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LTE Impacts on GPS
Test and Metrology Plan

Prepared by:

Dr. William Young, NIST
Dr. Daniel Kuester, NIST
Dr. Adam Wunderlich, NIST
Dr. Duncan McGillivray, NIST
Dr. Marc Weiss, NIST
Mr. John Ladbury, NIST
Dr. Sheryl Genco, NASCTN
Mr. Frank Sanders, ITS
Mr. Billy Riddle, NIST

Reviewed and approved by: xxxx, xxxx

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Preface

The “LTE impacts on GPS: Test and Metrology Plan” discussed in this document is intended to ensure these fundamental goals:

- a transparent, well-calibrated test method
- sound and statistically-valid data retrieval and processing
- a clear path from measurement setup to data collection to processed results
- inform discussions between different interests on proper measurement requirements

In pursuit of these goals, the NASCTN team initially focused on an anechoic chamber test environment, as such testing represents a necessary component in achieving all of the goals above. The content in this version of the document reflects the initial development of the anechoic test method, but does not incorporate insight from any preliminary anechoic chamber tests that would naturally solidify the test plan. Incorporation of preliminary results will occur during in the first testing stage.

The ability to maintain consistent test parameters that are shared between any testing environments greatly impacts the ability to draw strong correlations between data collected via different methods. Thus, direct correlation to previous test results depends on strength of the linkage between test parameters that are common to the methods. Comparison of results between this test and any other tests are outside the scope of this effort; that relationship must be established by additional analysis.

The waveforms used in this testing assume some basic features of a communication system architecture. An important aspect of this test includes an iteration with simultaneous activity both in the up and downlinks of the band, which are separated in the spectrum. The LTE waveforms assume certain levels, resource block usage, and data transfer rates. Typical for this type of testing, the downlink signal is a 10 MHz LTE channel with fully-allocated resource blocks; the uplink is a 10 MHz LTE channel with 70% resource block allocation.

There are several key features to this document, such as Section 7 Statistical Considerations and the calibration procedures in Appendix C, which provide valuable discussions that are highly relevant to similar test methodologies. In addition, Section 5 proposes testing of timing receivers by examining the output timing pulse train.

The test is designed to make a reproducible measurement with as few assumptions as possible. Namely, our approach aims to measure the response to a given ratio of GPS and LTE power levels in the GPS device, while limiting the number of extraneous variables. From this measurement, it will be straightforward to extrapolate the results to specific choices for various factors, such as:

- Antenna patterns
- Antenna polarizations
- Propagation environment
- Angle of arrival
- Separate antennas for GPS and LTE signal transmission.

NASCTN will solicit comments about the test plan from the engineering community within federal and non-federal groups and entities.

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1 Background

The National Advanced Spectrum and Communications Test Network (NASCTN) was established to support four key functions [1]:

- Facilitate and coordinate spectrum sharing and engineering capabilities,
- Create a trusted capability for evaluating spectrum-sharing technologies,
- Perform outreach activities to identify spectrum-related testing and modeling needs, and
- Protect proprietary, classified and sensitive information while facilitating maximum dissemination.

In support of these functions, this NASCTN effort focuses on potential impacts of proposed Long Term Evolution (LTE) activities adjacent to the L1 GPS band. The resulting test methods and data are intended to provide sound and transparent technical information that can support the technical dialogue between affected parties.

In January of 2011, the United States Federal Communications Commission (FCC) granted a waiver for the operation of a terrestrial communications network in a frequency band adjacent to that used by the Global Positioning System (GPS). This waiver required the users of the spectrum to prove that their transmissions would not interfere with existing GPS receivers. The resulting four-month (March to June, 2011) measurement effort brought together experts from the fields of communications, GPS, and EMC (Electromagnetic Compatibility), referred to as a GPS Technical Working Group (TWG). The TWG formed sub-teams to evaluate different types of GPS receivers (e.g. aviation, cellular, general location and navigation, precision timing, etc.) for possible interference effects. These efforts, including their test plans, paved the way for future efforts to assess potential interference between transmitters and GPS receivers.

However, even after the TWG presented their results, consensus on the definition of what constitutes interference to a GPS receiver has yet to be achieved. The GPS industry prefers to define interference as a 1 dB change in the carrier-to-noise-density ratio (C/N_0) as reported by the receiver. This implies that a 1 dB increase to the noise floor, as measured by any receiver in a shielded or direct-wired environment, is considered interference. Potential users of the spectrum adjacent to the GPS bands have proposed a definition based on the end-user experience. To complicate matters, many modern GPS receivers do not readily provide Key Performance Indicators such as C/N_0. This significantly impedes future evaluations of GPS receivers by users and license holders in frequency bands adjacent to GPS without the assistance and cooperation from GPS manufacturers.

2 Objective

The objective of this project is to establish a test methodology to investigate the impact of LTE transmission on GPS receivers. This test is not a pass/fail determination but rather covers a range of LTE power levels to determine the impact trends.

Specifically, an emulated 10-MHz-bandwidth LTE waveform is created by fully allocating the resource blocks with data representative of downlink activity. The uplink LTE is created by emulating a 3.5-Mbps LTE signal. A set of select GPS devices will be tested as part of test validation and the collection of a subset of data.

The testing will make use of an anechoic chamber. A representative subset of available devices will be tested in the anechoic chamber.

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3 Scope

The purpose of the GPS receiver measurement project is to develop a rigorous testing methodology and collect supporting data to establish the impact of LTE signals on GPS devices. The test method discussed here focuses on the anechoic chamber setup.

A key aspect in the investigation is the quality and availability of measurands such as the signal-to-noise ratio (SNR), C/N_0, position error, pseudo range error, etc. Emphasis is on real-world expected LTE signals. However, where practical, the LTE signal levels will be elevated to a power level that produces noticeable degradation so as to provide data that can inform LTE system architecture considerations. Since the specific architecture of deployment (e.g. base station density and location) is not yet known, to the extent possible, the testing is performed in a manner that seeks to be architecture agnostic.

An important consideration in the testing is the specifics of the LTE waveform. The downlink closest to the GPS band is generally considered the waveform most likely to cause disruption due to its high power and high utilization factor. The next waveform considered critical for interference testing is the uplink closest to the GPS band due to out-of-band emissions (OOBE).

