council*

Col Curtis Hernandez said he would address the on-going rewrite of the 2004 PNT Policy. While the policy has been highly successful, a revision is necessary to capture subsequent growth and apply the proper definitions to support future growth. The U.S. has over 350 million GPS-dependent mobile phones. GPS has also helped cut product delivery time from two weeks to "same or next-day" delivery. GPS applications for space users have also increased, including Autonomous Flight Termination System (AFTS), on-orbit autonomous navigation, and improved capabilities for applications such as weather satellites resulting in quicker and more accurate forecasts. Along with the increase in use of GPS there is also an issue of how much the U.S. critical infrastructure relies on it and the risks posed by GPS cybersecurity. Another issue is the need for a PNT backup. The 2004 policy called for such a backup, but since then it has become apparent that because GPS use is so diverse, it is likely that multiple backups is the best course to follow. Finally, all these issues are directed through governance. Whether the governance model established in 2004 remains suitable for present and future needs is an open question.

ADM Allen thanked Col Hernandez for raising the topic of governance. The Advisory Board represents a large user community and in his view, the circuitous path by which information reaches the PNT EXCOM, then the FCC, and finally Congress appears to be broken.

Mr. Goward said the present policy has been very successful in supporting the applications being served, but the execution of policy has not been as efficient. No progress has been made on a backup system. In fact, enforcement against malicious interference is now worse than in 2004. Little has been achieved to define what constitutes a resilient, toughened receiver. This needs to be known, so that people that make purchasing decisions are correctly guided.

Gov. Geringer suggested that Col Hernandez might also want to consider emerging trends and applications. If regulation is based on the past, then many valuable potential applications may be overlooked.

Col Hernandez said language that could paint things into a corner must indeed be avoided.

Mr. Shane echoed the Chair's comments on governance. When the Department of Transportation awards an international route to a domestic or foreign carrier, that decision does not become final until it has been approved by the President, because of its potential implications for oreign relations or the national defense. In PNT many decisions are being made, in effect, below the radar screen, even though those decisions carry similar international implications. Why aren't spectrum decisions deemed important enough to warrant similar Presidential review?

Dr. Betz observed that the 2004 PNT Policy references "backup capabilities" – plural. He doubts any single alternative to PNT can be equally broad-based in its application. A user's robustness depends not merely on the system, but also on the user device. How, at the policy level, can a balance between these two be established?

Col Hernandez said that he does not know at present. There is a need to create language that both educates and informs the user community.

Dr. van Diggelen urged that contacts be made beyond the usual stakeholders, to include manufacturers and users in order to gain better understanding of any unintended consequences of any decision.

Mr. Shields said he appreciates the attention being paid to future applications and asked what is being done about autonomous driving and GPS's critical role in that area.

Col Hernandez said his perspective is to acknowledge potential uses. In working on the revision, the focus is to move things along. Attention needs to be paid to avoiding actions that could compromise future applications.

ADM Allen added that he believes autonomous transportation is extremely complex, due to spectrum issues and communication between vehicles.

Mr. Higgins said user expectation of precise positioning is rising. In 10 to 15 years, 0.2-meter accuracy may be expected by everyone. Awareness is needed so that technological progress does not come to a halt.

* * *

**GPS Program Status and Modernization Milestones:**
*IIIF, OCX, & Emerging Capabilities of Users*
Maj Dave Sampayan, GPS Directorate *(GPS-D)*
*Space and Missile Systems Center (SMC)*

Gen David Thompson made some opening remarks. He regards input from the Advisory Board as vital and noted that GPS is provided to support of a host of activities beyond military applications. GPS is considered by the U.S Air Force as a kind of sacred undertaking. In his view the program remains strong. Progress has been continuous since GPS reached full operational capability (FOC) in 1995.

Maj Sampayan presented an overview of the current GPS system. The average age of the GPS IIA satellites is 25.5 years, which is also a testament to their reliability. He then addressed GPS modernization – in the space, ground, and user segments. In space, he noted the transition from GPS blocks II to III. Regarding the ground segment, he focused on the transition from the current Operational Control Segment (OCS) to OCX, the modernized operational control segment, with the use of a bridge system between the two. User segments will be updated to allow for the use of additional signals.

Maj Sampayan then presented the GPS Enterprise Roadmap. He described the features of the GPS III satellites -- increased accuracy and power, inherent signal integrity, incorporation of the new L1C signal, and a longer 15-year design life. GPS III Satellite Vehicle (SV) 01 was launched on December 23, 2018 and at this time is undergoing on-orbit check out. SV01 should be added to mission operations in early 2020. SV02 is in preparation for launch with July 25, 2019 as the target date. SV03 will reach "ready for launch" status this summer, and SV04 in the late summer. Six additional satellites are in various phases of production. Contracts have been awarded for SV11-16, with the goal of incorporating the lessons learned from earlier satellites.

OCX is currently completing launch and checkout for GPS III SV01, and preparing to support SV02 launch. The OCX Block 1/2 development continues to meet its milestones and should transition into operation by the second quarter, 2022. He called attention to its modernized and agile architecture.

Maj Sampayan then reported on the GPS Week Rollover Event, which on April 6, 2019 reset the GPS week number from 1023 to zero. The GPS constellation signal itself was unaffected by the reset. Multiple reports have been received of civilian receiver malfunctions, including in Australian weather balloons, NOAA outages, and grounded Boeing aircraft. The root of these problems has been determined to be non- Interface Control Document (ICD) compliant GPS receivers.

In conclusion, GPS continues to build itself as Global Utility. GPS is the Gold Standard; it remains committed to uninterrupted service and to maintaining and developing domestic and international partnerships.

Gov. Geringer noted that China is placing two or three satellites into orbit with each launch. If everything goes well, could China soon be in a position to claim that BeiDou is the Gold Standard?

Lt Gen Thompson said the challenge is two-fold. The Air Force would love to speed up satellite development; however, budget realities have to be acknowledged. Regardless, the GPS's level of service continues to increase.

Mr. Shields said Gov. Geringer's comment is highly pertinent. GLONASS is simply not in the same class as GPS and Galileo has experienced various holdups. However, BeiDou – mostly because of the speed at which they were putting satellites into orbit – is gaining on GPS. It is possible that by the mid-2020s the position of GPS may look very different.

Mr. Goward said that Gold Standard is not just a reference to the quality of the signal, but also the ground-based infrastructure. Gold Standard encompasses all PNT, not just its space-based aspects.

Dr. Betz said no firm definition of "Gold Standard" has ever been made. The Advisory Board may wish to provide advice on the matter. GPS has also been made great by what has been provided by third parties. Therefore, the Advisory Board should look at the expectations for the future involvement of such third parties.

Dr. Parkinson re-offered his earlier suggestion that dual or triple satellite launches would save enormously on costs. He noted that at one time multiple launches had been intended for GPS.

Mr. Shane reported that Iridium has been replacing its satellites, and in January 2019 sent up ten satellites in a single launch.

* * *

**Initial Approach on the GPS Space Service Volume (SSV)**
Mr. Robert Wright, *Principal Engineer*
*Lockheed Martin*

Mr. Robert Wright said he would discuss his understanding of SSV requirements as well as current studies and challenges faced. Missions in high earth orbit (HEO) and geosynchronous orbit (GEO) use GPS signals to improve orbit determination. The current performance of GPS within the SSV exceeds minimum requirements by a considerable margin. GPS use within the SSV also improves satellite real-time navigation performance and reduces complexity and cost of the on-board clock.

Dr. Parkinson noted that the most sensitive class of receivers are engaged in this effort.

Mr. Wright noted that GPS III will have similar SSV performance characteristics compared to GPS II, thereby satisfying user needs. He then presented a chart showing nadir (30 degree) and zenith (85 degree) access to GPS at GEO.

Mr. Lewis asked why the GPS L5 signal was not depicted on the chart.

Mr. Wright said that GPS space users for the most part mostly rely on L1.

Dr. Betz said this is a "chicken and egg" situation. It may be simpler from a requirements perspective to focus on a single signal in space where the ionosphere is not an issue, in which case L5 is the best signal to focus on.

Mr. Miller noted that Frank Bauer, while at NASA, pioneered the SSV concept. Mr. Miller also noted that there is indeed much interest in L5 among international GNSS partners, specifically Galileo.

Mr. Wright said this is a good point, so there will be a reevaluation of the SSV requirements at GEO to include L5. The SSV requirements include received signal strength, four SV availability, maximum outage time (the length of time during which four satellites are not in view), signal-in-space (SIS) user range error (URE) accuracy, geometric dilution of precision (GDOP), and whether civil and/or military signals are used. He noted the major focus of his briefing is the GPS signal main lobe. There are two key additional considerations: (1) spurious transmissions and (2) the relative power across the Earth. There is a 2 dB decrease in

the power level from Earth to nadir. This needs to be worked into the antenna requirements. Mr. Wright also presented a video showing how GPS signals would proceed beyond the edge of the earth. In response to a query, he noted 27 GPS satellites are represented in the video.

Mr. Higgins asked whether Mr. Wright anticipates a reduction in power back to the earth if a zenith antenna were used.

Mr. Wright said the power level has to be maintained, unreduced. He noted that the zenith antenna is small, only using 8-9 Watts.

Dr. Alexrad asked how many users would be supported by the zenith antenna. She thought some people believe a side transmission is preferable to a zenith transmission.

Mr. Wright noted zenith is preferable for extending coverage. At the same time, the zenith antenna presents several challenges. First, if the signal is facing aft then it is more difficult to monitor from earth. The second challenge is the 40 dB requirement regarding spurious transmissions, as it would require a doubling of the PRN count.

ADM Allen complimented the clarity of the visual.

After these questions, Mr. Wright continued with his briefing and discussed constellation modeling.

Dr. Parkinson asked if Mr. Wright has had exchanges with staff at the NASA Goddard Space Flight Center, who have extensive experience in this area.

Mr. Wright said he has and there is now an effort to also involve the user community.

Dr. Parkinson urged him to take advantage of everything that is being done, to save both time and money. He added that Mr. Frank Bauer is the leading expert.

After these questions, Mr. Wright continued with the briefing. He said the highest priority is not to downgrade any existing capability. The full plan is as follows: (1) Update the constellation models; (2) Assess system requirements and lower level requirements (e.g. antenna beam width); (3) Review antenna alternative possibilities (Nadir and Zenith); (4) Recommend requirements and designs, likely by this fall; (5) Down select recommended design; (6) Build prototype antenna; and (7) Complete the insertion plan and SV-13 design.

Dr. Parkinson expressed pleasure with the effort. He added that because NASA has demonstrated the ability to receive extremely faint signals, this might allow some relaxation of the requirements Mr. Wright faces.

Mr. Shane asked if Mr. Wright's team has been working with the Jet Propulsion Laboratory.

Mr. Wright said not yet, but he would be happy to reach out.

Dr. Betz wished to reinforce one point related to the isolex requirement over the 2 dB variation. This is a real constraint on the ability to expand the bandwidth that serves the earth. Is there an opportunity for either the Advisory Board or some other body to determine how important the isolex requirement is?

Dr. Parkinson suggested placing this matter on the agenda for the next meeting, along with an understanding of the implications if the requirement is relaxed.

Mr. Miller said he appreciates Mr. Wright having prepared his briefing on a relatively short notice. Much progress has been made in SSV. He is also grateful to the space user community and to U.S. Air Force Space Command for allowing NASA to participate in these efforts which, in his view, has also strengthened relationships between the two groups.

ADM Allen said the presentation has been quite helpful in establishing a baseline, and it would be helpful for an update to be presented at a future meeting.

* * *

**Global Navigation Satellite Systems – *What's up?***
Dr. Oliver Montenbruck*, Head*
*GNSS Tech & Nav Group, German Aerospace Center (DLR)*

Dr. Oliver Montenbruck said he would address GNSS developments over the past year. He presented a summary of the status of the various GNSS constellations, which have greatly expanded over the past decade. Currently, there are over 120 GNSS satellites in operation.

Between 2015 and 2016 BeiDou-3 launched five satellites to demonstrate technical capability. Following this success, it followed aggressively by launching 18 Medium Earth Orbit (MEO) satellites. BeiDou-3 must now be considered an operational system. A variety of signals are being transmitted. The constellation was intended to include 24 satellites in three orbital planes. Only a few slots remain to be filled. The signals transmitted are different from those of BeiDou-2, and involves use of wider bands. BeiDou has made a major effort to introduce new modulation techniques to avoid patent infringement issues. As a result, BeiDou now has some signals that in his view are superior to both GPS and Galileo, and are entirely Chinese intellectual property. The approach used is quite sophisticated. A unique advantage of BeiDou-3 is that is has a fully informational K-Band and intersatellite links. This is a fantastic step, which greatly reduces, though does not eliminate, the system's reliance on ground stations. At this time the intersatellite link measurements are not publicly available.

Turning to Galileo, the system is not yet complete. Over the past year Galileo has launched a campaign called "Accuracy Matters." Galileo currently has 22 operational satellites; two of which are in eccentric orbits because of a failure during launch. The ranging performance now being offered is remarkable. Galileo's range error is currently about 20 cm, compared to 50-60 cm for GPS. In January 2019 there was an announcement of new services based on the E6B and E6C codes. This is "an open access service based on the provision of precise corrections (orbit, clock, biases, ionosphere) transmitted in the Galileo E6 signal (E6B is the data component) at a maximum rate of 448 bps per Galileo satellite and connected to an uplink station allowing the user to achieve improved positioning performance." It remains to be seen how well this operates in practice. The Galileo program has been actively supporting scientific work and more exact information of the transmittal point on the satellites would allow orbit determination to determine reference scale. This would be a major step forward.

