SPACE-BASED POSITIONING, NAVIGATION AND TIMING
NATIONAL SYSTEMS ENGINEERING FORUM

5 MAR 2018

MEMORANDUM FOR THE NATIONAL COORDINATION OFFICE
SPACE-BASED PNT EXECUTIVE COMMITTEE
In Turn

SUBJECT: Gap Analysis Final Report

1. Attached is the completed NPEF Gap Analysis Final Report, in response to an action item from the Oct 2016 meeting of National Executive Committee (EXCOM) for Space-Based PNT to conduct an assessment of GPS receiver test methodology to ensure that existing and evolving uses of space-based PNT services are not affected.

2. The NPEF analyzed the results and methodology of the tests performed by the FCC TWG, NPEF, RAA, DOT, and NASCTN to determine if there were questions that were not answered and/or conditions that were not tested, to determine the maximum aggregate power level of out-of-band transmissions. In accordance with the NCO task, the NPEF used the recommendations of the PNT Advisory Board as the criteria for completing its assessment.

3. Please direct any questions regarding the Gap Analysis to the undersigned.

JAMES R. HOREJSI, GG-15
DOD NPEF Co-Chair

KENNETH K. ALEXANDER
DOT NPEF Co-Chair

Attachment:
NPEF Gap Analysis Final Report, dtd 1 Mar 18

SPACE-BASED POSITIONING
NAVIGATION & TIMING
NATIONAL SYSTEMS ENGINEERING FORUM

FINAL REPORT

Assessment to Identify Gaps in Testing of Adjacent Band Interference to the Global Positioning System (GPS) L1 Frequency Band

Prepared By:

National Space-Based Positioning, Navigation, and Timing
Systems Engineering Forum (NPEF)

Approved By:	
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James R. Horejsi, GG-15, USAF **DOD NPEF Co-Chair**	**Kenneth K. Alexander** **DOT NPEF Co-Chair**
Date: 3/01/2018	**Date:** 3/01/2018

SPACE-BASED POSITIONING
NAVIGATION & TIMING
NATIONAL SYSTEMS ENGINEERING FORUM

EXECUTIVE SUMMARY

The National Executive Committee for Space-Based Positioning, Navigation, and Timing (PNT EXCOM), with assistance from the National Space-Based PNT Coordination Office (NCO), tasked the National Space-Based PNT Systems Engineering Forum (NPEF) to conduct an assessment of testing methodologies used to analyze the impacts of adjacent band interference on Global Positioning System (GPS) receivers. The tasking additionally stated that this gap analysis "should be conducted based on the recommendations from the Space-Based PNT Advisory Board (PNTAB)." The tasking also directed the NPEF to identify any unanswered questions or untested conditions that would hinder the GPS community from determining the "maximum aggregate power level of out-of-band transmissions to ensure that the existing and evolving uses of space-based PNT services are not affected." [1]

In accordance with the NCO task statement, the gap analysis evaluated five tests performed by the following organizations:

1) Federal Communication Commission (FCC)-mandated Technical Working Group (TWG)
2) National Space-Based PNT Systems Engineering Forum (NPEF)
3) Department of Transportation (DOT) Adjacent Band Compatibility (ABC)
4) Roberson and Associates (RAA)
5) National Advanced Spectrum and Communications Test Network (NASCTN)

These organizations conducted tests to inform spectrum regulators on the compatibility of a terrestrial, Long Term Evolution (LTE) network infrastructure in the frequency band adjacent to the GPS L1 with the existing GPS infrastructure, which exists as a vital enabler for critical systems around the world. Since each test varied in scope, the NPEF began the gap analysis by establishing an evaluation framework, a set of evaluation criteria, and a set of standardized definitions for the various test environments. Despite the variations in scope, all tests, at a minimum, included an assessment of the impact from a proposed 10 MHz LTE downlink terrestrial network centered at 1531 MHz with a maximum effective isotropic radiated power (EIRP) of 32 dBW. Each test also addressed, in varying levels of detail, the potential for interference to GPS receivers from proposed LTE user equipment centered on 1632.5 MHz and 1651.5 MHz.