The scope is the impact of LTE on GPS performance. Specifically, LTE waveforms representing downlink bands will occupy 1526 MHz - 1536 MHz and 1670 MHz - 1680 MHz. The bands of 1627.5 MHz - 1637.5 MHz and 1646.5 MHz - 1656.5 MHz will contain uplink waveforms. The order of priority for testing are the 1526 MHz - 1536 MHz downlink and the 1627.5 MHz - 1637.5 MHz uplink.

The 1526 MHz - 1536 MHz and 1646.5 MHz - 1656.5 MHz pair combination represents a condition where the GPS devices will be in the presence of both down and uplink activity, and the architecture is assumed to follow the traditional cellular phone separation between up and downlink. However, since an architecture has not yet specified, the pair used for testing will include the 1526 MHz - 1536 MHz downlink and the 1627.5 MHz - 1637.5 MHz uplink. The maximum power level is not expected in both bands at the same time, but simultaneous activity in both the up and downlinks resemble a more realistic deployment scenario than operation in only the uplink or downlink portions of the band.

The categories of devices for testing include general navigation, and high precision position and timing. Aviation, space-based, cellular, and DoD devices of all categories are not included. The test procedure would likely require modification to include those additional categories of devices.

Precision devices will be tested with the antenna specifically designed and typically included with that system. Replacement antennas that may provide additional filtering and amplification are not part of this test.

The initial measurements will focus on stationary devices, with a moving satellite constellation.

Some important test considerations are: 1) the device-under-test (DUT) may not provide a mode of operation that allows collection of the desired measurands; 2) an accurate radiation pattern for the DUT will typically be unknown; 3) the DUT is generally not a metrology-grade piece of equipment. These factors shall be mitigated to the extent that is practical, but will contribute to the uncertainty of the final results.

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4 Deliverable

The output of this project will be a test methodology and measurement data from a set of GPS devices subject to nearby LTE activity. These data will be collected for several measurands identified in the sections below. Statistics on the collected data will be provided as discussed in the "Statistical Considerations" section below. Pass/fail criteria will not be discussed nor will conclusions be drawn by the testing team on the data collected.

The measurement process described here is intended to focus on the LTE waveform impacts on a GPS DUT. In order to compare those results to a field-deployment scenario, additional processing must be completed. To the first order, Appendix A describes how to carry-out that extrapolation process.

A key component will be the characterization of the setup. This is important to establish the veracity of the data. Appendices B through D discuss parameters important to characterization of the setup and a calibration process. Appendix E provides an analysis on intermodulation products due to the bands of interest.

5 Test Methods

5.1 Overview

The anechoic chamber tests utilize GPS and LTE emulation to characterize the impacts of LTE activity in the bands previously discussed on various devices that utilize GPS. The data on the ambient RF conditions and temperature will be monitored and collected as part of the test process. The anechoic chamber tests will not include atmospheric impairments.

The test methods are designed to minimize the influence on factors such as polarization mismatch and path loss during the testing. Those factors should be included as the measured data is extrapolated to in-field performance estimates. Factors that are typically considered in the extrapolation process are discussed in Appendix A.

5.2 Parameters

5.2.1 Device Under Test (DUT) Population

The initial targeted set of DUTs for the experiment are listed in Table 1 through Table 4. This list may be modified to either include additional devices or remove devices where extraction of measurands is not achievable. In some cases, extraction of useable data from the devices will require cooperation from the manufacturer. Some key features and web links are included each of the devices.

The highest priority devices were included in previous testing efforts. Lower priority devices are chosen for considerations such as ability to access the measurands (e.g. development boards) and representation of common user platforms (e.g. fitness devices). Both of these latter examples represent current and growing uses of GPS technology. The first round of testing will focus on the top two or three devices in each of the categories.

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Table 1. General Navigation and Location devices identified for testing. Some key features relevant to testing are included.

General Location and Navigation							
Unit	**Priority**	**Antenna**	**PC interface**	**Data format(s)**	**Extra KPIs**	**Sub-type**	**Website**
Motorola MW810	1	Internal	RS232 USB Bluetooth	NMEA UBX TAIP	NMEA params	First Responder	https://www.motorolasolutions.com/content/dam/msi/docs/business/products/mobile_computers/vehicle-mounted_computers/mw810/_documents/staticfiles/mw810_mobile_workstation_r2_user_guide.pdf
Garmin eTrex H	2	Internal	USB Flash	NMEA GPX	NMEA params	Hiking	https://buy.garmin.com/en-US/US/into-sports/discontinued/etrex-h/prod8705.html
Garmin eTrex 30x	3	Internal	USB	GPX	No	Hiking	https://buy.garmin.com/en-US/US/into-sports/handheld/etrex-30x/prod518048.html
Garmin Montana 650t	4	Internal	USB	NMEA GPX	NMEA params	Hiking	https://buy.garmin.com/en-US/US/on-the-trail/montana-650t/prod75228.html
Garmin Montana 680t	5	Internal	USB	NMEA GPX	NMEA	Hiking	https://buy.garmin.com/en-US/US/into-sports/hiking/montana-680t/prod523677.html
Fitbit Surge	6	Internal	Bluetooth?	TCX	No	Wearable	https://www.fitbit.com/surge
Apple iPad Air 2 (WiFi only)	7	Internal	USB Wi-Fi Bluetooth	App-dependent	Unknown	Tablet	http://www.apple.com/shop/buy-ipad/ipad-air-2

Table 2. High precision positioning devices identified for testing.