Dr. Montenbruck then addressed GPS. A GPS feature that has received little public discussion is flex-power. GPS has the capability to reallocate power for its signals and this has caused some concern in the user community. During flex-power tests, users of the legacy signals experienced much higher power than before, prompted by a de-activation or reduction in the M-code. Users were concerned this might also change some aspects in the signal, but while performance was degraded it never fell below the level GPS is committed to providing. Dr. Montenbruck then turned to GPS III and noted this is the 1st satellite to transmit the new L1C signal. Because M-Code is not modulated on the same signal chain, this allows for greater flexibility.

Finally, Dr. Montenbruck spoke about GNSS metadata. Precise GNSS data processing relies on data regarding the satellite vehicles. The GPS III phase center offsets (PCO) are released right after launch. There has been surprisingly good agreement (6 cm) with first L1/L2 PCO estimates from the European Space Agency (ESA). This is important for the GPS contribution to reference frame scale, with estimated phase variations at +/- 15 mm. It is yet unknown how attitude control law for rapid noon/midnight turns will work out. Dr. Montenbruck presented a chart showing the public availability of metadata for all GNSS systems.

In summary,

- Worldwide GNSSs are continuously evolving
- Galileo and global BeiDou-3 system approaching full deployment
- Plethora of signals in various frequency bands
- Open and regulated signals in all systems
- Great diversity of advanced modulation schemes
- Digital signal generation units offer improved signal quality (low biases)
- Trend to high accuracy services (QZSS, Galileo, …)
- Cybersecurity, jamming, and spoofing are persistent threats and require protection (GPS OCX, planned Galileo O/S and C/S authentication)
- GNSS for science and technology would encourage the closet possible collaboration between the science community, system providers, and equipment manufacturers
- Availability of proper satellite metadata is vital for high accuracy GNSS

Q&A:

Mr. Higgins asked about the crosslinks in BeiDou and whether the International GNSS Service (IGS) could ask for access to the cross-ranging data.

Dr. Montenbruck said that while currently the information has not been disclosed, it is clear that cross-links contribute to a much better orbit determination for the BeiDou system. While accuracy matters, reliability is also of high importance.

Dr. Betz noted, on satellite metadata, that less work is required if the data was published. However, could Dr. Montenbruck speak to the probable difference between the published and estimated metadata?

Dr. Montenbruck responded that since not everything can be estimated, the question is difficult to answer.

Dr. Beutler said, regarding space range errors, the data has improved. What does Dr. Montenbruck believe accounts for this?

Dr. Montenbruck said Galileo has extremely stable clocks and a more rapid upload cycle.

Gov. Geringer said he finds it ironic that, with BeiDou, the Chinese have created signals as their own intellectual property.

Dr. Montenbruck said that, at least in this case, the Chinese have worked to avoid any discussion of intellectual property rights.

* * *

**Update on Department of Transportation (DOT) Equities:**
*Ensuring Safety for all Modes of Transportation & Civil PNT*
Ms. Karen Van Dyke, *Director*
*Positioning, Navigation, and Timing (PNT) & Spectrum, DOT*

Ms. Karen Van Dyke noted she works in the Office of the Assistant Secretary for Technology and Research. In late February, the office received a new deputy assistant secretary, Diana Surchtgott-Ross, who at this time is awaiting Senate confirmation. The appointee is passionate about PNT.

Ms. Van Dyke identified DOT's key goals. First, DOT has a $1 billion research budget, and her office is responsible for coordinating that research and preventing duplicative efforts. Second, PNT resiliency, with a focus on solving the PNT backup issue. The third is spectrum protection, where the appointee strongly supports the conclusions of the DOT's Adjacent Band Compatibility research. Fourth, the creation of a one-stop shop for transportation data. Regarding research coordination, Ms. Van Dyke noted three working groups: emerging and enabling technologies, automated vehicles, and cybersecurity. Ms. Van Dyke emphasized that Ms. Surchtgott-Ross wishes to meet directly with the Advisory Board members. She will give the keynote address at the Civil GPS Service Interface Committee (CGSIC) meeting in September, concurrently with Institute of Navigatoin (ION) GNSS+ 2019 conference. Ms. Surchtgott-Ross is conversant with all relevant Congressional activity, along with DoD and Department of Homeland Security (DHS) activities related to GPS backup. Her goal was to complete the work on the "Way Forward" by August 2020.

Ms. Van Dyke noted that the FY17 National Defense Authorization Act (NDAA) identified critical factors. She noted the $10 million complementary PNT demonstration project funded in the FY18 NDAA. That project includes DOT-hosted industry roundtables in March and April 2019 and a May 3, 2019 release of the pertinent Request for Information (RFI). The first roundtable is for technology vendors wishing to understand what potential solutions might be available and to secure their views on pending legislation. The second roundtable is with handheld device manufacturers, reflecting the view that PNT is not merely about GNSS satellites, but also about the user community. The demonstration products will include scenarios exemplifying vendor capabilities and a report, in coordination with DHS and DoD, to Congress.

ADM Allen asked if Ms. Van Dyke could comment on the down select.

Ms. Van Dyke said that would be premature until all information is in hand.

ADM Allen asked how many demonstrations will be held.

Ms. Van Dyke said it will be some subset of the 21 potential demonstrators.

Ms. Van Dyke then reported on the joint EU-U.S. Transportation-Related Initiatives under WG-C. These include:

- Modal efforts to gather information, e.g. pilot reporting, ADS-B (aviation) and automatic AIS (maritime).

- Assessing Space-Based Augmentation System (SBAS) authentication schemes and performance attributes for International Civil Aviation Organization (ICAO) standards consideration.
- Consideration on L5/E5 Demonstration(s) - Early use opportunities ahead of safety-of-life operations - Observing performance in the pre-op/IOC/FOC
- Rail Initiatives on Multi-Constellation - European effort to standardize train location, guidance, and control – U.S. Federal Railroad Administration (FRA) Positive Train Location Report & Interoperable Train Control standard

Regarding EU-U.S. transportation work, DOT is focusing on resiliency through surveillance capabilities. She reported on DOT work with the IGS, where it has been an active participant. She also discussed the GNSS Monitoring Development, a joint project with the five GNSS service providers and the IGS.

Ms. Van Dyke then addressed connectivity and safety. She noted that the 37,000 vehicular deaths annually would not be acceptable for any other mode of transportation. Little headway has been made in reducing that toll. This points to the need to develop technology that reduces the incidence of collisions – vehicle-to-vehicle, vehicle-to-structure, and vehicle-to-pedestrian. This is a high priority because of the possibility that spectrum may be misallocated. A shortage of spectrum would be a major disadvantage. Further, warning systems are needed for truck and rail, to warn drivers of oncoming trains. Spectrum protection is a top DOT priority.

* * *

**Economic Studies of GPS and the National Geodetic Survey (NGS) Gravity Program:**
*Spectrum Regulatory Stability Needed*
Dr. Irving Leveson, *Founder*
*Leveson Consulting*

ADM Allen announced that a pressing family matter prevented Dr. Leveson's attendance. Dr. Leveson's presentation will, nevertheless, be uploaded to https://www.gps.gov/governance/advisory/meetings/2019-06/. Mr. Joseph Burns will, instead, present a briefing on UAVs.

* * *

**Interface between GPS and UAVs**
Mr. Joseph D. Burns, *CEO*
*Sensurion Aerospace*

Mr. Joseph Burns said he would address drone dependence on GPS. Such dependence is extremely high – currently, 98-99% of drones specifically use GPS. Commercial usage of drones is burgeoning. The Federal Aviation Administration (FAA) has registered over 500,000 "hobbyist" drones, though many of these may not be in use. The drone economy is being driven by commercial use. Some studies estimate the economic value of drone technology at $100 billion. A potential annual market of $15 billion exists for air taxis. Major areas of drone use are construction, surveying, utility inspection, mining, agriculture, and safety-of-life. One can be licensed to operate a drone of up to 55 pounds by simply taking an exam. This is the only existing FAA license that does not require a demonstration of proficiency. There is an increased interest in drones among Fortune 500 companies. For example, in photographic operations a drone costing $300 an hour to operate can substitute for a helicopter that costs $3,000 to $4,000 per hour.

Local cargo delivery is most likely to be the next major development for drones. This application will be very dependent on GPS as operators do not have "eyes on" the UAV as it is flown. A study done with the city of Chicago determined that the average weight of local deliveries by panel van is 250 pounds, which could be readily carried by a drone. Many companies appear to believe they can initiate drone operation without going through the FAA. Two other areas for future application are flying cars and autonomous air taxis. These will initially require use of an on-board pilot until safety and reliability is established.

GPS is fundamental to drone navigation. GPS is needed for precise information on speed and position. GPS is also important to surveillance and inertial updating. Precision navigation is an increasingly weighty concern in the industry. Operators need certainty that they are not flying into restricted air space or into a physical structure. Radio navigation is not widely available for drones and it is doubtful anyone is investing in such technology. Many drones use ultrasonic technology for close proximity and landing. Inertial navigation systems keep improving, but still require some sort of updating to maintain position.

The FAA is moving to approve use of autonomous air taxis for up to 19 passengers per vehicle, but this will require considerably more from a would-be operator than simply stating they have an excellent GPS-based system. A variety of certifications and augmentation systems will be required. Artificial Intelligence systems could be used to make decisions, but these are only valuable

if they have GPS signal input. Regarding spectrum use, in Europe and Japan the commonly used spectrum is 433 MHz; in the U.S., it falls between 800-900 MHz.

In summary, GPS use in drones needs to be protected, toughened, and augmented. This is a huge and growing market, and many drone manufacturers do not understand the importance of GPS.

ADM Allen noted that during the most recent Super Bowl there were 8 drone incursions into the game site's restricted airspace. One occurred 30 seconds before the Blue Angels flyover and forced a change in their flight path.

Gov. Geringer noted that racing drones use first-person view. Is this the same as line-of-sight?

Mr. Burns said that technology is good, but of limited use at larger distance to the operator.

Dr. Parkinson said there must be some organizations representing UAV technology users.

Mr. Burns said multiple organizations exist, including a drone advisory committee. These, however, tend to get isolated on the growth side and need reminding that something might not work all the time.

Dr. Parkinson said the voice of the UAV community needs to be heard, particularly by the FCC. He doubts it was widely understood how broad and important this topic is.

Mr. Burns said he certainly wishes to help get the word out.

Dr. Moore noted the presentation emphasized the increasing accuracy of drones but had made little comment on integrity. Is attention being paid to integrity in "beyond line of sight" operations?

Mr. Burns said it definitely has. This briefing did not touched on integrity issues because of the time limit.

Mr. Goward noted that DHS has recently published a fact sheet stating it had permission to disable or seize drones. Has the drone community taken a position on this?

Mr. Burns said it has. One of the first things done was geo-fencing that defines those areas where one is not allowed to fly. The drone community was behind this. As the use of drones moves into the transport of people, things become more complicated. While DHS is willing to bring down on unmanned craft, what would it do if the craft is carrying passengers?

* * *

**General Motors use of Precise GNSS and V2X for Automated Vehicles**
Mr. Curtis Hays, *Technical Fellow*
*GNSS, V2X and Maps, General Motors*

Mr. Curtis Hays explained that in 1997, as a Captain in the Air Force Research Lab, he was assigned to drive to the range where weapons were tested. The previous day an F-16 dropped a 250-pound bomb, and his task was to extract whatever remained in the hole that was created. The remains were located beneath the plywood that had been the target. He was impressed by what a remarkable technology this was for saving lives, as the precise targeting had prevented anything else from being hit. This experience made him a passionate advocate of the value of GPS and GNSS.

General Motors' (GM) central long-term vision is: zero crashes, zero emissions, zero congestion. All major automakers are transitioning from makers of cars and trucks to becoming technology and transportation companies. His efforts are focused on how to take advantage of technology to eliminate crashes. GM sells an automated vehicle – the Cadillac CT6 – with sensor technology like that used in drones. Depending on the GNSS system, the technology works at speeds of 0 to 85 mph on mapped roads. The driver, not the GNSS-based system, maintains responsibility for the vehicle's performance and is responsible for its insurance. If the driver looks away from the road, an alert goes off.

Precise GNSS use in the automotive industry is different from other areas. The median accuracy at present is 90 cm, which is more than enough to ensure accurate information on what highway lane the vehicle is in. If accuracy of 40 cm is achieved, then it would be possible to implement automatic lane change technology. Mr. Hays then defined current and future precise GNSS localization, namely:

Today:

- GPS L1 C/A, GLONASS G1

- Tightly coupled sensor fusion (MEMS yaw-rate gyro, differential wheel odometry). He commented that the MEMS sensors were becoming extremely good.
- Low cost L1 antenna. GM would not be placing a $5,000 antenna on a vehicle.
- Real-time PPP/RTK corrections (Trimble RTX)
- 10-Hz update rate
- 1.8-meter horizontal accuracy (95%) on highways, at the 2-Sigma confidence level.