The gap analysis concluded that three of the five tests evaluated during this effort included sufficient scope and methodology in compliance with the PNTAB's set of recommendations, namely the DOT ABC, NPEF, and FCC TWG tests. While some questions remain largely unanswered despite the substantial scope of these tests, the gap analysis concluded that the results from these three tests are sufficient and appropriate to inform spectrum policy makers on the major impacts of the proposed LTE network on GPS receivers. The FCC TWG and NPEF tests both concluded that there are no feasible mitigations to resolve the adjacent band interference issues introduced by the proposed network. Correspondingly, the DOT test results briefed during the March 2017 ABC public workshop revealed the power levels that GPS and GNSS receivers can tolerate from interference sources in the adjacent band in an effort to inform

the enforcement of a GPS interference protection criterion. GPS users rely on L-band spectrum to receive the signals transmitted from the GPS constellation, so the preservation of the spectral environment is fundamentally critical to GPS operations.

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INTRODUCTION

At the direction of the National Executive Committee for Space-Based Positioning, Navigation, and Timing, herein referred to as the EXCOM, and facilitated by the National Coordination Office (NCO), the National Space-Based PNT Systems Engineering Forum (NPEF) was tasked to conduct an assessment of Global Positioning System (GPS) receiver test methodology.

Scope of Task

Specifically, the NCO tasked the NPEF "to conduct a gap analysis between the testing presented by National Institute for Standards and Technology (NIST) conducted by the National Advanced Spectrum and Communications Test Network (NASCTN), the testing performed by Roberson and Associates (RAA), and testing conducted by the U.S. Department of Transportation (DOT) through its GPS Adjacent Band Compatibility Assessment." The analysis was subsequently expanded by the NCO to include previous testing conducted by the FCC-mandated Technical Working Group and testing performed by the NPEF in 2011. The task went on further to state: "This gap analysis regarding testing to determine the compatibility of GPS and Global Navigation Satellite Systems (GNSS) to adjacent band power levels should be conducted based on the recommendations from the Space-Based PNT Advisory Board (PNTAB)." The full text of the task statement can be found in Appendix B.

Specifically the NPEF was asked to examine:

1) The results of testing conducted by the Federal Communication Commission (FCC)-mandated Technical Working Group (TWG) in 2011. [2]

2) The results of testing conducted by the NPEF in 2011. [3], [4]

3) The Adjacent Band Compatibility (ABC) Assessment undertaken by the Department of Transportation (DOT) to derive adjacent band power limits, as a function of offset frequency, to ensure continued operation of all applications of GPS services. [5], [6]

4) The Roberson and Associates (RAA) test plan and results on deployment of LTE Ancillary Terrestrial Component (ATC) and harmful interference. [7]

5) The National Advanced Spectrum and Communications Test Network (NASCTN) test plan, sponsored by Ligado Networks (formerly LightSquared), and its results on the impact of LTE Signals on GPS Receivers. [8]

While the NPEF tasks were directed to be conducted in cooperation with the EXCOM Departments and Agencies to the (maximum) extent possible, the NCO directed the NPEF to produce an independent report to the Executive Steering Group (ESG) and EXCOM.

The analysis assessed the results and methodology of the testing done by TWG, NPEF, RAA, NASTCN, and the DOT to determine if there are questions that were not answered and/or conditions that were not tested to determine the maximum aggregate power level of out-of-band transmissions to ensure that the existing and evolving uses of space-based PNT services are not affected. In accordance with the PNT EXCOM action item, the NPEF considered the recommendations of the PNT Advisory Board in completing the NPEF assessment.

TEST REPORTS ANALYZED

The following sections provide an overview of the scope and conclusions for each test included in the gap analysis.

FCC Technical Working Group (TWG)

The FCC formed the TWG to “study the GPS overload/desensitization issue as described in DA 11-133.” [2] LightSquared co-chaired the TWG with GPS Industry Council (GPSIC) and the two groups worked together to submit a joint work plan to the FCC outlining their test methodology. The working group divided into seven sub-teams for test execution, each focusing on a specific category of GPS receivers. Each sub-team included participants from both LightSquared and the GPS community with a common goal to execute a valid test and provide mitigation information (if possible) to “prevent harmful interference to GPS.” [2]

The test evaluated the impact of LightSquared’s original three-phase proposal (i.e., one 5 MHz channel centered at 1552.7 MHz, two 5 MHz channels centered at 1552.7 MHz and 1528.8 MHz, and two 10 MHz channels centered at 1550.2 MHz and 1531.0 MHz); lower 10 MHz downlink channel on a stand-alone basis and uplink in 1626.5-1660.5 MHz (for some receiver categories). The downlink channels were tested with maximum EIRP of 32 dBW.