High Precision Positioning						
Unit	**Priority**	**Antenna**	**PC Interface**	**Data format(s)**	**Extra KPIs**	**Website**
Trimble NETR9	1	Trimble Zephyr Geodedic Antenna Model 2	Ethernet Bluetooth Onboard	NMEA,T02, RINEX v2, RINEX v3, Google Earth KMZ	all NMEA RINEX	http://www.trimble.com/Infrastructure/Trimble-NetR9.aspx
Leica GR30	2	Leica AR10, or Leica AS10	Ethernet USB RS232 Onboard	NMEA, RINEX, MDB, HATANAKA, CMR, CMR+, RTCM BINEX	all NMEA RINEX	http://leica-geosystems.com/products/gnss-reference-networks/receivers/leica-gr50-and-gr30

Table 3. Precision timing devices identified for testing

Precision Timing						
Unit	**Priority**	**Antenna**	**Accuracy**	**Ext. Oscillator Support**	**Lock state indicator**	**Website**
Arbiter 1088B GPS Satellite Clock (40ns)	1	Arbiter AS0087800 GPS Active Timing	40 ns	Yes	Yes	http://www.arbiter.com/catalog/product/model-1088b-gps-satellite-precision-time-clock-40ns.php
MicroSemi Symmetricom SyncServer S650	2	Microsemi Kit	<15ns	Yes	Yes	http://www.microsemi.com/products/timing-synchronization-systems/time-frequency-distribution/network-appliances-servers/syncserver/syncserver-s650

Table 4. Development boards identified for testing.

Development Boards							
Unit	**Priority**	**Chipset**	**Antenna**	**PC interface**	**Data format(s)**	**Extra KPIs**	**Website**
Ublox M8 Board	1	Ublox M8 Chrystal	Internal External Kit	USB 2.0 RS232	NMEA UBX	all NMEA C/N0	https://www.u-blox.com/en/product/evk-m8
SwiftNav Piksi v2.3.1	2	Maxim Integrated MAX2769	Internal External Kit	USB UART	NMEA RINEX	Pseudorange C/N0	https://www.swiftnav.com/sites/default/files/swift_datasheet_030716.pdf
Adafruit Ultimate GPS Breakout Board	3	Global Top 013	Internal External Kit	UART	NMEA	all NMEA C/N0	https://www.adafruit.com/products/746

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5.2.2 Global Positioning System (GPS) Satellites

The configurations for the satellite constellation are based on a nominal and limited exposure setting, respectively. Values selected for these conditions are similar to those in the 3GPP Specification TS 37.571-1, though not identical. Details for the constellation are listed in Table 5. Losses from the calibrated test signal radiation to the DUT will be verified according to Appendix D.3.

The emulated GPS signals will not include atmospheric propagation impairment effects based on input that not all GPS devices are compatible.

For some devices, a “live sky” may be necessary in order to evaluate its performance. The anechoic facilities have the infrastructure required provide “live sky” GPS signals.

Table 5. Satellite constellation setup.

Nominal	
Number of generated satellites	8 to 12
GPS L1 C/A signal for all satellites	-130 dBm
Propagation conditions	AWGN
Limited Exposure	
Number of generated satellites	6
GPS L1 C/A signal for 1st satellite	-129 dBm
GPS L1 C/A signal for 2nd satellite	-132 dBm
GPS L1 C/A signal for 3rd satellite	-135 dBm
GPS L1 C/A signal for 4th satellite	-138 dBm
GPS L1 C/A signal for 5th satellite	-141 dBm
GPS L1 C/A signal for 6th satellite	-144 dBm
Propagation conditions	AWGN
Augmentation signals	
WAAS	-128.5 dBm
GPS constellation power levels based on hypothetical power available from a 0 dBi antenna in the location of the DUT.	

5.2.3 Augmentation Signals

The intent of the testing is to focus on the LTE impacts on GPS. When possible, the DUT will be tested initially without augmentation signals. Augmentation signals such as Wide Area Augmentation Signals (WAAS), Real Time Kinematic (RTK), and Mobile Satellite Services (MSS) will be included as needed and time permitting.

5.2.4 Long Term Evolution (LTE) Signaling Scenarios

The LTE waveforms emulated for signaling in these tests will be generic because the architecture of the proposed LTE system is not known to authors of this test plan. Emulated LTE waveforms and power levels will be chosen to mirror those in a few key scenarios relevant to the topic under study:

1. LTE Downlink (base station transmission) only, radiated toward a GPS L1 receiver,
2. LTE Uplink (User Equipment (UE) transmission) only, radiated in close physical proximity to a GPS L1 receiver,
3. Dual LTE uplink and LTE downlink activity - 1 and 2 (above) superimposed. For example, the downlink will be attenuated by 96 dB from maximum power (representing a free-space path loss of approximately one km) and the uplink will be stepped through a range of power levels.

The LTE uplink and downlink frequency bands are each 10 MHz allocations as specified in Table 6. The LTE downlink band at 1670 MHz-1680 MHz may not be generated during tests if a cavity filter is not available with this passband.

Table 6. Up and downlink frequencies.

Number	LTE Link Direction	LTE Band (MHz)
1	Downlink	1526 - 1536
2	Downlink	1670 - 1680
3	Uplink	1627.5 - 1637.5
4	Uplink	1646.5 - 1656.5

Waveforms will be designed to match the emissions masks under consideration in [8]. These emission masks specify effective isotropic radiated power (EIRP) power spectral density (PSD) limitations or LTE UEs and base stations. They are illustrated by Figure 1 in relation to GPS L1 and LTE operating bands under consideration.