Future:

- GPS L1/L5, Galileo e5a, GLONASS G1, BeiDou
- Low cost multi-frequency, multi-constellation automotive antenna
- Improved Trimble RTX
- 100+ state Kalman Filter for camera feature points, IMU, GNSS, wheel odometry. Mr. Hays said that very interesting technological advances were happening in this area. He believes the "urban canyon" problem would be solved relatively quickly.
- 20-Hz update rate
- 50-cm horizontal accuracy (95%) on all mapped roads. He noted that just the previous day GM had announced a major effort to expand its system of mapped roads. Effectively, this would mean a 50% increase in mapped roads.

Customers speak highly of the Cadillac CT6's super-cruise feature and said they wished it could be used for their entire commutes. Such feedback has increased pressure to expand mapping. Super-cruise takes the vehicle on a mapped road, becomes comfortable with a given lane, and when a light comes on the driver can remove hands from the steering wheel and feet from the pedals. Precise GNSS (sub-meter) would provide the following benefits:

- Same Reference Datum as HD Map– complimentary data
- Common Reference Datum between Adjacent Vehicles (V2V)
- Redundancy
- Mitigate limitations with perception sensors
- Road Class Identification (referenced with map)
- Interstate, state, county, pavement type, etc.
- Lane Identification
- Especially important for lane change maneuvers, entering/exiting highway, turning at intersections, V2V
- Higher quality, lower cost HD map crowdsourcing.

The automotive field uses two classes of sensors. First, perception sensors, which determine how close one is to something else. Second, absolute localization, which relates to high definition mapping of all the attributes of the road, e.g. stop signs, etc. Self-driving vehicles require both kinds of sensors. Nissan recently announced its own version of hands-free driving. The entire industry is working on the technology. While autonomous driving is the future, the act of putting the driver in the back seat remains a considerable time off. All major GNSS companies are investing in integrity monitoring. Customers need accuracy and artificial intelligence to inform them when their required level of accuracy is not being achieved. Maps need constant updating, reflecting construction activities or accidents. GM is continuously looking for ways to extract data from the vehicle. GM is especially concerned about the threats to adjacent band conflicts. No risk to GPS can be tolerated.

Q&A:

Gov. Geringer said precise mapping might be the weakest link. Will some standard be adopted?

Mr. Hays noted that DOT has been working to encourage state agencies to report construction. Further, crowdsourcing has potential. Information takes time to validate and deploy. This is a challenge.

* * *

**The Use of GPS in Positive Train Control (PTC) Implementation:**
*Federal Railway Administration (FRA) Administration*
Ms. Carolyn Hayward-Williams, *Director of Technical Oversight*
*Office of Safety, FRA*

Ms. Carolyn Hayward-Williams said it is a very exciting time in the rail industry. Significant advances are occurring thanks to technologies that rely on GPS. Today, the topics to be addressed include Positive Train Control (PTC) and the Interoperable Electronic Train Management System (I-ETMS). Industry has invested billions in these technologies in order to improve safety. This stems from the 2008 Chatsworth accident that caused 25 deaths and considerable destruction. In response, Congress mandated in the Rail Safety Improvement Act of 2008 the introduction of PTC on 50% of the nation's rail lines, particularly those carrying passengers or hazardous materials. Congress set an October 2015 deadline, later extended to 2020. To date, PTC has been implemented on 48,000 miles of the U.S. railway track. Mr. Dennis Stonecypher will provide a more detailed description.

Mr. Dennis Stonecypher explained that while several forms of PTC exist, today's briefing focuses on the I-ETMS, which is the most common system in use and relies on GPS for its navigation function. The system consists of an on-board segment, a communications segment, a wayside segment, and an office segment. PTC systems required by FRA regulations are required to reliably and functionally prevent: (1) train-to-train collisions, (2) over speed derailments, (3) incursion into an established work zone, and (4) movement through a main line switch in the improper position. The system uses Predictive Speed Enforcement, in which the system notifies the train operator anytime the train exceeds the speed limit by 5 mph. Should the train operator not reduce speed within a certain amount of time then the system automatically brakes the train. Mr. Stonecypher then presented a videotape showing the speed control and braking capability of the system. Alaska has presented special challenges because of terrain obstruction of GPS signals. The current system only uses signals from GPS. Alaskan railways are undertaking some tests to support seeking a waiver from the FCC that would allow it to also use other GNSS signals.

Q&A:

ADM Allen noted that the FCC recently cleared Galileo for U.S. use. Is Galileo now being used, or is there some further permission needed?

Mr. Stonecypher said they are cleared to use Galileo; the hope is to expand the permission to GLONASS and BeiDou.

Dr. Parkinson said that GNSS integrity is often addressed through the FAA's WAAS. Could the PTC system make use of WAAS?

Mr. Stonecypher said he is unfamiliar with WAAS. In any case, PTC legislation lacks any specific restrictions on which GNSS or augmentation systems may be used.

Dr. Parkinson suggested that the construct used by the FAA is similar to what the FRA might wish to have. FAA folks could be of help.

Ms. Hayward-Williams welcomed the feedback. She noted that some of the Class I railway systems are looking towards moving from a safety advisory system to a more automated system. This would include, for example, technologies that automatically specify which of a series of parallel tracks a train was on.

* * *

**Concise Update on Department of Homeland Security (DHS) Security Priorities:**
*PNT Resilience – Identify and Mitigate Vulnerabilities*
Mr. James Platt, *Director*
*PNT Office, DHS*

Mr. James Platt reported on the National Risk Management Center (NRMC). It was established in November 2018 to take a fresh look at the risks to critical national functions. In the past, a lot of effort has gone into identifying risks. The focus is now on how risks affect people and how they could be avoided. For example, while there are advantages to receiving signals from multiple GNSS systems, each new signal introduces new risks. In the past, risk has been managed by "stove piping" critical functions. The current effort looks at foundational elements that may affect multiple sectors. This approach supports infrastructure prioritization. Further, it provides guidance as to where the "next dollar" on risk abatement should be spent by a given organization.

Mr. Platt listed the national critical functions, which include "provide positioning, navigation, and timing services." The general effort will determine the realistic challenges that must be addressed. For example, shoplifting costs American business $50 billion a year, but no national program is directed to address this. The point is that this effort will not just be dollar driven.

Mr. Platt then presented the composition of the ICT Supply Chain Risk Management Task Force. If one is a supply chain manager or end-user, one may not be aware that risks exist at every point in one's supply chain. Identifying where in the supply chain that risk exists can be difficult. Thus, GPS/GNSS chips that are not in compliance with ICDs could nevertheless end up being built and introduced into a critical sector supply chain. Another area being looked at is 5G mobile communications.

Mr. Platt next addressed EMP/GMD risk assessments, which includes the following steps: (1) Establish and staff DHS/CISA EMP coordinator position; (2) Develop analysis framework that incorporates SSAs and other interagency partners; (3) Develop DHS R&D requirements that support analysis framework for prioritization by DHS S&T; and (4) Coordinate with the NSC, CISA components, and interagency partners to develop R&D and analysis portfolios to implement the EMP Executive Order and the DHS EMP Strategy. The next steps include technical collaboration with the Department of Energy (DOE) and DoD to develop standardized EMP threats. This will enable integrated analyses by interagency partners and the initiation of projects to scope EMP vulnerabilities in key infrastructure systems. Attention also needs to be directed at the architecture. A best practice group on architecture standards is being developed to identify levels of receivers that meet the requirements.

ADM Allen noted that it appears legislation has led to a set of requirements. Could Mr. Platt provide some detail on how things will proceed?

Mr. Platt said he is in continual contact with Ms. Van Dyke of DOT. This effort is current with DOT activities, and everything they are learning is shared with DOT. Also, the demonstration timing project is still moving.

ADM Allen suggested there should be a presentation on the demonstration timing project at the next Advisory Board meeting. Mr. Platt and Ms. Van Dyke may wish to collaborate.

Gov. Geringer noted that the Advisory Board had long urged that GPS be declared a national critical infrastructure. Mr. Platt's presentation refers to GPS as a critical function. Is the latter essentially the same as the former in the level of protection it merits?

Mr. Platt said it is. This follows from focusing on a deeper understanding of underlying technologies. The focus will also go beyond GPS to PNT in a broader sense. Steps taken during design and implementation will reduce risks to GPS. One always has to address risk management. People have defaulted to a certain PNT system and assume it will always be correct and available.

Mr. Lewis said he has visited nine state-level emergency management headquarters. Each had a GPS point of contact. Does Mr. Platt's organization coordinate with these state-level emergency management teams?

Mr. Platt said it has not been a primary focus. Several webinars have been held with state emergency managers. In his view, states appeared to be aware of their dependence on GPS for timing.

* * *

**Proposed PNT Threat Environment Model for Military and Civilian Use**
Mr. Mark Johnson, *Assured PNT Campaign Lead*
*Collins Aerospace*

Mr. Mark Johnson said "assured PNT" is the combination of high availability and high integrity – always available, and always trustworthy. While much at Collins Aerospace is on the military side, it applies equally to the civil side. The PNT environment is contested. Instances range from the 2013 accidental jamming of the Newark Airport by a truck driver to the 2018 disruptions of telephone service in Norway traceable to a Russian military exercise. Signal interference is a major and worsening problem. This has been better recognized on the military than the civil side. GPS needs to be precise and absolute. A key issue is the absence of standard definitions. In the absence of common taxonomies, people tend to talk past each other. Collins Aerospace has had over 100 discussions with customers on this topic.

Too often people try to solve the problem of assured PNT while not actually solving it. The highest priority is assurance of precision timing, which has numerous military uses. On the civilian side, such timing is needed for precision landing, agriculture, surveying, construction, mining, and more. Unless PNT is absolute (as compared with relative PNT) precision applications could be lost.

Next, Mr. Johnson presented a PNT Threat Environment Model. In terms of threat conditions, these range horizontally from "permissive," meaning that regular GPS is operating continuously, through a "day without space." Each is affected by outage duration and reach: GPS available, GPS unavailable locally, or GPS unavailable worldwide. In cases of short local disruptions, systems with proper inertial capability can coast through. Interference includes jamming, spoofing, and systemic attacks. The solution needed depends on the cause. While many people feel they could solve the problem through inertial sensors, this will only be useful for about ten minutes. Hopefully users will make this framework, or something similar, and use it to make plans relative

to the problem they wish to solve. For many people, GPS had become a "part number" – a component of something larger – and they want another part number to replace it. No such part number exists.

Mr. Johnson then described a multi-sensor approach to threats to PNT. A short regional outage could be addressed with inertial systems, but more severe threats require adding time and other non-GNSS navigation systems. Anyone capable of jamming GPS is likely capable of jamming other GNSS.

In summary, the modern world is dependent on Assured Precision Absolute PNT. Threats to PNT are real and becoming more prevalent. There is a strong need for a consistent threat model and definitions to enable analysis and requirements development. There are technologies available today to solve most threat conditions, but GPS remains foundational to these solutions. Thankfully technology is being developed towards solving threat conditions where GPS, or other GNSS, are not available.

Gov. Geringer said he is pleased to see advocacy of a consistent threat model. He noted that the PNT EXCOM recently requested such a model. Should the Advisory Board also pursue creating a GPS threat model?

ADM Allen said nothing restricts the Advisory Board from doing so.

Mr. Miller said the threat model is an excellent idea and that the PNT EXCOM's point was to focus on the civil side. To the extent that this model is applicable to the civil side, the Advisory Board has every right to examine it further.

Mr. Shane asked Mr. Johnson if, when discussing available technologies, he was referring to beam-carrying antennas that would not be applicable to hand-held devices.

Mr. Johnson replied that for anti-jam, the reference was to a beam-carrying antenna. Handheld devices remain the most challenging.

Mr. Burgett said Mr. Johnson's threat assessment is very interesting, and asked why he thinks a long-term regional outage is a more likely event?

Mr. Johnson said that in the military space this is already being done.

Mr. Burgett asked about the likelihood of it affecting civil space.

Mr. Johnson said it is very doable; the technology to do it is available on the Internet.

Mr. Goward said the Resilient PNT Foundation has created a model that views risk as equal to threat likelihood multiplied by its consequence. This is a generic model and available to anyone.

Mr. Johnson said he would love to see the Advisory Board take on this task.

ADM Allen said this is a good observation. He added that if one takes the presentation just made by Mr. Platt it might usefully be combined with what Mr. Johnson had just presented.

* * *

**GNSS Radio Frequency Interference Detection from Low Earth Orbit (LEO)**
*Results and Lessons Learned for Future Deployments*
Dr. Todd Humphreys, *Associate Professor, Aerospace Engineering*
*University of Texas at Austin*

Dr. Todd Humphreys said his institution has spent the past decade developing software-defined radio, referred to as GRID. In 2017, the software was placed on the International Space Station (ISS) for ionospheric studies, specifically radio occultation. The system is unique in that it permits the long-term recording of raw samples. During these studies GRID detected spoofing events in the Black Sea. In repeated instances, clusters of ships reported their location as being at a nearby airport. These spoofing events seemed geographically concerted with the travel of Russian President Vladimir Putin. An attempt was made to locate the source of the spoofing. Over three days in spring 2018, activity was recorded and the data downloaded back to Earth for further study. At L1, it appeared to be routine spoofing. At L2, it was less clear what was happening. We were able to lock onto some of the spoofing signals, and tracking the false signals carrier phase made it possible to locate the source of the spoofing. Surprisingly, the location was in the eastern Mediterranean. The Black Sea spoofing was being eclipsed by the Russian-run Khmeimim airbase in Syria. Dr. Humphreys quoted Gen Raymond Thomas (Former Commander, U.S. Special Operations Command) who in April 2018 said "Syria is the most aggressive electronic warfare environment on the planet." Interference from Syria was also evident in the

carrier-to-noise ratio observed by the GRID receiver under normal operation. If one generated a heat map, Syria immediately lit up. Unique to the Syrian signal was that it was a spoofing signal whose intent appeared to be the denial of service.