As test execution progressed, the working group grew divided on several issues, which are described in the final report in sections titled “LightSquared Perspective” and “GPS Industry Perspective”. The GPS community concluded that “based on the analysis performed, LightSquared should not be permitted to use the L-Band spectrum for a densely-deployed, non-integrated terrestrial-only network.” [6] Conversely, the LightSquared participants proposed a new test metric of 6 dB degradation in carrier-to-noise density ratio (C/N_0). In the FCC TWG final report, LightSquared explained for general location devices, for example, that “analysis established that all devices tested against the Lower 10 MHz channel experienced a 4 dB change in C/N_0 only at signal strengths greater than -25 dBm; a signal strength which will occur only in up to 1.2% of LightSquared’s service area…” [2] These conclusions are representative of the divergences articulated throughout the FCC TWG final report.

National Space-Based PNT Engineering Forum (NPEF) Test

The NCO established the NPEF as a permanent working group to provide analysis and discussion of systems engineering issues and technology development opportunities related to GPS and its augmentation systems. The PNT EXCOM tasked the NPEF to “conduct an assessment of the effects of LightSquared’s planned deployment of a terrestrial broadband network to Global Positioning System (GPS) receivers and GPS-dependent systems and networks.” [3]

The NPEF conducted the first of two tests in March 2011 to investigate the impacts of interference on a select set of GPS receivers. The NPEF highlighted test conclusions throughout the report in the form of recommendations. Recommendation 1 states “LightSquared should not commence commercial services per its planned deployment for terrestrial operations in the 1525-1559 MHz Mobile- Satellite Service (MSS) Band due to harmful interference to GPS operations.” [3]

In October 2011, the NPEF conducted a second assessment that “focused on receivers supporting applications categorized as “General Location/Navigation” and on the first proposed phase of LightSquared’s revised deployment, which uses a single 10 MHz portion of spectrum (1526-1536 MHz) designated as ‘10L’) for Ancillary Terrestrial Component (ATC) transmissions.” [4] The NPEF highlighted test results throughout the final report in the form of conclusions. Conclusion 1 states that “based on test results, LightSquared’s lower 10 MHz signal configuration causes harmful interference to the majority of general navigation GPS receivers tested.” [4]

Department of Transportation (DOT) Adjacent Band Compatibility (ABC) Tests

The DOT conducted an assessment to develop GPS spectrum interference protection criteria meant to “inform future proposals for non-space, commercial uses in the bands adjacent to the GPS signals.” The DOT executed the primary test in April 2016 at the White Sands Missile Range anechoic chamber. At the time of this report, the final test report from the DOT ABC assessment is not yet published. However, the test results and subsequent conclusions were presented in March 2017 at the sixth GPS Adjacent Band Compatibility Assessment Workshop. [6]

The test quantified the C/N_0 degradation caused by 1 MHz noise and 10 MHz LTE signals in the bands adjacent to GPS L1. The center frequencies of the interference sources was varied, but the test results allowed the assessment of a 10 MHz LTE signal at 1526-1536 MHz with a maximum EIRP of 32 dBW and reduced EIRP levels. The goal of the test was to determine the “the adjacent-band transmitter power limit criteria…necessary to ensure continued operation of GPS services, and determine similar levels for future GPS receivers...” [5] While the exact values vary by receiver category and LTE network architecture and the resulting aggregate power, the test results indicate that the maximum tolerable EIRP of interference sources in the frequency bands adjacent to GPS are in the milliwatt or microwatt range. [6]

Roberson and Associates (RAA) Test

“Ligado Networks (“Ligado”)…hired Roberson and Associates, LLC (RAA) to conduct tests to determine whether deployment of an LTE network in channels adjacent to spectrum used for GPS, using the parameters for which Ligado has applied in its license modification applications, affects the ability of GPS devices to provide accurate position information to users.” [7] In May 2016, RAA tested four categories of receivers for impacts from 10 MHz uplink and downlink LTE signals in the frequency band adjacent to GPS. The four frequency bands used to simulate the LTE interference source included: 1526-1536 MHz, 1627.5-1637.5 MHz, 1646.5-1656.5 MHz and 1670-1680 MHz. RAA concluded that “Ligado’s proposed LTE deployment is clearly compatible with existing GPS operations as implemented by leading device manufactures.” [7] The final report from the RAA test also discusses RAA’s conclusion that C/N_0 is altogether an invalid metric to establish protection criteria for GPS and GNSS receivers.