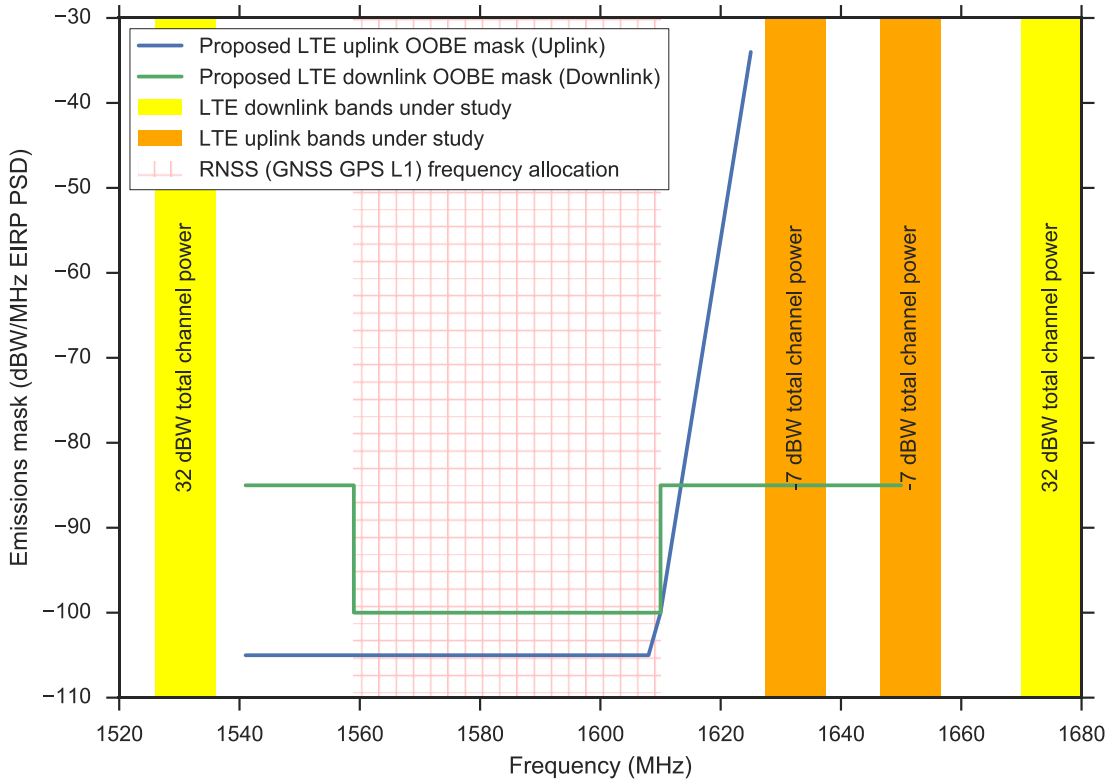


Figure 1. Proposed in-band and out-of-band LTE emission masks under study near the radio navigation satellite service (RNSS) allocation used by GPS L1

5.3 Setup

5.3.1 Equipment

The nominal equipment needed to conduct these measurements are listed in Table 7. Substitute equipment that meets the necessary performance criteria may be used. The final report will include the actual equipment used during the testing.

Table 7. Equipment for anechoic chamber testing.

Item	Example Manufacturer Part Number	Manufacturer Specification	Quantity
GPS emulator	Spirent GSS8000	(Provided by EPG)	1
LTE emulator	Rohde Schwarz SMW200A (or similar)	With LTE emulation option	1
Isolator	Fairview Microwave SFI1020 (or similar)	1- 2 GHz Isolation > 19 dB	2
LTE amplifier	TBD	TBD	1
Programmable attenuator	Mini-Circuits RCDAT-6000-110 (or similar)	0.25 dB steps; 0.3 dB uncertainty	3
LTE downlink in-band OOB rejection filter	Custom	TBD	1
Diplexer	KP Microwave F00150	Separates an input into separate channels - LTE downlink bands and uplink bands	2
Combiner	MECA DC802-2-1.500V	800 MHz – 2200 MHz Isolation > 22 dB	1
Antenna (RHCP for anechoic chamber)	ETS-Lindgren 3102	RHCP conical log spiral Nominal 1 GHz-10 GHz; use gain calibration @ 3m	1
Antenna (LTE source for outdoor, validation horn)	ETS Lindgren 3115 (or similar)	Nominal 1 GHz-18 GHz; use gain calibration @ 10m	1
Spectrum Analyzer	TBD		1
Network Analyzer	TBD		
Signal generator for LTE OOB emission	TBD	TBD (Requires ARB capability)	1
Time Interval Counter	Keysight Technologies 53220A (or similar)	Single shot resolution 100 ps	1

Temperature monitor	TBD	TBD	1

Precision Timing Cable	Web Link	Length
FSJ1-50A, HELIAX® Superflexible Low Density Foam Coaxial Cable, corrugated copper, 1/4 in, black PE jacket	http://www.commscope.com/catalog/andrew/product_details.aspx?id=1342	53.4 m
LDF2-50, HELIAX® Low Density Foam Coaxial Cable, corrugated copper, 3/8 in, black PE jacket	http://www.commscope.com/catalog/wireless/product_details.aspx?id=1351	55 m

5.3.2 GPS Position Testbed

The position tests investigate how the LTE waveform impacts the GPS receiver's ability to provide accurate position. Figure 2 depicts the setup in the anechoic chamber that provides the GPS environment and the LTE waveform. Some of the key features are the addition of out-of-band emission (OOBE) noise and the custom OOBE filter on the downlink signal. The test process is to setup the desired GPS constellation state, and then follow the process depicted in Figure 8. The inclusion of augmentation signals such as WAAS and RTK will be included as necessary. It is important to recognize that these tests are focusing on the change in the baseline due to the LTE activity, not on the precise locations.

The test setup depicts a single antenna radiating both the GPS and LTE signal. This setup will need to be checked carefully to ensure proper isolation between the two signal paths. The calibration process (Appendix C) will ensure that proper isolation is maintained, and that the cable and coupler losses and antenna gain and polarization factors (e.g. circular versus linear) are accounted for in the setup. The purpose for using a single antenna rather than two separate antennas is to remove potential orientation bias between the transmitting antennas and the DUT, and thus reduce the uncertainty in the ratio of LTE to GPS power received by the DUT. In post analysis, factors such as antenna mismatches and path loss can be included to relate the measurements to deployment scenarios.

Adequate isolation between channels is necessary to ensure that coupled signals between signal paths do not cause problems. This needs to be verified experimentally before testing begins. If the isolation provided by coaxial paths and large attenuation levels is not sufficient, additional isolators can be added to the testbed. When possible, isolators will be removed in order to minimize the number of devices in the signal chain and maximize flatness across the wide 1526 MHz – 1680 MHz operating band.

If proper isolation in the LTE and GPS signal paths is not achievable with a single antenna, then a two antenna setup will be used, with separate signal paths for the LTE and GPS waveforms. The same calibration process will be required as the use of two antennas by no means ensures the isolation between the signal paths. In addition, care must be taken to minimize the impacts of antenna coupling on the antenna patterns. A primary drawback to using two antennas is the increased uncertainty in the power ratio of the LTE and GPS signals received by the DUT antenna.