In summary, this shows that suitable instruments in LEO can reveal the scope, nature, and location of terrestrial GPS interference. This is a tremendous asset in that it can be used to "keep eyes" on hotspots around the world. Moreover, against receivers performing cold starts, spoofing is more efficient for denial of GPS than jamming: a 1Watt spoofer is more potent than a 1 kWt narrow/wideband jammer at the same stand-off distance. Goals for protecting and toughening GPS that are stated in terms of the the jamming to signal ratio, or J/S (e.g., 85 dB J/S to withstand a 1kW jammer at 2 km) assume uncorrelated jamming, not spoofing. Such thinking may need to be recalibrated. While this applies only to cold start, cold start remains a necessary capability for many applications of interest.

Dr. Parkinson said the presentation was very enlightening. The question is: what do you do about it?

Dr. Humphreys said the solution space has several levels. First, it depends on what one meant by "it." One could report to the International Telecommunication Union (ITU) and ask that the Black Sea area be cleaned of spoofing. Also, beam-steering antennas would be an excellent mitigation, but not a complete solution. Challenges remain because one is, in effect, fighting a cost-based battle against an adversary.

Mr. Shane said Dr. Humphreys has appeared to have found the spoofer in Syria, but not the jammer in the Black Sea. Will the search continue?

Dr. Humphreys said that during 2018 the spoofer in Syria appeared to operate about 90% of the time. Any time it was in use, one could not hear anything else that might be going on, including what might be happening in the Black Sea.

Dr. Parkinson asked if it is possible to mount a beam-steering antenna on the ISS.

Dr. Humphreys said he would love to do so, but he's unable to do so at present. A study determined the strength of the Syrian spoofer to be only 100 W.

Mr. Hatch said he believes that a difference between jamming and spoofing is that the latter requires greater information about the target.

Dr. Humphreys said when a spoofer is deployed for denial of service, one does not need information. In fact, multiple spoofing can overwhelm a receiver in cold start.

Mr. Hatch said Dr. Humphreys' reference to cold start is clarifying.

Dr. Betz said that if there were hundreds of spoofing signals, then J/S is different. But if there was a single spoofer, could Dr. Humphreys design a cold start receiver with an omni-directional antenna that would acquire the correct signal?

Dr. Humphreys said he could.

* * *

**The Role of Civil Signal Authentication in Trustable Systems**
Mr. Logan Scott
*Logan Scott Consulting*

Mr. Logan Scott said his briefing would focus on civil navigation. He posed a rhetorical question: is it preferable to have a GNSS receiver that operates in real time with less than certain integrity, or one that operates with a six-second delay but full integrity? This would depend on the use case. An airplane generally needs real-time. However, if the pilot is only using the signal to align the inertial, then a six-second delay is tolerable. In the case of an atomic clock, if only using the signal to align the clock, the six-second delay is also acceptable. For autonomous vehicles a six-second delay with a higher assurance of integrity is also preferable. This is because the basic use of the GNSS is to initialize the world view. System trust takes time and memory. With a six-second delay, the receiver has time to look for problems that may make it possible to head off an attack and provide assurance that the signal is coming from a satellite. "Watermarks" could be used to establish the authenticity of the signal.

CHIMERA has both fast [6 second] and slow [3 minute] watermark signals. At present, this is experimental. The receiver is not informed of the key until after it has been used. This allows the user to establish whether the watermarks are correctly located. The use of a cryptographic key provides assurance that the signal is authentic. One goal is to create a system with a very low false positive rate, combined with a high likelihood of identifying spoofing. An issue related to spoofing is that often users do not recognize that receivers are computers and, therefore, subject to cyberattack. As an analogy, there were two ways to cheat at

Pokémon Go. One could either put a fake GPS signal into the phone or hire someone who works through a spoofer. The latter is preferable as its cost is only $1.49. The question becomes: how does one monetize this? After performing a Google search of Uber spoofing apps I found over 600,000 responses. Spoofing is an effect, not a method. If one can corrupt a traffic database, then false maps could be created and, in turn, that would lower confidence in autonomous driving. Similarly, it is possible there will be cyberattacks on U.S. census data, because altering that data would redirect the flow of money.

Almost any navigation signal can be watermarked with backwards compatibility. It can also be done for Loran. Implementing CHIMERA is not difficult. Message signing can be done in software. NTS-3 will broadcast CHIMERA on an experimental basis; a 2022 launch is anticipated.

Mr. Goward complimented the presentation and asked if the system could be implemented more rapidly; that is, within two years, on WAAS?

Mr. Scott said it could, as the modulator is on the ground.

Mr. Goward asked Gen Thompson whether there was any likelihood that DoD could expedite this by putting it on WAAS for its own purposes.

Gen Thompson said the Air Force has assembled a group whose purpose, first, is to make the GPS signal more resilient, and, second, to look at alternatives. He said he would relay the question to this group and report back.

Mr. Goward said he assumes this would require specially enabled receivers.

Mr. Scott said it would. There were many reasons why one would want an RF receiver. If one is operating on a six-second delay, then an RF receiver is needed for the "spoofing research." The receiver could, in effect, investigate the future.

Mr. Goward said this is a great capability, but users will have to be persuaded to adopt it. Other anti-jamming and anti-spoofing devices have been presented. The issue is getting them adopted. In any case, user reluctance should not be a reason to desist from pursuing and advocating the possibilities.

Mr. Scott noted that what he presented was Version 1 of the system. A lot of interesting work is also being done in Europe. What he presented is basically a "Keep It Simple, Stupid" model to determine whether the approach can work.

* * *

**Proposed Guidelines for Resilient PNT Receivers**
Mr. William Woodward
*Chairman, SAE PNT Technical Committee*

Mr. William Woodward said he would provide background on SAE, explain why they have developed a PNT committee, summarize their publications to date, detail current efforts, and, finally, explain what is needed to create a PNT workforce. SAE's mission is to advance mobility solutions of general benefit. Largely, it is a voluntary agency with 128,000 paid members. Two of its biggest customers are DOT and DoD. SAE is a frequent developer of commonly used standards. The SAE PNT subcommittee first met in May 2017. The subcommittee published five standards in its first year, which is very rapid progress. His role is not to be the subject matter expert, but to recruit people to help get the standards published.

A major task of the subcommittee is to listen to the PNT community. For example, when he learns of a new piece of PNT backup, he asks how it will interface with existing equipment. His job is to smooth everyone's efforts by having standards in the works and published in time to be used in contracts. Mr. Woodward presented a list of standards that are currently under development. This includes user equipment for Loran. There is no cost to those who work on the SAE committees and there are many ways one can contribute.

Having resilience requires a trained workforce. The rapid development of PNT technology creates considerable challenges for educators to train and to certify personnel in a timely way. When technologies change much of the information is held by small groups. We need to get this information to people that will buy and install new equipment. As an experienced textbook writer he knows how time consuming it is to publish and distribute even a fifth edition of a textbook. What SAE has done with fiber optics in the aerospace sector is to create training standards. Seventeen years ago, to ensure that the aerospace fiber optics industry adopted these same high standards, AS-3B created ARP5602, A Guideline for Aerospace Platform Fiber Optic Training and Awareness Education. This is a statement of what SAE wants instructors to teach and, once taught, lead to students being certified. The certifications are done by the Electronics Technicians Association. He listed some of the specific certifications that have been established.

Many people working with PNT have a poor understanding of the basics of the system. The fiber optics training standards and certifications worked extremely well for the global aerospace and avionics industries. PNT training standards are a natural fit for this successful model. Training standards and certifications ensure one has a skilled workforce.

ADM Allen suggested soliciting feedback from industry on what SAE is doing. He welcomed the presentation as he had been unaware of the activity.

Mr. Woodward provided contact information for anyone who might be interested in participating in the effort.

* * *

**DARPA Position, Navigation, and Timing Technology and their Impact on GPS Users**
Dr. John Burke, *Program Manager*
*Microsystems Technology Office, DARPA*

Dr. John Burke said he would provide an overview of current DARPA activities. GPS has come to the fore as the dominant choice for providing PNT. The discussion now is how to improve the system. Many DARPA programs exist to make GPS more robust. This briefing will address clocks, inertial systems, and opportunities for external measurements. A central question is how one can combine all these inputs into a simple system. In part, this requires adding new features without changing existing systems.

ASPN (All Source Positioning and Navigation) is a government-owned software with a standardized sensor integration system that incorporates non-traditional sensor sources to augment PNT in GPS-depleted environments. ASPN has been demonstrated on air, land, and sea platforms and is available for use. The quality of its operation depends on the sensors used.

STOIC (Spatial, Temporal and Orientation Information in Contested Environments) is an integrated system of three independent capabilities that together form an independent backup to GPS. Key STOIC accomplishments are a VLF positioning system, optical clocks, and time transfer over TDLs.

AMBIIENT (Atomic Magnetic Biological Imaging in Earth's Native Terrain) is an effort to use magnetometers to determine anomalies on the earth's crust. It is well suited for low-altitude use and provides a cross-effective check on information from GPS.

Efforts regarding clock stability include ACES (Atomic Clock with Enhanced Stability) and A-PhI (Atomic-Photonic Integration). ACES supplied the clock function at much lower cost than a cesium atomic clock. A fundamental research program – A-PhI – will begin next week. This effort will take highly accurate clocks to a chip scale technology. A central problem with atomic clocks is their very tight temperature range requirements. An ACES prototype should be available in a year. The most difficult part of the project, the physics, has been completed.

Efforts in inertial navigation include PRIGM (Navigation-Grade Inertial Measurement Unit). PRIGM is going well and is expected to be marketed in about one year.

Finally, BLACKJACK, is an effort involving LEO PNT payloads to augment GPS.

Q&A:

ADM Allen complimented the ACES chart and asked which parts of it are open vs. proprietary.

Dr. Burke said virtually everything presented is commercially available. However, manufacturers may be evasive about revealing how their systems work.

Dr. Parkinson noted his background is in inertial navigation and urged caution in trying to sell it based on the numbers that Dr. Burke presented.

Dr. Burke said he was describing a long-term research program that might run 10-20 years, not something that DARPA would present in the near-term.

Dr. Parkinson said that he supports the goal but recalls an instance where unmerited claims were made for inertial capabilities and ended up undermining the speaker's credibility.

Dr. Betz said the presentation is a good update on DARPA activities. Even if the effort described in slide 10 fell short by a factor of two, it would still provide a micro-second of accuracy over a week, a truly substantial change.

Lt Gen Thompson said he feels disheartened as his goal is for GPS to provide the underlying PNT capability. When operating in a GPS degraded or denied environment, will one have an adequate IMU that provides precision navigation long enough to deliver weapons? Is Dr. Burke saying this is 20 years away?

Dr. Burke said basing precision strike capability solely on inertial is an extremely hard problem.

Lt Gen Thompson said GPS gets a weapon to its delivery zone, but then needs to maintain accuracy for a number of minutes.

Dr. Burke said that is what PRIME is intended to deliver.

Lt Gen Thompson asked how far PRIME is from readiness.

Dr. Burke said it should be commercially available in a year or two.

* * *

**Non-Inertial Navigation in the 21st Century and Beyond**
Dr. Val Parker, *President*
*Non-Inertial Navigation Technology, LLC*

Dr. Val Parker began with a quote from 2014:

> *"I hate GPS" Ashton Carter, President Obama's nominee for Secretary of Defense, told a reporter, just a few weeks ago. The good Mr. Carter suggests in his interview that, in 20 years our dependence on satellites will be eliminated by new chip clocks, gyros and accelerometers. Continued research is good, but we can't wait 20 years. The father of GPS, Dr. Brad Parkinson, has called our dependence upon GPS "a single point of failure" and America's "largest unaddressed critical infrastructure problem." Unfortunately, not everyone in government and industry understands the problem and the need to move quickly to implement a technology that is proven and immediately available.*

This quote was very misleading in terms of what inertial systems can do. Inertial navigation is a partner of GPS, not a replacement. Gyros are "a sleeping beauty" in that they only go into action during acceleration, deceleration, or change of direction. There is a distinction between GPS telling one that they *were* in a position and the Inertial Measurement Unit (IMU) reporting that they *are* in position. Thus, his organization is directing its attention to non-inertial navigation.

Dr. Parker reported on NIRPS (Navigation Independent Relative Positioning System) and PTN (Position Through Navigation). NIRPS provides continuous detailed information of the flight trajectory, allowing recall and matching with the Kalman delayed positional information of the airplane. The TONIN (Technology of Non-Inertial Navigation) system is calibrated relative to Earth's axis (resembling GPS), which allows for a straightforward transition from one system to the other. The partnership of GPS-NIRPS can create a reliable interoperable mutual backup system that negates natural and human interference.