National Advanced Spectrum and Communications Test Network (NASCTN)

The National Advanced Spectrum and Communications Test Network (NASCTN) addresses spectrum-sharing issues "in an effort to accelerate the deployment of wireless technologies among commercial and federal users." [8] Ligado Networks submitted a proposal to NASCTN to develop a test method to investigate the impact of LTE signals in the adjacent band on GPS devices operating in the L1 frequency band. In May 2016, NASCTN tested four categories of receivers (three if grouped according to gap analysis categories) to develop a test methodology and support a broad understanding of GPS receiver performance in accordance with a Cooperative Research and Development Agreement (CRADA) with Ligado.

The test assessed the impact of 10 MHz uplink and downlink LTE interference signals. Since this test was not purposed to support a decision or draw a conclusion, the test report states that "data was presented without defining or use of pass/fail criteria as the establishment of those criteria was not part of this project." [8]

ASSESSMENT METHODOLOGY

The PNT Advisory Board advises the U.S. Government on GPS-related policy, planning, program management, and funding profiles. The PNT Advisory Board published their minimum criteria for the evaluation of interference impacts from high-power terrestrial transmitters in repurposed radio bands. In accordance with the PNT EXCOM's direction to conduct the gap analysis "based on the recommendations from the Space-Based Advisory Board (PNTAB)", the NPEF evaluated each test against the six PNTAB criteria. [9]

Evaluation Criteria

The NPEF translated each PNTAB criteria into questions to facilitate an objective evaluation. These questions were developed to capture the intent of the criteria, while simplifying each test's evaluation to a yes or no answer. The following sections describe each PNT Advisory Board criteria and discuss each of the five test efforts' adherence to that criteria.

#	***PNTAB Criteria***	***Assessment Question***
1	Accept and strictly apply the 1 dB degradation Interference Protection Criterion (IPC) for worst case conditions. *(This is the accepted, world-wide standard for PNT and many other radio-communication applications.)*	Question: Did the test apply the 1 dB degradation IPC as its evaluation metric?
2	Verify interference for all classes of GPS receivers is less than criteria, especially precision (Real time Kinematic – requires both user and reference station to be interference-free) and timing receivers *(economically these two classes are the highest payoff applications – many $B/year)*	Question: Did the test include all classes of satnav receivers (in sufficient quantity) in its interference analysis?

3	Test and verify interference for receivers in all operating modes is less than criteria, particularly acquisition and reacquisition of GNSS signals under difficult conditions (see attachment of representative interference cases)	Did the test evaluate all satnav receiver operating modes?
4	Focus analysis on worst cases: use *maximum* authorized transmitted interference powers and *smallest-attenuation* propagation models (antennas and space losses) that do not underrepresent the maximum power of the interfering signal (including multiple transmitters).	Did the test assess the impact of interference using max power/minimum attenuation assumptions?
5	Ensure interference to emerging Global Navigation Satellite System (GNSS) signals *(particularly wider bandwidth GPS L1C – Galileo, GLONASS)*, is less than criteria	Did the test assess the impact of interference on reception of all emerging GNSS signals?
6	All testing must include GNSS expertise and be open to public comment and scrutiny.	Did the test solicit and adequately respond to feedback from GNSS experts and the public?

ANALYTICAL RESULTS

The results for each of the six criteria are described below:

Criteria 1

1	Accept and strictly apply the 1 dB degradation Interference Protection Criterion (IPC) for worst case conditions. *(This is the accepted, world-wide standard for PNT and many other radio-communication applications.)*	Question: Did the test apply the 1 dB degradation IPC as its evaluation metric?

The PNT Advisory Board supports and recommends the application of a 1 dB IPC for adjacent-band interference testing. This metric is used to ensure harmful levels of interference are prevented and is a widely-used metric for the detection of radio-frequency environment degradation. [10] Even a test that evaluated a comprehensive range of GPS and GNSS receivers in a sufficient test environment may still render misleading test results if the test applied a metric other than the 1 dB IPC as its pass/fail criteria. A 1 dB noise threshold is an industry standard that avoids assigning all available link margin to a specific error/interference source, which is a critical characteristic of sustainable spectrum management.