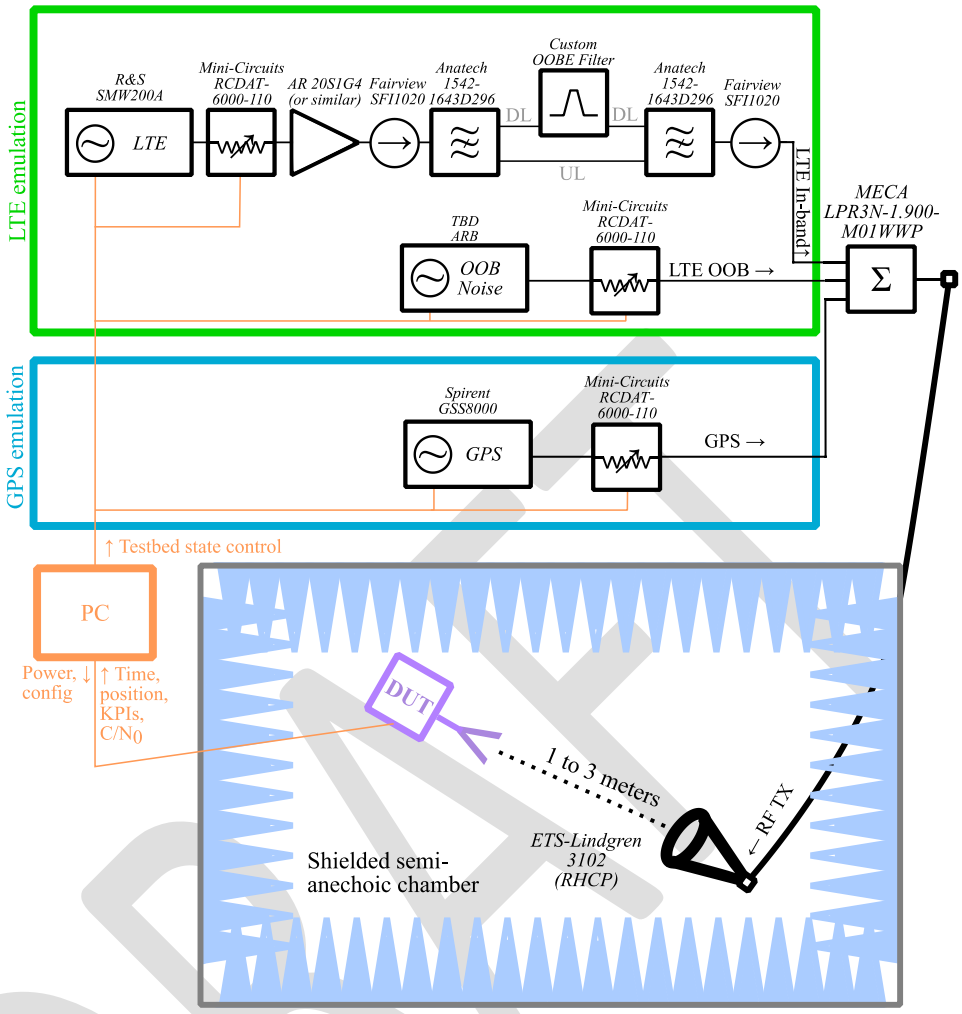


Figure 2. Setup for position measurements in the anechoic chamber.

5.3.3 GPS Time Testbed

Timing variations can be greatly influenced by the GPS receiver, antenna, and receiver-to-antenna cable individually, and impedance matching among them. Hence it is important to measure them as a combined unit. The cable length also contributes to timing variations, and a length should be chosen that maximizes these variations [2].

Each GPS satellite transmits its own version of UTC with errors in the transmitted values as well as due to the propagation medium. Timing receivers all produce a 1 PPS to realize the best estimate of UTC, and many can also provide data that give the individual satellite UTC values as offsets from the 1 PPS out.

Figure 3 illustrates the test setup for timing tests. Some additional considerations for the calibration and measurement process from the position test are discussed below

First, the time accuracy of the receiver is first measured without an LTE signal. This should be done with minimal filtering by an oscillator in the receiver. The test focuses on the performance of the antenna,

cable, and receiver system, not the ability of an oscillator to filter these. For example, a rubidium (Rb) or cesium (Cs) atomic frequency standard could greatly slow the appearance of any bias, but could not stop it. The calibration continues until the variations in UTC from the receiver stabilize.

Second, during the test, LTE signals are introduced in the adjacent band at minimal power levels, then stepped up until the receiver loses lock. This is the process shown in Figure 8. Timing data are stored to allow determination of UTC accuracy and stability for the 1 PPS and, if available for each individual satellite.