The Safe Sky program was launched with the objective to prevent a repetition of 9/11. Under this program, an aircraft's flight path is electronically entered into a computerized flight control system and locked into the "Flight Card." By inserting the "Flight Card," the pilot automatically initiates flight based on GPS/NINT input. Changes to the flight path can only be made by inputs of both the pilot's password and permission from the control tower. Safe Sky, by preventing any 9/11-type disasters, midair collisions, unintentional loss of control, etc., can address the "Achilles Heel" of current systems, that is, the latency of gyro navigation and the dependence on outside information. A fully functional TONIN system provides on-board navigation independent of outside sources.

TIPS (Terrestrial Independent Positioning System) utilizes a combination of nature's two most trusted phenomena: the speed of light and the axial rotation of the earth. TIPS provides real-time information on location, spatial orientation, and heading for terrestrial crafts with marine-grade resolution independent from outside sources, including GPS.

Slow but steady progress is being made on non-inertial navigation. The functionality failure of the current IMU-GPS arrangement resides in inherent limitations of Gyro Navigation. Deployment of the TONIN Systems eliminates the shortfalls of the Inertial Navigation. The capability of the TONIN-Technology to continuously and autonomously measure Space-Speed Velocity provides for a wide range of opportunities in Aerospace and Terrestrial Applications. Current discussions sometimes speak of a three-second delay. If one is traveling at 4,000 m/s, then a three second delay is substantial. This new system operates with a 0.3 millisecond delay, which is far better. The general effort is to remove the hiccup that occurs when one system reports to another. Once that hiccup is removed, super-precision timing will no longer be needed. In conclusion, the proposed GPS-NIRPS is a reliable interoperable mutual backup system arrangement that assures the Cybersecure Reliable Real-time Navigation. Also, PTN is the conclusive solution to the current PNT problems.

Dr. Parkinson asked how sensor attitude and orientation is maintained over time.

Dr. Parker said three sensors are used. Unlike GPS, the system does not accumulate mistakes.

Dr. Parkinson cited the need to go from Dr. Parker's axis to the world axis to integrate velocity and get position. How is this accomplished?

Dr. Parker said the device generally measures position from the starting point. His is a new approach; more questions will be raised over time. If the effort to create a microchip succeeds, manufacturing will follow in two years. Mass production will result in very low unit costs.

Capt. Burns expressed wariness of a flight control system based on the plugging in of a key card. This could go wrong in multiple ways.

Dr. Parker acknowledged that hiccups have to be addressed before the product is complete. At a minimum, the system allows the placing of something on the airplane to eliminate a mistaken flight path. The important point is that changes require joint authorization from two sources.

* * *

**Research on GPS Resiliency and Spoofing Mitigation Techniques across Applications**
Mr. Yoaz Zangvil*, Co-Founder and Chief Technology Officer*
*Regulus Cyber*

Mr. Yoaz Zangvil said his firm is an Israeli startup specializing in cyber security. Its research focuses on smart sensors. It has become much easier and less expensive to undertake spoofing of GNSS. Five years ago, spoofing required expensive equipment. Today, virtually anyone can undertake an attack at low cost. Such an attack can be simple or complex, depending on who initiates it and how much they are willing to spend. The cost of a particular model of software-defined radio (SDR) has dropped from $193 in 2017 to $88 in 2019. A different device that also includes a power bank and USB cable costs $158. Many GNSS receivers are not equipped to report when they are being jammed. Jammers can also be set up to schedule an interference event at a later date. Other setups are capable of real-time spoofing static/dynamic scenarios, replaying recorded and generated files, and smart jamming. A more sophisticated jamming setup could involve use of a long-range 3D antenna.

Regulus is taking steps to allow the combatting of spoofing. These are based on open source hardware and software, including: (1) Developing pyramid GNSS technology – spoofing detection for commercial GNSS receivers; (2) Lab and field tests to verify reliability of detection technology; (3) Advanced GNSS spoofing capabilities - using open source hardware and modified software; (4) Identifying vulnerabilities in commercial GNSS receivers; and (5) aiding the development of mitigation techniques.

Regulus has tested handheld phones and autonomous vehicle systems. The findings for vehicle systems present both safety and non-safety concerns. Safety concerns include spoofing that directs drivers to the wrong exit, causing aggressive braking and steering, sudden acceleration or slowing, and presenting confusing navigation cues on a planned route. Non-safety issues include misreporting the vehicle's disclosure. When manufacturers were presented with these tests their reactions were mixed. While some companies sought additional time to review Regulus' results, most took the view that GPS is not their responsibility.

His company is looking at both short-term and long-term solutions. Short-term solutions emphasize detection and protection – fortifying the receiver in ways that does not require re-designing the chip. Long-term solutions focus on mitigation, involving a redesign of the chip to provide spoofing protection in new receivers.

Dr. van Diggelen said consumer devices are very good at detecting spoofing when stationary, if GNSS spoofing is showing the device as moving. Why would the same not apply to vehicles, which are stationary at red lights, etc.?

Mr. Zangvil said that is correct.

Dr. van Diggelen said he believes the technology to detect spoofing could be built out of commercial sensors.

Mr. Zangvil said he is not denying this, just that such approach does not ensure a complete solution.

Dr. Parkinson said he believes velocity is a powerful technique. A cellphone has access to other velocities. Two rotating antennas would provide another set of velocities. However, while one should be able to get raw velocity, matching that velocity to an external source is an extremely difficult problem.

Mr. Zangvil said if one looks at a GNSS receiver and the various settings that may be used, one commonly starts from a stationary position with no velocity data available. That is the easiest time for a spoofer to take over a target. Many receivers, once spoofed, are unable to recover proper functioning. Therefore, it is not sufficient to tell the receiver it was being spoofed.

Gov. Geringer said that given earlier comments about the need to include younger people, he is pleased Regulus is making itself noticed. He thanked Mr. Miller for including them on the agenda.

* * *

**Brief Update on Newly Launched Congressional GPS Caucus and other Educational Efforts**
Mr. David Grossman, *Executive Director*
*GPS Innovation Alliance*

Mr. David Grossman said GPS has a great story to tell, but the story is not being told effectively. In response, a bipartisan, bicameral GPS Caucus was formally launched on March 12, 2019. The caucus stems from conversations with many Congressional offices. Its purpose is to bring heightened awareness to GPS's wide-ranging economic and societal benefits and to serve as a platform for briefings and technology demonstrations in support of GPS's long-term well-being. The co-chairs of the Senate GPS Caucus are Sen. Tammy Duckworth [D-Illinois] and Sen. Joni Ernst [R-Iowa]. The House co-chairs are Rep. Dave Loebsack [D-Iowa] and Rep. Don Bacon [R-Nebraska]. As of June 4, eight additional House members have joined.

Educational efforts include the hosting by GPSIA of a "GPS 101" briefing on Capitol Hill, with remarks from Sen. Duckworth, Rep. Loebsack, and Col Curtis Hernandez of the NSpC. On March 12, House Resolution 219 was introduced, recognizing "the contributions made by the men and women of the U.S. Air Force for their work in operating and maintaining the GPS constellation and affirming the importance of continuous availability, accuracy, reliability, and resiliency of the GPS constellation." A similar Senate Resolution 216 was unanimously adopted on May 21. Educational efforts are being pursued through social media, South x Southwest, the GPSIA blog, and testimony to pertinent committees. Plans include a briefing on the Importance of GPS 911 scheduled for summer 2019, and a GPS Technology Demo on Capitol Hill, set for fall 2019. He invited Advisory Board members to suggest additional educational activities.

Mr. Miller said this is a fantastic development. Has there been discussion of the spectrum issue?

Mr. Grossman said such a conversation has been started. However, the present emphasis is to build a foundation.

Mr. Shane welcomed this overdue effort that will produce not only cheerleaders, but leaders. If progress does not seem adequate, then deadlines should be set. He feels somewhat like Rip Van Winkle: having been away from the discussion for a decade, he has returned to learn the same issues are being discussed. The GPS Caucus could be a way forward.

Mr. Grossman noted that the educational need continues in part due to turnover on Congressional staffs. GPSIA does not own the effort; it is owned by the members of Congress who lead it.

Mr. Goward asked what policy and legislative agenda the caucus has.

Mr. Grossman said that is still in development. The first year is educational.

Mr. Shield welcomed the creation of the caucus. He noted that, outside of the co-chairs, all members named are Democrats.

Mr. Grossman said the caucus is bipartisan and members of both parties are welcome.

* * *

*The session of Thursday, June 6, 2019 adjourned at 5:32 p.m.*

* * *

# Session of Friday, June 7, 2019

**BOARD RECONVENES:**

ADM Thad Allen, Chair, convened the Friday, June 7, 2019 session. He said the previous day was highly successful, both for the breadth and scope of the briefings and for the Advisory Board's ability to adhere to its schedule. For the 2019-2021 term the Advisory Board has had its largest membership turnover in some years. The central task moving forward is not to perpetuate the present, but to direct attention over the horizon. The Advisory Board needs a strong narrative of what it wishes to accomplish. If the Advisory Board waits to be told what to do, it will be waiting for a long time. Its charter is quite broad, so the Advisory Board should make full use of its capabilities and identify its primary areas of concern and action. One unanswered question is what does the phrase Gold Standard mean? When he first joined the Advisory Board eight years ago, he was "seething" over the decision by the Office of Management and Budget (OMB) to eliminate funds for the eLoran backup system. In some areas, matters of concern to the Advisory Board have not yet recovered from that decision.

ADM Allen asked the new Advisory Board members for their initial thoughts.

* * *

**Concise Observations of New Members:**

**1) Dr. Patrick Diamond:** I am encouraged by the emphasis on protecting the user community, of which I'm a member. The DOT policy presentation from Ms. Van Dyke was insightful. Further, the threat assessment model presented by Mr. Johnson was excellent. Both can be tied to a discussion of what a "resilient receiver" is and how it fits into the threat model. Dr. Humphreys' talk on radio frequency interference was eye-opening. DARPA has unique assets that have to be maintained. Also, he was not aware of how fully developed BeiDou and Galileo are. Perhaps Galileo and GPS could look into becoming more integrated. Finally, the creation of the GPS Caucus in Congress is a most welcome development.

**2) Dr. Frank van Diggelen:** The Advisory Board is more focused on GNSS and PNT and less limited to only GPS as he had anticipated. This broader approach is welcome and overlaps with Google's. Google is a huge GNSS user – self-driving cars, mapping, and other areas. Simultaneously, Google has a huge GPS platform, with two billion Android platforms in use. One can no longer purchase a GPS-only cellphone. Google is also very interested in indoor location. If anyone present opens their cellphone to its maps function, they will see a blue dot giving the Advisory Board meeting's location. That dot does not come from GPS, but from triangulation of wi-fi sources. Both Google and Apple continuously map wi-fi locations, and 911 positioning is also delivered through wi-fi. He likes the Advisory Board's broad focus and hopes to add to it.

**3) Dr. Dorota Grejner-Brzezinska:** She greatly enjoyed the previous day's demonstrations. She was surprised the GPS Adjacent band broadband proposal is still active, and it's odd the FCC has yet to reject it. For some time, the scientific community has been seeking expansion of the GPS constellation. While the current constellation met the military requirements, broad value would be realized from a system that supports more advanced engineering and science applications. The DOT presentation was impressive. Also, "smart" technologies are developing rapidly, and this may be an area to which the Advisory Board should devote more attention. She would also welcome more discussion of science and of PNT education. It is concerning that the specialty of geodetic science is losing expertise. Her own program at Ohio State University, which is seen as one of the best in the U.S., had weakened in recent years. Programs elsewhere are also shrinking. Reasons include the retirement of experts in this field, declining student populations, and a shift toward students not from the U.S. The Advisory Board may wish to make recommendations in this area. Also, she recommended that Advisory Board members be provided with the presentations in advance of the meetings.

ADM Allen said that's a very good suggestion.

Mr. Miller said the effort is made to get briefings out to board members as expeditiously as possible.

ADM Allen said presentations to the Advisory Board are posted more rapidly than by any other body on which he has served. The timing of release is governed by when the preparers' slides are received.

**4) Dr. Terry Moore:** The issue regarding broadband transmissions in the GPS Adjacent Band needs a quick resolution. Even though this is a U.S. issue, clearly analogous issues could appear anywhere (Dr. Parkinson noted the Advisory Board is aware of planned bandwidth intrusions in Europe through in-band pseudolites). He also values Dr. Humphreys' presentation. He is involved with the European Space Agency and Galileo Science Advisory Board and noted their efforts to promote scientific uses of GNSS. He strongly encourages the near-term addition of laser retro-reflectors. Other Galileo matters include inclusion of accelerometers aboard spacecraft and the possibility of intersatellite ranging. The two Galileo satellites inadvertently placed in incorrect orbit are performing very useful service in investigating relativistic effects in clock behavior. The satellite

placement error was perhaps the most useful mistake in GNSS history. A recent paper has proposed using the full constellation of clocks to sense gravity waves as they migrate. Two bodies on which he serves, the Galileo Science Committee and the UK Technical Committee, would meet the following week. He will be glad to transit any message that might be useful.