The RAA test opted to use key performance indicators (KPIs) instead of a purely C/N_0 metric. RAA collected C/N_0 data, but used 2-dimensional and 3-dimensional position error as the pass/fail metric for each applicable receiver. In fact, the RAA report states that the testing “found no meaningful correlation between 1 dB change in C/N_0 and GPS device’s KPI performance.” [7] In accordance with the scope of the test, NASCTN did not employ pass/fail metrics at all, but instead collected a variety of measurands such as 3-dimensional position error, C/N_0, and time to first fix to "support a broad understanding of GPS receiver performance." [8] The FCC TWG, NPEF, and DOT tests employed the 1 dB IPC as the evaluation metric.

Criteria 2

2	Verify interference for all classes of GPS receivers is less than criteria, especially precision (Real time Kinematic – requires both user and reference station to be interference-free) and timing receivers *(economically these two classes are the highest payoff applications – many $B/year)*	Question: Did the test include all classes of satnav receivers (in sufficient quantity) in its interference analysis?

Modern-day GPS and GNSS receivers enable a diverse array of applications. Interference testing must include the full array of receiver categories to ensure a comprehensive test scope representative of this diverse user base. For this gap analysis, the NPEF defined a comprehensive set of receiver categories to standardize the assessment of receiver inclusivity amongst the tests. The GPS and GNSS receiver categories used to perform the gap analysis included: general location, timing, high-precision, cellular, space-based, general aviation, certified aviation, and military.

The NPEF grouped real-time kinematic receivers in the high-precision receiver category, but noted that this receiver type has a unique operational context. Also, since access to certified aviation and military receivers is controlled, tests were not evaluated for the inclusion of these receiver categories. Certified aviation receivers do not require testing since existing certified aviation receiver standards already specify the maximum tolerable interference environment.

The NPEF conducted two tests. The first NPEF test did not include receivers in the cellular category while the follow-on NPEF test was de-scoped to focus on general location, high-precision, timing, military, and cellular receivers (via a complimentary test led by the National Telecommunications and Information Administration (NTIA)). The RAA test did not assess receivers in the space-based or timing categories. The NASCTN test did not assess receivers in the cellular, aviation, or space-based categories, but did include high-precision receivers with an extended real time kinematic (RTK) feature. The NASCTN test report explained that "devices specific to aviation, space-based, cellular, or military applications were outside of the scope." [8] In the DOT ABC test, all classes of receivers were tested in the 2016 testing except for certified aviation receivers. These receivers did not require receiver and antenna equipment testing because the certified aviation receiver standards specify the maximum tolerable interference environment to ensure all receiver functions are protected and the receivers are tested at these levels during certification testing. The FCC TWG and DOT tests assessed all six receiver categories.

Criteria 3

3	Test and verify interference for receivers in all operating modes is less than criteria, particularly acquisition and reacquisition of GNSS signals under difficult conditions (see attachment of representative interference cases)	Did the test evaluate all satnav receiver operating modes?

This criteria highlights the need for tests to consider all phases of GPS receiver operation during testing to ensure the 1-dB IPC is satisfied in accordance with criteria 1. A GPS receiver's operating mode affects its sensitivity to radiofrequency interference. The gap analysis defined the operating modes as acquisition and tracking. Acquisition modes (i.e., cold start, warm start, and hot start) depend on the initial state of the receiver. The exact conditions for warm and hot start vary by receiver type and application, but the GPS community defines cold start operating mode as when the receiver has no prior information about its own position or satellite visibility, requiring it to perform extensive searching to locate and track the GNSS signal-in- space. Due to the resource-intensive nature of this test case, the gap analysis did not evaluate tests against the cold start acquisition mode, however the NASCTN test did perform some cold start acquisition testing using automated test scenarios.

The FCC TWG, NPEF, NASCTN, and DOT tests assessed warm and hot start acquisition modes. The RAA test report makes no mention of acquisition mode testing. All the tests evaluated GPS/GNSS receivers in code tracking mode.

Criteria 4

4	Focus analysis on worst cases: use *maximum* authorized transmitted interference powers and *smallest-attenuation* propagation models (antennas and space losses) that do not underrepresent the maximum power of the interfering signal (including multiple transmitters).	Did the test assess the impact of interference using max power/minimum attenuation assumptions for the interfering signal?