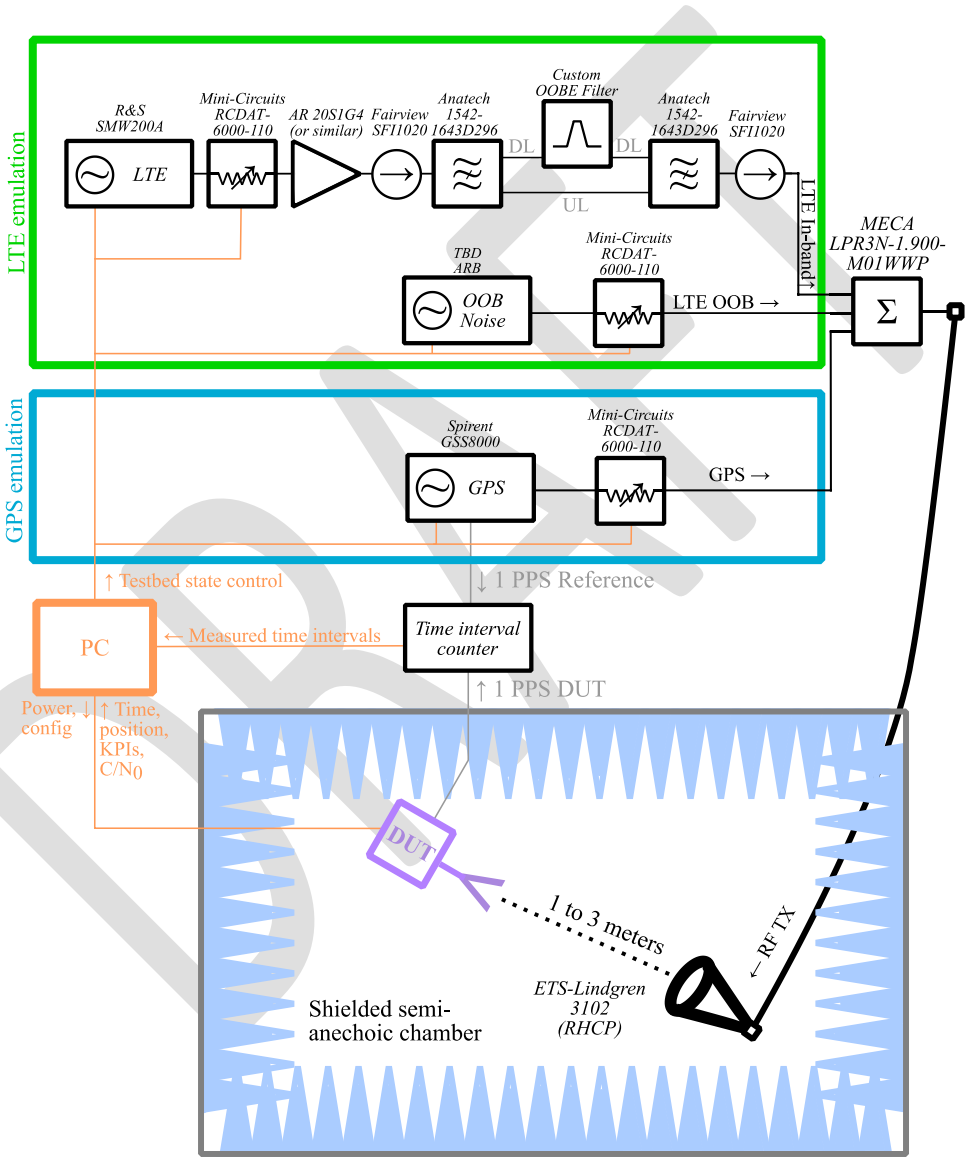


Figure 3 Setup for precision timing tests in the anechoic chamber.

5.3.4 In-Band LTE Emulation

The LTE in-band downlink (base station transmission) signaling will be synthesized for all tests at the full 10 MHz frequency allocation and full resource block allocation.

The uplink interference signal is meant to represent a single LTE UE uploading streaming video to a base station over a weak link. The data load is a pseudo-random binary sequence. The channel is 10 MHz wide (half of a 10 MHz allocation) consisting of 50 available resource blocks (RBs). The base station compensates for the weak link with fair scheduling, limiting the number of RBs allocated to our UE; we assume a relatively large 35 RB (70%) allocation. The UE compensates for the weak link by transmitting the quadrature phase-shift keying (QPSK) at its maximum allowed EIRP following Figure 1. Proposed in-band and out-of-band LTE emission masks under study . Resource blocks are distributed by Type-2 PUSCH frequency hopping, resulting in an RB allocation time plan as illustrated in Figure 4 and a spectrum like that in Figure 5. This uplink corresponds with 7 Mbps maximum data rate.