**5) Mr. Jeffrey Shane:** The International Air Transport Association, of which he is General Counsel, has 293 commercial members. In his view the airline industry is ably represented by Capt. Joe Burns. His own interests focus on policy. He, too, has seethed over the canceling of eLoran. However, it is possible that the Loran-related delay could allow for better methods to advance. Regarding the procedures for Advisory Board meetings, he would like to see the briefings sooner and have fewer, or at least slower, presentations. Some Advisory Board members are technically versed, and others on how policy is made. Few are both. Clarity is needed on what policy issues the Advisory Board currently faces. The Boeing 737 MAX has been grounded sequentially by various governments. This suggests that regulators do not agree on what "airworthy" means. While the FAA is regarded as the lead agency in such matters, countries still acted prior to any FAA recommendation. Consensus is needed. Re-approving the Boeing 737 country-by-country will create considerable uncertainty.

ADM Allen noted that when uncertainty exists as to what constitutes the Gold Standard, action reflects assumptions based on a judgment of public opinion.

Mr. Miller agreed that the level of briefs has been dense. The following day's agenda is looser, with more discussion time. While the Advisory Board has responded well to every task it is given, it cannot passively await tasks to be assigned. The issue regarding proposed broadband transmissions in GPS adjacent band is an example of Advisory Board initiative.

Mr. Shane said a session is needed to clarify what issues the Advisory Board is addressing for the EXCOM.

Dr. Parkinson said the EXCOM consists of highly intelligent individuals who are, however, largely technically uninformed. In consequence, the Advisory Board needs to tell the EXCOM what it needs to be tasked with. He encouraged members to suggest topics for presentations.

**6) Mr. Gary Thompson:** His agency is the technology focus in North Carolina. Service on the Advisory Board will allow him to disseminate knowledge widely in the state. Continued emphasis on a GPS backup is vital. Interference and jamming could have very serious impacts in emergency circumstances. Airspace safety, in particular UAVs, is very important. He also urged the Advisory Board to have a presentation on the 2022 change of DATUM that will affect all geodesy users. The U.S. has excellent programs in this area but needs more students.

ADM Allen seconded Mr. Thompson's comments about a briefing on the change in DATUMs.

**7) Dr. Todd Walter:** The presentations on the previous day were fascinating. Still, he shares the view that fewer talks with more time for discussion is preferred. As with other technically versed individuals, he needs to learn how technical understanding is turned into policy. Also, the Gold Standard term may now be archaic. Currently, GPS has set the standard in publication of standards, consistency, and transparency. Other GNSS systems need more transparency. He seconds Dr. Montenbruck's emphasis on the need for reliability. In the world of aviation, when people discuss spoofing and jamming, they are not using shared definitions. "Interference" means different things to different people. The taxonomy must be clarified. While discussion often focused on "doomsday" scenarios, many common problems caused by simple forms of jamming and spoofing should be addressed.

* * *

**Concise Update on Department of State (DOS) International Engagements:**
*Bilaterals and International Committee on GNSS (ICG)*
Mr. David Turner, *Deputy Director*
*Office and Space and Advanced Technology (SAT) DOS*

Mr. David Turner restated 2010 U.S. Space Policy, including: (1) Provide civil GPS services, free of direct user charges and available on a continuous, worldwide basis; (2) Maintain constellation consistent with published performance standards and interface specifications; (3) Make use of foreign PNT services to augment and strengthen the resiliency of GPS; (4) Encourage global compatibility and interoperability with GPS; (5) Promote transparency in civil service provision; (6) Enable market access to industry; and (6) Support international activities to detect and mitigate harmful interference.

Four space policy directives have been released, and more are in progress. They address all aspects of policy, including space based PNT. Regarding GNSS, recent additions include a regional South Korean system and the Australian SBAS.

Mr. Turner also reviewed bilateral cooperation efforts, noting that Japan's QZSS system has expanded from four to seven satellites. Europe is the only region with which the U.S. has a binding agreement, signed in 2004. Working group meetings are held with Europe several times annually.

Dr. Parkinson asked if Mr. Turner is satisfied with the Galileo waiver obtained from the FCC.

Mr. Turner said things have gone as well as they could have, but acknowledged that additional steps are needed.

Mr. Higgins noted that the Galileo E6 signal, important to surveyors, has not received FCC authorization.

Mr. Turner said authorization remains possible.

Mr. Turner expressed concern with issues related to the ECC Report 23. Ms. Ann Ciganer will follow this presentation, and will address these in more detail.

Ms. Ciganer noted that while the 2004 agreement was with the European Union, all 25 member states were individual signatories. Was the U.S. having discussions with the individual signatories?

Mr. Turner said it was. The Department of State has concerns about the limits applied to the bandwidth and concerns about unwanted emissions. He would leave a more detailed explanation to Ms. Ciganer.

Mr. Turner then reported on continuing bilateral work with China and India. China is quickly becoming a global provider. The U.S. and China signed a public joint statement in November 2017 about compatibility and interoperability between GPS and BeiDou civil signals. Regarding multilateral activities, the 13th ICG meeting was held in Xi'an, China in November 2018. Two hundred persons from 27 countries attended. Australia was added as a member of the Provider's Forum. Highlights of the conference include work on Interference, Detection, and Mitigation and on spectrum protection. Both are long-term ICG concerns. A new feature is seminars for the spectrum managers of non-GNSS nations. The next such seminar, to be held in late June in Fiji, will include a special presentation on precise point positioning. He encouraged attendance.

Mr. Higgins asked whether the spectrum protection workshops acknowledged that other countries are having similar spectrum intrusion problems.

Mr. Turner said they have.

Dr. Axelrad sought detail on the long-term assessments.

Mr. Turner said that the ICG for years has urged adoption of similar performance standards, similarly measured and defined. Once standards are created, the question becomes how they are monitored. He is doubtful that core GNSS systems will undertake this task. Therefore, external monitoring is required. A trial project is in progress to learn what IGS should monitor and how that matches against what the ICG wishes to know.

Dr. Beutler said Dr. Montenbruck's presentation on the previous day was a good initiative.

Dr. Axelrad asked if the U.S. is contributing sufficiently to monitoring.

Mr. Turner said that since he does not control the relevant budgets, he cannot not answer. However, the U.S. is very much involved.

Ms. Van Dyke said DOT is reviewing how it could collect information on other systems. The U.S. government is not precluded from gathering such information.

Mr. Goward said fairly clear evidence exists that Russia is transmitting false signals into the international realm. How could this be addressed?

Mr. Turner said if U.S. service providers are affected, a process exists for engaging through the ITU.

Mr. Goward asked if this means DOS can act only when direct impact on U.S. interests occur?

Mr. Turner cautioned Mr. Goward against assuming the topic is not under discussion in the U.S. government. He asked, rhetorically, "If the reported interference were occurring to protect a head of state, what should be said to whom in hopes of having it stopped?"

Mr. Goward said that, in such a circumstance, he sees no way to compel another nation regarding activity within its own boarders. However, when it impacts international waters and airspace degrading the safety of life, other nations have standing and a duty to raise the issue.

Mr. Turner said DOS talks to Russian experts in multilateral settings. They are very engaged. However, he does not know how other governments resolved matters internally.

Mr. Goward said international organizations, agreements, and treaties exercise some control over international spaces. If false transmissions continue, then at minimum they should be reported in a public forum.

Gov. Geringer noted that interoperability is "me to you"; "you to me"; or "us to each other." A country can refuse to do business with a foreign corporation that does not use the country's GNSS system. This is not a technical issue but a policy one. Future interference is increasingly likely to be a policy matter.

Mr. Turner said Gov. Geringer is correct. Discussions on interoperability are an attempt to create a building block, but they would not prevent a country from mandating specific GNSS. In any case, the Department of State will respond to any clear barrier.

ADM Allen said industry is not waiting on official action in various areas. The Galileo signal had already been incorporated in receivers prior to FCC approval.

Mr. Turner noted that Gold Standard is not simply a technical matter, but also a matter of how things work for the user.

Mr. Shane agreed that industry is not waiting for permission. Cellphones are among the most compliant because they are enforced by the carriers. Much good work has been done to align GPS, Galileo and BeiDou on L1 and L5. Is there a path to gaining approval to use the additional signals in the U.S.?

ADM Allen said he believes the discussion is getting ahead of itself. This topic could be addressed in the scheduled Roundtable.

Dr. Parkinson asked if any other GNSS system has presented a waiver request to the FCC.

Mr. Turner said he is unaware of any.

* * *

**Radio Equipment Directive (RED) Implementation Update**
Ms. Ann Ciganer, GPS Innovation Alliance

Ms. Ann Ciganer explained that GPSIA includes GPS/GNSS user equipment manufacturers. Several months ago, a European chip manufacturer, and member of ETSI, expressing concern, joined the ETSI Working Group (WG SES SCN) responsible for developing the RED GNSS EN 303 413. In May 2016, GPSIA wrote to the U.S. government and the European Commission Galileo Program expressing concern about implementation of RED in ETSI development of a RED GNSS harmonized standard. In consequence, the Galileo Program representatives encouraged GPSIA to participate in ETSI. A brief review of RED implementation helps to illustrate the concern. The EU submitted Notification of the RED proposal to the World Trade Organization (WTO) in 2013 informing that the EU Directive in force has three essential requirements, including avoidance of harmful interference (Article 3.2), that the regulatory approach is considered to remain valid, and a fundamental revision of the Directive is not necessary. In 2014, RED was adopted with three essential requirements, including avoidance of harmful interference (Art.3.2). In 2018, the EC submitted a report to the European Parliament on operation of the RED informing on three essential requirements, including the "efficient use of spectrum" (not the complete RED OJEU 2014 Article 3.2 on avoidance of harmful interference). What happened? In April 2015, in Mandate/536, the EC modified the RED (OJEU 2014) Article 3.2 in a manner that can be read as introducing spectrum use policy and a regulatory framework for electronic communications (terrestrial wireless broadband) into RED harmonized standards developed by European standards organizations, like ETSI. The performance and characteristics of GNSS receivers in Europe – and, potentially, worldwide – could be read as being under the modification of the EU Radio Equipment Directive to develop sharing and mitigation techniques to accommodate interference from new entrant adjacent and/or in-band terrestrial wireless broadband. Implementation of M/536 in ETSI development of RED harmonized standards further depends on ETSI Guide 203 336 which lists only classical terrestrial, channelized radiocommunication receiver parameters required by the RED assessors for application to receivers in ETSI RED EN. This means that a "one size fits all" regulatory approach is being applied to spectrum use receivers effectively based on the operating paradigm for terrestrial broadband. While the directive (as cited OJEU May 2014) explicitly excludes military, airborne, and marine safety of life equipment, implementation of M/536 modification of RED Article 3.2in ETSI RED harmonized standards has the potential to affect all stakeholders including those not explicitly covered under RED. More importantly, regulation of commercial and consumer

receivers under M/536 in this manner will raise the noise floor throughout the bands included in an ETSI RED EN, thereby affecting all stakeholders, not only commercial and consumer. In GPSIA's view, a key decision point is approaching. GPSIA urges stakeholder engagement at the decision level to ensure continued GNSS utility. Specifically, Ms. Ciganer urged the following: (1) recommend U.S. Government GPS/GNSS stakeholder engagement with EU, EU member states, and European Commission (EC) at decision level to ensure continued availability of the GPS/GNSS spectrum environment to support your mission(s); (2) seek timely EU, EU member states, and EC support for ETSI Guide (EG 203 336) to include GNSS receiver parameters within scope of radiodetermination, a newly explicit RED category, and; (3) seek timely EU, EU member states, and EC support for EC assessor to either sustain EN 303 413 (cited OJEU 12/2017) or cite the current WG SES SCN revision of EN 303 413 (ETSI REN SES 00445) in the OJEU.

Dr. Parkinson wondered why Europeans are not taking the lead.

Ms. Ciganer said the 2004 U.S.-EU agreement has 25 separate state signatories. She does not know which Galileo users in these countries are aware of this issue. They need to be made aware as critical decisions are pending.

Dr. Parkinson said he remains puzzled by the lack of engagement by high-level PNT persons in Europe.

Mr. Goward asked if other private companies based in Europe are engaged.

Ms. Ciganer said various European firms have expressed concerns. She cannot explain the absence of more mobilization by the national operators because the proposal will end up driving receiver design.

Dr. Parkinson said he doubts GPSIA has as much leverage in Europe as European firms would.

Mr. Shane asked if an alliance has been sought with other GNSS systems. Does this need to be a U.S. vs. Europe challenge?

Ms. Ciganer agreed that it is not a U.S. vs. Europe challenge because RED GNSS receiver standard covers the signals from multiple GNSS operators, including European Galileo GNSS. GNSS operator ICDs/ISs provide power on the ground and do not specify values or minimum performance levels for receiver parameters Assignment of a value and performance limit by, for example, an ECC report (as indicated in ETSI Guide 203 336) could affect receiver use of GNSS operator signals differently which should concern all GNSS operators.

Dr. Parkinson said he is not criticizing Ms. Ciganer's efforts. Generally, such problems are not addressed until someone high-enough up in a relevant government act.

Ms. Ciganer emphasized that key decision milestones are occurring in July and October/November. Ms. Ciganer presented three slides on Commission Implementing decision 2018/661, CEPT ECC Report 263 (Under Mandate 536) and CEPT ECC Report 299. Ms. Ciganer urged everyone to review these slides demonstrating regulation of MSS L-band receivers required to develop mitigation techniques under M/536 modification of RED from 5G interference introduced in an adjacent band in a European compatibility study report. While RED does not explicitly cover airborne and marine equipment, review the potential for harmful interference to aeronautical and maritime operations.

Mr. Turner said the Department of State addresses this as a technical issue. He added that while some things are government-to-government, others needed to happen at the manufacturer level.