The FCC TWG, NPEF, and RAA tests were executed to assess the impacts of a specific proposal whereas the DOT and NASCTN tests sought to provide analytical insights into GPS spectrum protection and testing methodologies, respectively. The FCC TWG was established to "examine the potential for overload interference/desensitization to GPS receivers, systems, and networks from operation of LightSquared Subsidiary, LLC's (LightSquared's) planned deployment of a terrestrial broadband network in the mobile-satellite service (MSS) spectrum licensed to LightSquared in the 1525-1559 MHz and 1626.5-1660.5 MHz frequency bands." [2] The NPEF initial test was an "assessment of the effects of LightSquared's planned deployment of a terrestrial broadband network to Global Positioning System (GPS) receivers and GPS-dependent systems and networks." [3] Similarly, the NPEF follow-on test was executed to "test and validate data on the performance of personal/general navigation Global Positioning System (GPS) receivers in light of LightSquared's modified proposal to confine its operations to the lower 10 MHz signal (1526- 1536 MHz) of the Mobile-Satellite Services (MSS) frequency band.” [4] The RAA test sought to “conduct tests to determine whether deployment of an LTE network in channel’s adjacent to spectrum used for GPS, using the parameters for which Ligado has applied in its license modification applications, affects the ability of GPS devices to provide accurate position information to users.” [7]

Conversely, the tests conducted by NASCTN and DOT did not aim to address a specific proposal, but instead provided data to inform the broader spectrum interference and protection discussion. The NASCTN test was tasked to: “(1) develop a test method to investigate the impact of adjacent-band long-term evolution (LTE) signals on global positioning system (GPS) devices that operate in the L1 frequency band, and (2) perform radiated measurements on a representative set of GPS devices to validate the test method.” [8] The NASCTN test report states that “the LTE network deployment under study was intended to be generic and architecture agnostic;” Similarly, the DOT test was executed to “develop new Global Positioning System (GPS) spectrum interference standards to inform future proposals for non-space, commercial uses in the bands adjacent to the GPS signals.” [5] The test evaluated receiver impacts over a range of adjacent-band frequencies and LTE interference source EIRP levels. The tests conducted by both NASCTN and DOT included the parameters detailed in Ligado’s proposal modification application, so those parameters served as the baseline for the gap analysis.

The state of the interfering signal as seen at the input of the GPS/GNSS receiver serves as the primary concern in spectrum protection discussions. As such, interference analysis calculations should use worst case path loss parameters (e.g., maximum transmitter EIRP, minimum radio propagation path attenuation) to ensure protection in every operational scenario. For the proposal in question, these parameters are specified as a downlink signal in 1526-1536 MHz with a maximum EIRP of 32 dBW. The FCC TWG, NPEF, NASCTN, and DOT tests included these parameters within the scope of their testing. The RAA test included interference signals within the proposed bandwidths, but did not test against maximum LTE EIRP levels. The RAA test report explains that the “LTE signal…was applied starting at -80 dBm, with LTE levels incrementing until reaching -10 dBm.” [7]

Criteria 5

5	Ensure interference to emerging Global Navigation Satellite System (GNSS) signals *(particularly wider bandwidth GPS L1C – Galileo, GLONASS)*, is less than criteria	Did the test assess the impact of interference on reception of all emerging GNSS signals?

The success of GPS paved the way for GNSS applications around the world. The GPS L1C signal enables interoperability between GPS and international satellite navigation systems. The gap analysis defined emerging signals to include L1C-compatible signals broadcast from GPS, Galileo, GLONASS, and BeiDou. The bounds of multi-GNSS applications are rapidly expanding, so spectrum policy must protect the GNSS spectral environment to support this growing field.

The DOT test evaluated the adjacent band compatibility of the full suite of emerging signals. The FCC TWG, NPEF, and NASCTN tests assessed the impact on emerging signals from GPS, but did not assess the impact on signals from Galileo, GLONASS, or BeiDou. The RAA test assessed only the legacy GPS L1 C/A signal.

Criteria 6

6	All testing must include GNSS expertise and be open to public comment and scrutiny.	Did the test solicit and adequately respond to feedback from GNSS experts and the public?

GPS has evolved into a vital resource for the world and an enabler of critical global applications. Any proposal that threatens to degrade the GPS/GNSS radiofrequency environment must be evaluated against the backdrop of the service's criticality. As a dual-purposed civil system, the public deserves full transparency into any testing that informs decisions impacting civilian GPS users. Furthermore, the testing must be informed by experts in GNSS to ensure its setup, scope, analysis, and conclusions are technically accurate and contextually relevant.

The FCC TWG, NPEF, and DOT tests included both public comment and unconstrained GNSS expertise. The NASCTN testing included limited public comment and GNSS expertise engagement due to scope constraints. The RAA test did not provide transparency to, nor solicit input from the public or GNSS experts.