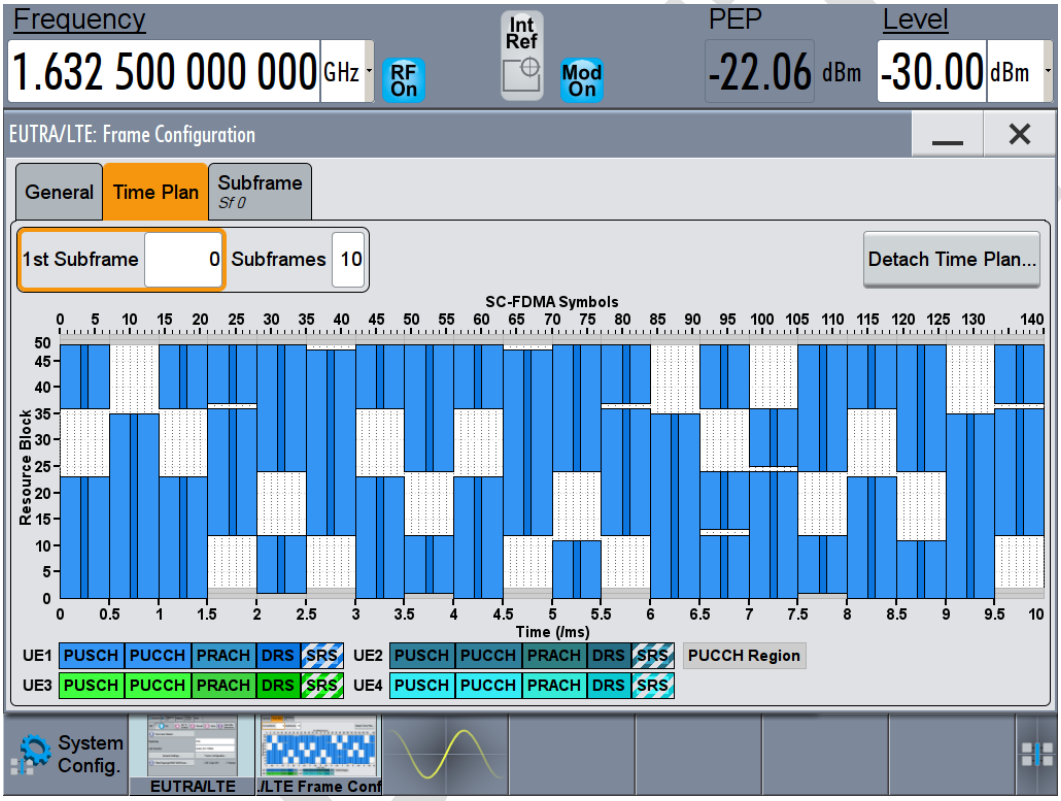


Figure 4. Example LTE uplink resource block allocation

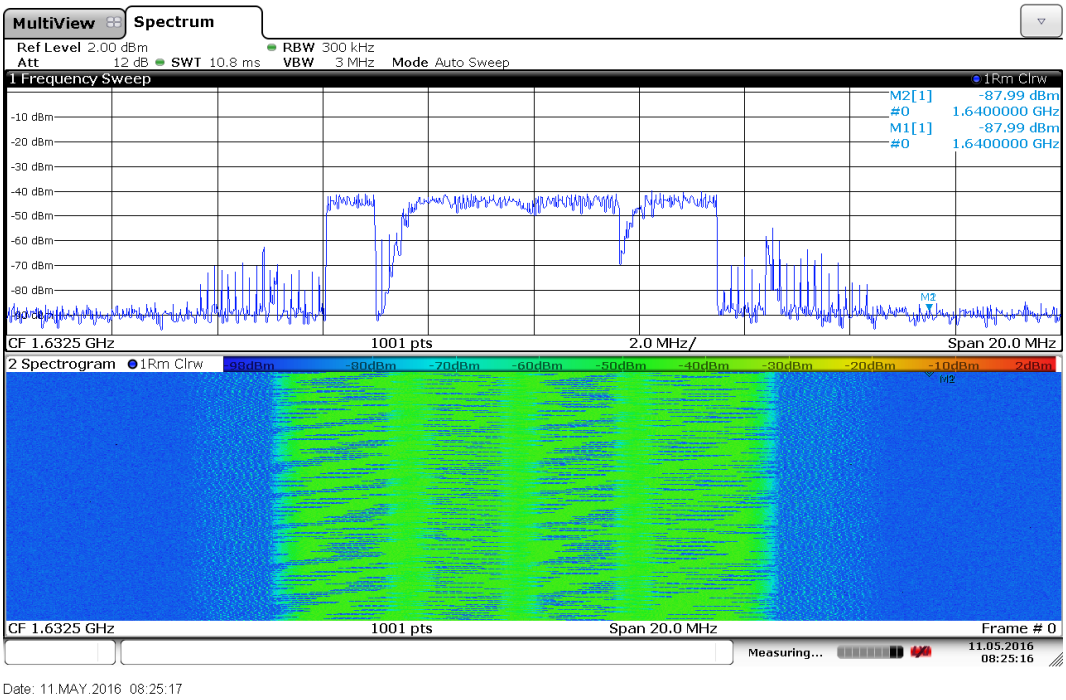


Figure 5. Example PSD measurement of a 10 MHz LTE uplink

The LTE in-band waveforms used in testing will also include scenarios that include both uplink and downlink activity. In the dual link configuration, the waveform shall depend on the results from testing up and downlink bands individually. The pair combination will include activity closest to the GPS band. The scenario is where a fully-allocated downlink signal is being one device near the GPS device and another UE is sending data to another base station. These data will provide insight into the acceptable density of UE and base station nodes on GPS.

In-band LTE signals in the test system will be filtered to help ensure that the OOBE levels (section 5.3.5) are determined by synthesized noise and not the spectral “skirts” of the LTE waveform synthesizer. A commercial, off-the-shelf (COTS) duplexer in the test system will isolate the LTE uplink and LTE downlink frequencies, and help limit OOBE from the in-band generation path.

The OOBE of the LTE synthesizer will be minimized (potentially with the help of added filtering) to ensure that in-band and OOBE signals are controlled by their designated signal paths. Roll-off of the in-band LTE downlink path will be achieved in part with a cavity filter which is taken to be representative of a practical deployment. The LTE uplink path specifies OOBE in the GPS L1 band at 98 dB below the in-band level. Cavity filtering is not generally practical for deployable UEs, but may be used in the emulated path to ensure that uplink OOBE spectral density is strongly dominated by the OOBE signal path.

A key consideration in the testing process is the expected physical separation between the UE and the GPS receiver. The LTE emissions masks are defined at the LTE systems, but the risk of interference is determined by the LTE level at a GPS receiver. The relationship between these is an attenuation level determined by the propagation environment; meaningful use cases need to be considered carefully to

determine a reasonable range of attenuation levels for test. In the anechoic environment, this attenuation can be translated to range with the Friis transmission equation.

In the LTE uplink, the UE radiator is assumed mobile, and a proximity of less than 1 meter is possible in a deployment. Tests can gauge the equivalent response of a DUT at different distance in an anechoic chamber by adjusting the transmit power. Figure 1 shows the path loss due to separation distance. Intuitively, a test run with the DUT separated from the transmit antenna by 3 m needs to transmit extra power to determine the response of the DUT at a separation distance 0.5 m. This power correction in Figure 6 below shows the path loss due to separation distance. This path loss must be taken into consideration when determining power levels at the DUT. Actual losses from the calibrated test signal radiation to the DUT in the test will be verified according to Appendix D.3.

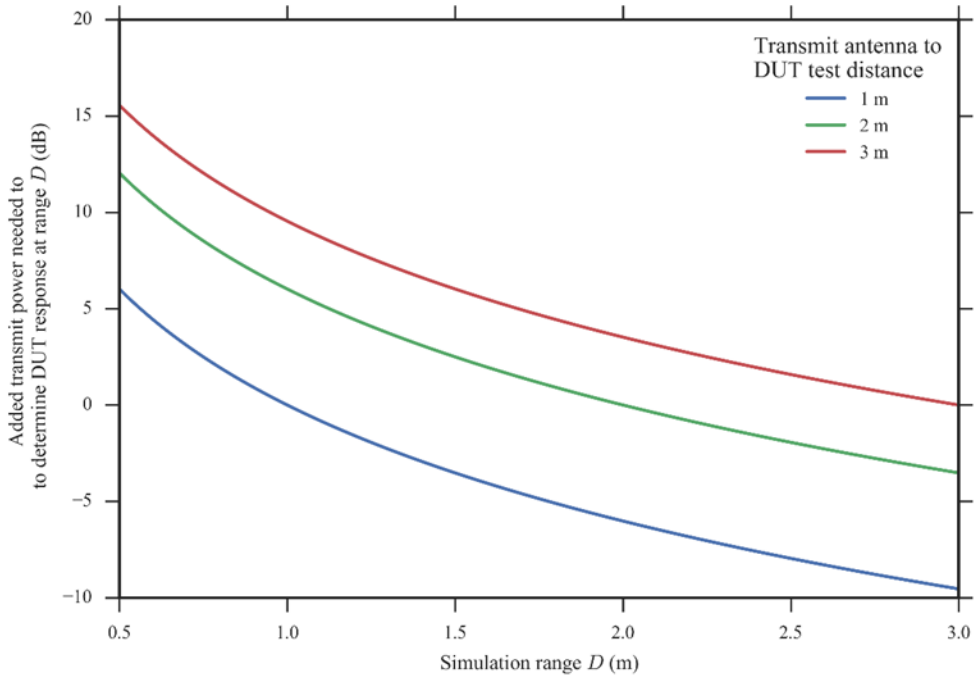


Figure 6. Path loss calculations based on the Friis transmission equation.