ADM Allen asked if Mr. Turner is requesting assistance from the Advisory Board.

Mr. Turner said he would need to consider that.

Dr. Parkinson said this issue is similar to the one with GPS adjacent band compatibility – meaning, a regulation that will affect GNSS because it does not acknowledge the very faint nature of the GNSS signals. Evidence supporting this – like the DOT's Adjacent Band Compatibility effort – was needed to support the case.

* * *

**Additional Representatives/International Perspectives:**

ADM Allen requested presenters to be as brief as their material allows.

**1) Dr. Gerhard Beutler,** *Switzerland*

Dr. Gerhard Beutler said he would address efforts to determine Earth's gravity field since the advent of the Space Age. Satellite orbits are calculated based on a number of observations. Orbit determination results either directly in an ephemeris or in parameters that allow generating the ephemeris. The global characteristics of the Earth's gravity potential emerge from satellite motion. He identified the CHAMP, GRACE, and GOCE missions as pathfinders. GPS measurements, gathered by the on-board receiver, may be used to determine a kinematic orbit using Precise Point Positioning. These kinematic positions serve as pseudo-observations in a generalized orbit determination process to solve for the gravity field and orbit parameters. Many satellite arcs/orbits must be combined to obtain the parameters of a gravity field.

Addressing the issue of time variation, periodic variations and trends of the geoidal heights are key results of the analysis of GRACE monthly fields. The GRACE mission strongly suggests that the Earth's gravity field should be monitored on a permanent basis. GRACE-FO is a step in that direction. This mission is being undertaken in partnership between NASA, the German Research Centre for Geosciences (GFZ), and DLR, as GRACE had been. GRACE-FO is in essence a carbon-copy of GRACE, with the addition of an ultra-precise optical Inter-Satellite Link (ISL), which is 10 to 100 times more accurate than the standard microwave ISL. GRACE-FO was launched May 22, 2018, and on May 24 the GRACE-FO Level-1 data product became openly available at NASA and GFZ.

ADM Allen said, referencing an earlier comment, that he thought the Advisory Board should receive an update on the key points of geodesy at each meeting.

**2) Dr. Sergio Camacho-Lara,** *Mexico*

Dr. Sergio Camacho-Lara presented an update on GNSS issues at the United Nations (UN). In his view these should be regularly discussed to support Advisory Board input into the UN. Much work at the UN is being done by the ICG. He referenced Dr. Parkinson's query on the absence of European movement on the RED issue, and added that to gain support for a proposed action one has to understand the forum in which it is presented and how decision-making is carried out. In particular, this is the case with the UN Committee on the Peaceful Uses of Outer Space (COPUOS) and with the International GNSS Committee (ICG), He suggested that the ICG could urge the UN COPUOS to include a discussion on RED, or any other subject, under the agenda item on GNSS in its Scientific and Technical Subcommitee. As the UN provided a neutral setting, diverse views on a subject can be discussed. When an issue is urgent, COPUOS can agree to have, perhaps two or three meetings of interested parties, some months apart, to reach agreements.

Dr. Parkinson said he sensed tremendous urgency from Ms. Ciganer. Mr. Camacho-Lara's suggestion would have great merit in an orderly world, but in practice may not be feasible.

Mr. Goward suggested it might be helpful if, coming into each meeting, Advisory Board members arrived with a list of the outcomes they hoped to depart with, which could then be discussed at the session. This could lead to decisions on which matters were to go forward as action items.

Dr. Camacho-Lara agreed. On GNSS systems, it is his understanding that GLONASS will be fully operable again in 2019, Galileo will be complete in 2020, and BeiDou will be operational by next year. This leads to further discussion of GPS as the Gold Standard of GNSS. ICG has been working through COPUOS, including intercessional meetings of the ICG working groups. A number of work plans are being implemented to promote the use of GNSS technologies as tools for economic and scientific applications. These meetings are held throughout the world, which is important to promote support for GNSS issues by a growing number of countries. For instance, as the ICG is committed to spectrum protection and the various host countries of ICG meetings have representatives at the ITU, one can expect for spectrum protection matters by these ICG meeting host countries. Non-GNSS provider nations need to be aware of the benefits to them from GNSS, and of the various threats to the signal they utilize. He also called attention to the importance to many nations of GNSS-based efforts to detect earthquakes, particularly those on the Pacific Rim.

**3) Mr. Matt Higgins,** *Australia*

The Australian government has allocated AU$ 225m over 4 years for national positioning infrastructure development. It has two components: the SBAS and the so-called NPI Capability, which is about the CORS infrastructure (independently from SBAS RIMS). The SBAS RFI has been released. My understanding is that it is a first round of market sounding for the latest developments and capabilities to then inform the details of what will actually be procured in a second phase, namely, building, operating, and delivering SBAS as a service. SBAS Interoperability WG is meeting in my hometown of Brisbane next week

hosted by Australian Govt. Regarding CORS, state governments are signing off on agreements to hand back operation of the so-called Tier 2 CORS to Geoscience Australia (about half of the current 100 or so stations) to consolidate operations under the NPI initiative. Geoscience Australia has also commenced the process of doubling the current density of such stations. Also worth mentioning is that several states (including my Department) operate so-called Tier 3 stations for RTK networks, etc., and those stations will be retained at State level but with improved integration into the NPI.

I have also presented in the past that we are modernizing our datum to GDA2020 to account for the 1.8m of tectonic motion since we defined our current datum in 1994. The state, territory, and federal governments have committed to adoption of GDA2020 by 30 June 2020, so we are getting to the pointy end.

Australian Space Agency is now up and running and creating a better focus for many space related topics, which is good. As members are probably aware there has been discussion of a possible UK GNSS due to Brexit and I am aware that there has been discussion between the Australian and UK governments on that but I am not privy to any details.

The next IGNSS conference is in Sydney in Feb 2020. A feature of that will be reports on the various SBAS test bed projects that have been run over the past year or so in key application areas. There will also be presentations on the latest developments with the NPI and SBAS work. As always, I would be very pleased to welcome any Board members or speakers to participate in our conference.

Moving from an Australian focus to a more international focus, at the last meeting I presented on system delivered Precise Point Positioning (PPP) and that topic will be the subject of one of the workshops at a UN ICG workshop in Fiji in a couple of weeks (already mentioned by Dave Turner). It will include discussion on the interoperability issues that I raised in my previous presentation. Other topics include how to sustain CORS infrastructure in countries like so-called Small Island Developing States; especially in relation to capacity building, including education aspects that have been mentioned by other Board members today. There is also a workshop on spectrum protection.

I also presented at the last meeting some results with the Xiaomi Mi8, which was the first smartphone with the L1 L5 capable Broadcom chip. I now also have a Huawei phone. It has a dual frequency chip, but I believe it was developed in China (i.e. I don't think it is a Broadcom chip). It is worth noting that this morning at the front of this hotel, it was tracking all 4 global constellations, which is most likely due to it being an Australian variant of the phone.

Finally, in the past I have talked about applications and developments that Brad and his colleagues didn't think of when they designed GPS. My example for this meeting is that Wuhan University has launched a small satellite that broadcasts a GNSS signal using a GNSS receiver on board to steer a relatively inexpensive clock to generate the ranging signals. It opens up a number of interesting possibilities. One is that because it is in a low orbit and passes quickly over China, it gives an additional measurement that can improve the convergence time with precise point positioning. Plus, it is worth noting that it was launched by a University, not a country.

Ms. Ciganer asked what spectrum will be used by a potential UK/Australia GNSS.

Mr. Higgins said he does not know.

Dr. Moore said he cannot comment on spectrum. To date, £96 million has been invested in development.

**4) Dr. Refaat M. Rashad,** *Egypt*

Dr. Refaat Rashad said he would address two points. The first is uninterrupted GPS service, which requires space, ground segment, and user segments. GPS is vulnerable because it is a very weak signal. The problem is interference, intentional or not. The Advisory Board's recommendation has been Protect, Toughen, and Augment. However, there is another class of potential interference, such as the issues with GPS adjacent band compatibility. In these situations the main threat to GPS might be in the form of a government administrator who, for whatever reason, gives a go-ahead to something that compromises the GPS signal. The second point is education. Most PNT programs are at graduate student level. Such programs are also needed for undergraduates, who are the source of future professionals. A broader approach to education, one that extends outside the "closed room" of the community, is needed.

**5) Mr. Dana Goward**, *Resilient Navigation and Timing Foundation*

Mr. Dana Goward said a systematic way is needed to assess risk. What are the major problems that need to be faced? DHS looked at risk as the product of threat, vulnerability, and consequence. For example, the likelihood of a major blizzard striking south Florida might be one in a billion while vulnerability is 100% and damage $5 billion. However, given the unlikelihood, the actual risk is $5. Miami also faces risks from hurricanes. Applying the same formula would make it clear that Miami should prioritize hurricanes above blizzards as a threat. In the case of intentional harm, risk is a product of the malicious

intent times the capability of making good on that intent. For example, while a Martian attack would be devastating, the Martians have no capability to launch an attack. The risk, therefore, is zero. How might one apply this approach to threats to GPS? The RNT Foundation has assessed 22 different threat vectors, both natural and malicious, and made a threat assessment for each. He welcomed further suggestions for this list and hoped to harness the wisdom of the crowd.

Dr. Parkinson asked if assessments could be made of future opportunities.

Mr. Goward said they could. Once necessary judgments about threat, vulnerability, and consequence are made, determining the risk is a simple mathematical equation. Mr. Goward presented a table: Vectors by Risk Score. For example, moderate solar activity has a risk score of 24, whereas the greatest threat would be the cumulative negative impacts over the course of a year of low-level jamming by criminals and privacy seekers. The table is not definitive; rather, it is a model of what can be done. He welcomed the Advisory Board to use the report and welcomed collaboration with anyone doing similar work.

Dr. Parkinson asked if the reallocation of frequencies is reflected in the threat assessment.

Mr. Goward said it is reflected under "interference."

An Advisory Board member said he is pleased to see this chart, as it is the same used by the aviation industry.

* * *

**Roundtable Discussion --- Recommendation Formulation**

*All members, led by Chairs*

ADM Allen said the remaining task is to determine what the Advisory Board will be focusing on for the next two years. He asked Mr. Miller asked if there was anything administrative he can pass on.

Mr. Miller first suggested that the Advisory Board note it has received best regards from Mr. John Stenbit, who will be present at the next meeting, November 20-21, 2019. The Advisory Board could schedule a teleconference in order to prepare for the next meeting and make sure the group is well prepared, as was done in August 2018.

ADM Allen said an initial summary of the meeting, including potential areas of action, will be distributed by email to the Advisory Board members. Advisory Board members should respond to this email with whatever comments they think are pertinent, including suggestions for additions. He also noted that Dr. Parkinson has prepared a list which is neither official nor necessarily complete, but is a good starting point for immediate work.

Dr. Parkinson noted that the Advisory Board rightly takes pride in 25-year old satellites, but that a balance needs to be struck between satellite renewal and the funding consequences thereof.

ADM Allen called attention to 5G. He noted that the Advisory Board has created a series of White Papers. He hopes these will evolve into a permanent government structure that will ease identification of areas in which subject matter experts need to be brought in. We need to have a basis for ensuring all needed topics are covered and all necessary topics are included in future meetings. For example, various pieces related to geodesy could perhaps be brought together under a single umbrella.

Dr. Parkinson sought volunteers to prepare brief White Papers on the topics discussed on markets and industries noted as "critical infrastructure" such as power grid, telecom, finance, transportation, aviation, agriculture, and others.

Mr. Pat Diamond volunteered for the telecom and finance segments as a matter of record.

ADM Allen said the Advisory Board has been preoccupied with the "tyranny of the present," but it needs to look to the larger world circumstance.

Mr. Hatch urged a list be created on spoofing and jamming, including what the difficult and simple problems to address are, how they can be addressed, and by whom.

Mr. Goward volunteered to address what is meant by Gold Standard.

Mr. Murphy said there are barriers to receiver toughening, including such things as export barriers. It might be good for the Advisory Board to hear a report on the pertinent issues. He will draft a short problem statement on such potential barriers.

Mr. Miller asked that all comments be sent to him. He will consolidate and organize them as a step to determining whether a teleconference is needed prior to the November session.

[Post-Meeting: Mr. Shane volunteered to produce white paper from IATA on the importance of stable and reliable GNSS for the commercial aviation sector]

* * *

*The 23rd meeting of the PNT Advisory Board adjourned Friday, June 7, 2019, at 12:07 p.m.*

* * *

## Appendix A: National Space-Based PNT Advisory Board Membership

**Special Government Employees:** Experts from industry or academia who temporarily receive federal employee status during Advisory Board meetings.