UNANSWERED QUESTIONS

In addition to the PNTAB criteria, the PNT EXCOM tasked the NPEF to identify any unanswered questions or untested conditions that require resolution before determining the compatibility of an LTE network in the frequency band adjacent to GPS. The NPEF concluded that each relevant area of study was addressed to some extent, but identified six areas of study that could benefit from future testing. Even though these areas of study were identified as gaps, many can be addressed by analysis. The following sections briefly describe each area of study and are listed alphabetically.

Aggregate Interference

The radiated tests conducted to assess the impact from LTE base-stations in the frequency band adjacent to GPS L1 utilize a single transmitter to emit the interfering signal. However, the actual implementation of an LTE network requires thousands of base-stations strategically arranged in an architecture that optimizes the network's performance. As such, the true impacts of an adjacent-band LTE network can only be assessed in the context of the aggregated interference from the LTE network. Thus far, the spectrum community has estimated this impact by analysis.

Additionally, discussions concerning the appropriate interference protection criteria for GNSS receivers to date focus on the impact experienced as a result of solely the proposed network. However, the GNSS L1 frequency band (and its adjacent bands) are already inhabited by operational systems. Thus, future studies should account for the current RF environment when quantifying the compatibility of a new LTE network with the existing GPS environment.

Cold Start Receiver Acquisition Mode

GPS signal acquisition entails an extensive search process that requires the receiver to detect the presence of the desired GPS signal, determine the signal code delay and carrier frequency, and eventually synchronize with the signal. The signal quality, universally quantified by C/N_0, is directly proportional to the dwell time in a receiver's Doppler bin, and in turn, the receiver's acquisition time. Cold start receiver acquisition mode represents the most sensitive operational mode for a typical GPS receiver, and as such, should be the limiting case for spectrum protection from adjacent-band interference. The NASCTN used test automation to develop a methodology to test the impact of adjacent-band interference on receivers in the cold start acquisition mode that could be adapted in future tests to provide additional information on this topic.

Impacts from LTE Handset Transmission Interference

The proposed LTE network includes a request to repurpose two frequency bands for user equipment uplink transmissions. While each test included in the gap analysis addressed the impact to GPS receivers from LTE handset uplink transmissions to some extent, they all focused primarily on downlink (or base station) transmissions in the frequency band below GPS L1. The potential for interference from LTE handset transmissions depends heavily on the handsets' use case, aggregation, and proximity to the GPS receiver. The uncertainties in the proposed network's deployment architecture and use cases call for future testing to more accurately assess the impact to GPS users from LTE handset transmissions. Due to this uncertainty, the gap analysis concluded that the existing test data may not represent the true worst-case scenario for terrestrial and space-based GPS receivers due to the potential for high-volume LTE user equipment transmissions in close proximity to GPS users.

Multi-GNSS Impacts

Criteria 5 of the PNTAB's minimum criteria for the testing/evaluation of interference potential of high power terrestrial transmitters in repurposed radio bands highlights the need to protect the radiofrequency environment of emerging GNSS signals. The number of multi-GNSS applications is destined to grow as GPS' L1C signal continues to facilitate interoperability between GNSS service providers, paving the way for economic growth, innovation, and enhanced health and safety-of-life applications. The DOT test assessed the impact on multi-GNSS receivers, but the dynamic nature of the GNSS landscape constantly ushers in new multi-GNSS user equipment forced to operate in a more densely populated RF environment. Future tests could provide additional information on this topic to compliment the DOT ABC test data.

Multipath in Urban Environments

GPS receivers operate across a diverse set of environments. Urban environments present a unique challenge to GPS receivers due to the volume and density of RF-dependent devices, and the complex physical terrain (e.g., buildings, trees, reflective structures, etc.) which introduces constructive and destructive interference from multipath. This environment would be best analyzed in future tests conducted in a live sky environment.

Motion Scenarios

Many GPS receivers operate in a kinetic state and must maintain a stable level of performance in a dynamic environment. The RAA test evaluated GPS receivers in a motion scenario, but the test did not apply the 1-dB IPC as its evaluation metric, so it fails to effectively inform the GNSS spectrum community on the issue. This area of study could benefit from future testing that includes GPS receivers in motion test scenarios. The density of emitters in the motion test scenarios should duplicate an architectural laydown with densities consistent with any proposed deployment, since GPS receivers on vehicles in motion that are impacted by one emitter need to reacquire the satellites and the distance between the emitters may or may not permit time for reacquisition depending upon the speed of the vehicle and the spacing between the emitters.