- **Thad Allen** (Chairman), Booz Allen Hamilton
- **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**, Airo Drone
- **Patrick Diamond**, Diamond Consulting
- **Dorota A. Grejner-Brzezinska**, The Ohio State University
- **Ronald R. Hatch**, private consultant (retired John Deere)
- **Larry James**, Jet Propulsion Laboratory
- **Timothy A. Murphy**, The Boeing Company
- **T. Russell Shields**, Ygomi
- **Gary Thompson**, North Carolina Emergency Management/Geodetic Survey
- **Frank van Diggelen**, Google
- **Todd Walter**, Stanford University

**Representative**s: Individuals designated to speak on behalf of particular interest groups.

- **Gerhard Beutler**, International Association of Geodesy (Switzerland)
- **Sergio Camacho-Lara**, UN Regional Education Center of Science and Space Technology - Latin America and Caribbean (Mexico)
- **Ann Ciganer**, GPS Innovation Alliance
- **Dana Goward**, Resilient Navigation and Timing Foundation
- **Matt Higgins**, International GNSS Society (Australia)
- **Terry Moore**, University of Nottingham (UK)
- **Refaat M. Rashad**, Arab Institute of Navigation (Egypt)
- **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)
- **Tom Powell**, Aerospace
- **Brian Ramsay**, The MITRE Corporation

## Appendix B: Presentations

Briefings are posted at: https://www.gps.gov/governance/advisory/meetings/2019-06/

1. Determining the Earth's Gravity Field in the 20th and 21st Century / Dr. Gerhard Beutler
2. DARPA Positioning, Navigation, and Timing (PNT) Technology and their Impacts on GPS Users / Dr. John Burke
3. Update on GNSS Issues at the United Nations / Dr. Sergio Camacho-Lara
4. Urgent Action Performance (Capability) of GPS/GNSS Receivers in Europe – Potentially Can Be Read Worldwide as Unilaterally Regulated Under a Mod of RED Using a Radiocommunication (Terrestrial Broadband) Regime / Ms. Ann Ciganer
5. Which is the Bigger Problem? / Mr. Dana Goward
6. Brief Update on Newly Launched Congressional GPS Caucus and Other Educational Efforts / Mr. David Thompson
7. Precise GNSS & V2X for Automated Vehicles / Mr. Curtis Hay
8. Positive Train Control / Carolyn Hayward-Williams; Dennis Stonecypher
9. Space-Based PNT: 15 Years in 15 Minutes / Col Curtis Hernandez
10. GNSS Radio Frequency Interference Detection from LEO / Dr. Todd Humphreys
11. A PNT Threat Environment Model for Military and Civilian Use / Mr. Mark Johnson
12. Economic Studies of GPS and the NGS Gravity Program / Dr. Irving Leveson
13. Global Navigation Satellite Systems – What's up / Dr. Oliver Montenbruck
14. Non-Inertial Navigation in the 21st Century and Beyond / Dr. Val Parker
15. Summary for New Members and Update: A Grave threat to GPS / Dr. Bradford Parkinson
16. National Risk Management Center / Mr. James Platt
17. GPS Enterprise Status and Modernization / Maj David Sampayan
18. The Role of Civil Signal Authentication in Trustable Systems / Mr. Logan Scott
19. U.S. GPS International Activities Update / Mr. David A. Turner
20. Ensuring Safety for all Modes of Transportation & Civil PNT / Ms. Karen Van Dyke
21. Proposed Guidelines for Resilient PNT Receivers / Mr. William Woodward
22. Space Service Volume Approach / Mr. Robert Wright
23. Research on GPS Resiliency & Spoofing Mitigation Techniques across Applications / Mr. Yoaz Zangvil
24. Drone Dependence on GPS / Mr. Joseph D. Burns

## Appendix C: Sign-In List

**Thursday, June 6:**

PNT Advisory Board members:

Brad Parkinson, Stanford University
Penina Axelrad, University of Colorado
John Betz
Gerhard Beutler, AIUB
Dorota Brzezinska, Ohio State University
Scott Burgett
Sergio Camacho, CRECTEALC
Dana Goward, RNT Foundation
Matt Higgins, IGNSS Australia
Terence McGurn, self
Refaat Rashad, Arab Institute of Navigation
Russ Shields, Ygomi
Frank van Diggelen, Google

NASA personnel:

Barbara Adde, NASA
Ben Ashman, Goddard Space Flight Center
Frank Bauer, NASA
Madeleine Bronstein, NASA/Overlook
Adam Greenstone, NASA
Phil Liebrecht, NASA/HQ
Chris Ishisoko, NASA
William Notley, NASA
A. J. Oria, NASA/Overlook
Caitlyn Singam/NASA intern

Other attendees:

Ken Alexander, National Coordination Office
Steve Bartlett,
Valentine Birladenning, Lockheed-Martin
Tim Bransford, lawyer
David Buckman, Lockheed-Martin
Guy Buesnel, Spirent
John Burke, DARPA
Jim Burton, National Coordination Office
Pauline Cook, member of public
Bruce Cox, NextNav
Robert Crane, NCU
Ark Crews, LM
Dale Dalesio, Continental Electronics
Dee Ann Divis, Inside GNSS
Scott Feairheller, US Air Force
Misty Financial, US Air Force
Rich Foster, Microchip
Joe Frankino, National Coordination Office
Neil Gerein, Novatel
David Grossman, GPSIA
Richard Gullickson, VIPGN
Mark Johnson, Collins Aero
Curtis Hay, GM
Carolyn Hayward-Williams, Department of Transportation
Curtis Hernandez, National Space Council
Todd Humphreys, University of Texas/Austin
Charlene King, consultant
Chris Kurby, iPosi
Rich Lee, iPosi
Mark Lemelle, John Deere
Stephen Malys, DARPA
Harold Martin, National Coordination Office
Oliver Montenbruck, DLR
Terry Moore, University of North
Dan O'Laughlin, MITRE
Terry Ott, Public NTP
Sophia Parker, NINT
James Platt, Department of Homeland Security
William Porter, RNTF
Edward Powers, Aerospace
Bill Pramenko
Colleen Pramenko, Virginia Tech student
Greg Ratta, ASRC Federal
Judith Ritchie, SAE
Joe Rolli, Harris
Mike Rosso, Conselec
David Sambrano, United Airlines
Logan Scott, LSC
Cecelia Sells,
Mark Settle, WBK
Dennis Stonecypher, Department of Transportation
Michael Striffolino, Department of Homeland Security
Doug Taggart Overlook
Karen Van Dyke, Department of Transportation
Bill Woodward, SAE
Robert Wright, LM
Yoaz Zangvil, Regulus Cyber
Kurt Zimmerman, Trimble
Two illegible

**Friday, June 7:**

PNT Advisory Board members:

Joe Betz,
Gerhard Beutler, AIUB
Joe Burns
Sergio Camacho, CRECTELC
Jim Gerringer, ESRI
Matt Higgins, IGNSS Australia
Tim Murphy, Boeing
Jeff Shane, IATA
T. Russell Shields, Ygomi
Frank van Diggelen, Google

NASA personnel:

Madeleine Bronstein, NASA/Overlook
A. J. Oria, NASA/Overlook

Other attendees:

Guy Buesnel, Spirent
Pauline Cook, member of public
Bruce Cox, NextNav
Dale Dalesio, Continental Electronics
Pat Diamond, Diamond Consulting
Dee Ann Divis, Inside GNSS
Rich Foster, Microsemi
Neil Gerein, Novatel
Curtis Hay,
Mark Lemelle
Erin Neal, Velocity GR
Dan O'Laughlin, MITRE
Angela Peura, ASRC
Bill Pramenko, VipGlobalnet
Brad Ramsey, MITRE
David Sambrano, United Airlines
Cecelia Sells, VIP Globalist
David Turner, Department of State
Karen Van Dyke, Department of Transportation
Yoaz Zangril, Regulus Cyber

## Appendix D: Acronyms & Definitions

| | |
|---|---|
| $ | U.S. Dollar Currency |
| £ | British Pound Currency |
| 4G | 4th Generation Mobile Communications Standard |
| 5G | 5th Generation Mobile Communications Standard |
| A$ | Australian Dollar Currency |
| ADS-B | Automatic Dependent Surveillance-Broadcast |
| AFSPC | Air Force Space Command |
| AFTS | Automated Flight Termination System |
| AIS | Automated Identification Systems |
| BeiDou | China's GNSS |
| bps | bits per second |
| CGSIC | Civil GPS Service Interface Committee |
| CHAMP | Challenging Mini-satellite Payload mission |
| cm | centimeter |
| COPUOS | Committee on the Peaceful Uses of Outer Space |
| CRECTEALC | Regional Center for Space Science and Technology Education for Latin America and Caribbean, affiliated to |
| DARPA | Defense Advanced Research Projects Agency |
| dB | decibel |
| DHS | Department of Homeland Security |
| DLR | German Aerospace Center |
| DoD | Department of Defense |
| DOE | Department of Energy |
| DOS | Department of State |
| DOT | Department of Transportation |
| E1 | Galileo E1 Signal (Carrier Frequency 1575.420 MHz, Reference Bandwirdth 24.552 MHz) |
| E5 | Galileo E5 Signal (Carrier Frequency 1191.795 MHz, Reference Bandwirdth 51.150 MHz) |
| E6 | Galileo E6 Signal (Carrier Frequency 1278.750 MHz, Reference Bandwirdth 40.920 MHz) |
| EC | European Commission |
| EMP | Electromagnetic Pulse |
| eLoran | Enhanced Loran |
| ESA | European Space Agency |
| ETSI | European Telecommunications Standards Institute |
| EU | European Union |
| EXCOM | Executive Committee |
| FAA | Federal Aviation Administration |
| FACA | Federal Advisory Committee Act |
| FCC | Federal Communications Commission |

| | |
|---|---|
| FOC | Full Operational Capability |
| FRA | Federal Railroad Administration |
| FY | Fiscal Year |
| G1 | GLONASS G1 signal (equivalent to GPS L1) |
| Galileo | European GNSS |
| Galileo O/S | Galileo Open Service |
| Galileo C/S | Galileo Commercial Service (now renamed Galileo High Accuracy Service, or Galileo HAS) |
| GEO | Geosynchronous Orbit |
| GDOP | Geometric Dilution of Precision |
| GFZ | German Research Centre for Geosciences |
| GLONASS | Russian GNSS |
| GM | General Motors |
| GNSS | Global Navigation Satellite System |
| GOCE | Gravity field and steady-state Ocean Circulation Explorer mission |
| GPS | Global Positioning System |
| GPS-D | GPS Directorate |
| GPS IIA | GPS Block IIA |
| GPS III | GPS Block III SVs 1-10 |
| GPS IIIF | GPS Block III SVs 11-32 |
| GPSIA | U.S. GPS Innovation Alliance |
| GRACE FO | Gravity Recovery and Climate Experiment Follow-On mission |
| HEO | High Earth Orbit |
| HD | High Definition |
| Hz | Hertz |
| I-ETMS | Interoperable Electronic Train Management System |
| IATA | International Air Transport Association |
| ICAO | International Civil Aviation Organization |
| ICD | Interface Control Document |
| ICG | International Committee on GNSS |
| IGS | International GNSS Service |
| IMU | Inertial Measurement Unit |
| IOC | Initial Operating Capability |
| ION | Institute of Navigation |
| ISL | Inter-Satellite Link |
| ISS | International Space Station |
| ITAR | U.S. International Traffic in Arms Regulations |
| J/S | Jamming to signal ratio |
| km | kilometer |
| kW | kilowatt |
| L1 C/A | 1st GPS Civil Signal |

| | |
|---|---|
| L1C | 4th GPS Civil Signal (interoperable with Galileo) |
| L2C | 2nd GPS Civil Signal (commercial) |
| L5 | 3rd GPS Civil Signal (safety-of-life / aviation) |
| LEO | Low Earth Orbit |
| Loran | Long-Range Aid to Navigation (typical refers to the system up through Loran-C, now decommissioned in the U.S) |
| M-Code | GPS encrypted military signal |
| MEMS | Micro-Electro-Mechanical Systems |
| MEO | Medium Earth Orbit |
| MHz | Megahertz |
| mm | milimeter |
| mph | miles per hour |
| NASA | National Aeronautics and Space Administration |
| NDAA | National Defense Authorization Act |
| NGS | National Geodetic Survey |
| NOAA | National Oceanic and Atmospheric Administration |
| NRMC | National Risk Management Center |
| NSpC | National Space Council |
| OCS | GPS Operational Control Segment |
| OJEU | Official Journal of the European Union |
| OCX | Modernized GPS Operational Control System |
| OMB | Office of Management and Budget |
| PCO | Phase Center Offset |
| PNT | Positioning, Navigation, and Timing |
| PNTAB | National Space-Based PNT Advisory Board |
| PPP | Precise Point Positioning |
| PRN | Pseudo Random Noise Code |
| PTA | Protect, Toughen, and Augment |
| PTC | Positive Train Control |
| QZSS | Quasi-Zenith Satellite System |
| RED | Radio Equipment Directive |
| RF | Radio Frequency |
| RFI | Request for Information |
| RPV | Remotely Piloted Vehicle |
| SBAS | Space-Based Augmentation System |
| SCaN | Space Communications and Navigation program |
| SDR | Software Defined Radio |
| SIS | Signal in Space |
| SMC | Space & Missile Systems Center |
| SSV | Space Service Volume (Volume of space between 3000 km and GEO altitudes) |

| | |
|---|---|
| SV | GPS satellite vehicle |
| U.S. | United States |
| UAV | Unmanned Aerial Vehicle |
| UK | United Kingdom |
| UN | United Nations |
| URE | User Range Error |
| U.S. | United States of America |
| USAF | U.S. Air Force |
| UTC | Universal Time Coordinated |
| V2V | vehicle-to-vehicle communication |
| V2X | Connected-vehicle-to-everything communication |
| W | Watt |
| WAAS | FAA Wide Area Augmentation System |
| WTO | World Trade Organization |