CONCLUSIONS

Figure 1 summarizes each test's adherence to the PNTAB's minimum criteria for testing/evaluation of interference potential of high power terrestrial transmitters in repurposed radio bands.

COMPLIANCE WITH PNTAB CRITERIA

PNTAB Evaluation Criteria	TWG	NPEF Rounds 1 & 2	RAA	NASCTN	DOT
1. Used 1 dB IPC as metric	●	●	○	○	●
2. Included all classes of receivers	●	○	○	○	●
3. Included all modes of operation	●	●	○	●	●
4. Focused on stressed conditions	●	●	○	●	●
5. Addressed impact on emerging GNSS	○	○	○	◑	●
6. Included GNSS experts and public	●	●	○	◑	●

Figure 1. Summary of PNTAB Criteria Evaluations

While the NASCTN and RAA tests set forth significant effort to inform the compatibility of the proposed LTE network with the existing GNSS L1 spectrum environment, the gap analysis found each test's scope and framework to be insufficient when evaluated against the PNTAB's set of minimum criteria.

The gap analysis identified several unanswered questions that, if studied further, could provide additional information. However, the NPEF concludes that the data from the FCC TWG, NPEF, and DOT tests, when combined, are sufficient and appropriate to determine the maximum tolerable aggregate power level of transmissions in the band adjacent to GPS L1.

The NPEF strongly recommends that decisions impacting the GPS RF environment be informed by data from tests that align with the PNTAB's set of minimum criteria and with full consideration of the potential operational, scientific, and economic impacts.

APPENDIX A: REFERENCES

[1] H. Martin, *Director, National Coordination Office,* 2017.

[2] "FCC Technical Working Group (TWG) Final Report," Federal Communications Commission, 2011.

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Note: Readers are encouraged to review source documentation for more detailed information about each test.

APPENDIX B: TASK STATEMENT COVER LETTER

SPACE-BASED POSITIONING
NAVIGATION & TIMING
NATIONAL EXECUTIVE COMMITTEE

UNITED STATES OF AMERICA

April 19, 2017

MEMORANDUM FOR: CO-CHAIRS, NATIONAL SPACE-BASED POSITIONING, NAVIGATION AND TIMING ENGINEERING FORUM

FROM: Harold W. Martin III
Director, National Coordination Office
for Space-Based Positioning, Navigation, and Timing

SUBJECT: Tasking to Identify Gaps between the Roberson & Associates tests, the NASCTN Testing, and the DOT GPS Adjacent Band Assessment Study

During the October 27, 2016 Space-Based Positioning, Navigation, and Timing (PNT) Executive Committee (EXCOM) meeting, the Space-Based PNT Advisory Board (PNTAB) raised concerns in regards to the scope of the National Advanced Spectrum and Communications Test Network (NASCTN) test plan for Global Positioning System (GPS) receiver testing presented by the National Institute of Standards and Technology (NIST). Although the PNT Advisory Board and several EXCOM departments and agencies had submitted recommended changes to NIST regarding the NASCTN testing methodology to ensure comprehensive testing, the test plan was limited in scope based on requirements of its customer, who was funding the testing.

EXCOM Action Item 1610-E05 which resulted from the discussion states:

The National Space-Based PNT Coordination Office (NCO) will work with the National Space-Based PNT Engineering Forum (NPEF) and PNTAB to identify gaps between NASCTN's testing and the U.S. Department of Transportation's (DOT's) Adjacent Band Assessment Study, relative to the recommendations of the PNT Advisory Board. If required, develop and resource a proposal for NASCTN to complete a gap study.

As a result of this Action Item, the NPEF is tasked to conduct a gap analysis between the testing presented by NIST, conducted through NASCTN, the testing conducted by Roberson and Associates (RAA), and the testing conducted by the U.S. Department of Transportation (DOT) through its GPS Adjacent Band Compatibility Assessment. This gap analysis regarding testing to determine the compatibility of GPS and Global Navigation Satellite Systems (GNSS) to adjacent band power levels should be conducted based on the recommendations from the PNTAB.

I request the NPEF provide an initial "quick-look" assessment identifying parameters not tested and/or adequately tested by May 31, 2017 in the form of an unclassified talking paper. The final

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