5.3.5 Out-of-Band Emissions (OOBE) LTE Emulation

Out-of-band emissions (OOBE) are critical aspects of the LTE uplink and LTE downlink spectrum masks that need to be fully emulated to support testing across a wide range of power levels (or equivalently various separation distances). These waveforms will be synthesized in a separate instrument from the in-band emissions, then added to in-band emissions with a combiner.

Wideband LTE OOBE waveform generators are not known to be commercially available to the authors of this test plan, and therefore not expected to be feasible for testing. As a surrogate, OOBE transmit signaling will be additive white Gaussian noise (AWGN) filtered to meet the OOBE emission limit masks of Figure 1. Signal levels will be calibrated as discussed in Appendices B.3 and C.2, respectively, and validated according to the procedure in Appendix C.3.

The waveforms will be predesigned to last for several seconds and uploaded as the baseband modulation input to signal generator. The I/Q waveforms will be circular AWGN in baseband with bandwidth of 109 MHz centered at 1595.5 MHz (1541 MHz – 1650 MHz), filtered to match the emissions mask. Because there are separate uplink and downlink emissions masks, OOBE noise will need to be generated for each and summed together in baseband.

5.3.6 Measurement Locations

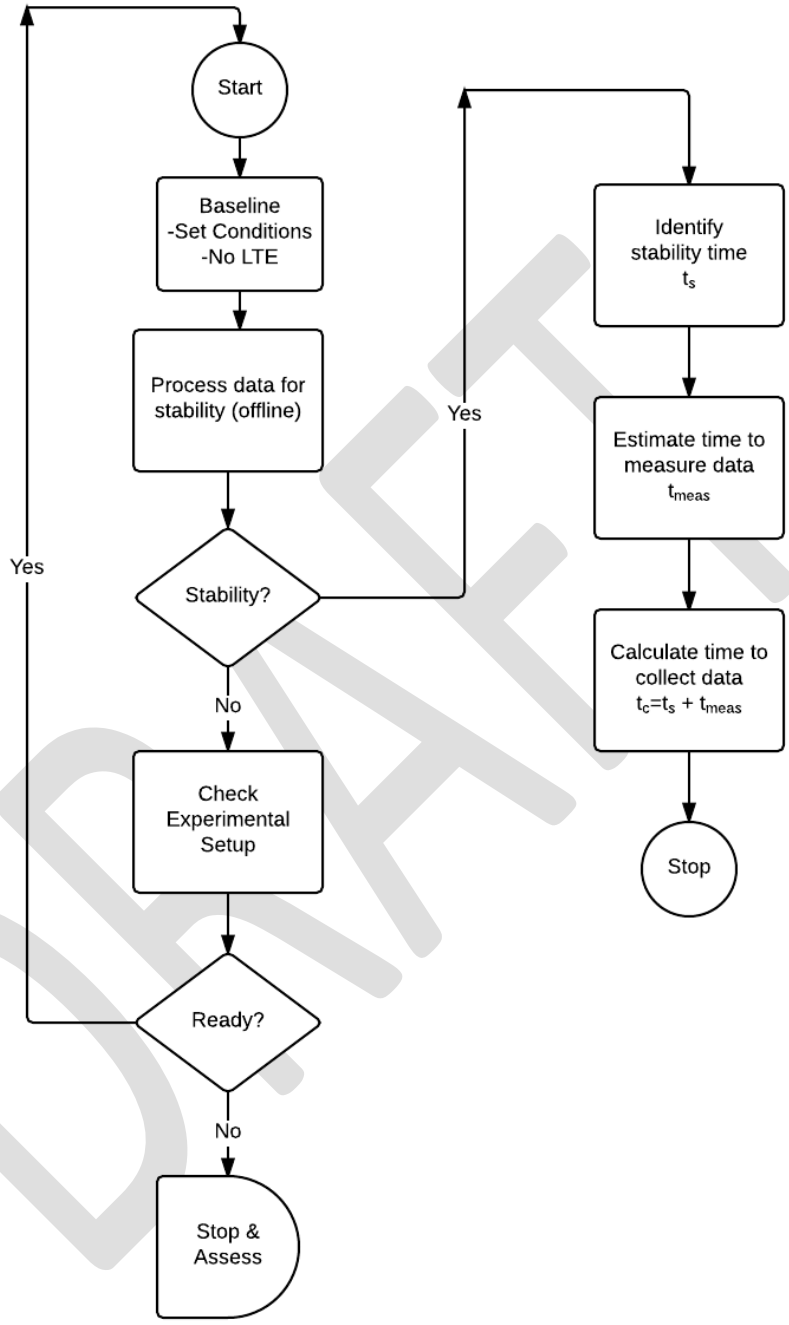
Potential locations under consideration for testing are below.

- Electronic Proving Grounds (EPG); Fort Huachuca, Arizona.
- White Sands Missile Range, New Mexico.

5.4 Tests to Establish Data Collection Timing

The primary measurement protocol requires stepping through a range of power levels and collecting data from the DUT at each level. The amount of data collected at each LTE power level is based on establishment of steady state conditions, as described in the Statistical Considerations section below. Power level increments are determined by an initial investigation of the DUT behavior and the eventual maximum power level sought.

The process for establishing the time needed to collect sufficient data at each step is shown below. The first part, shown in Figure 7, is to capture a relatively long time series of data with no LTE signal activity. Offline processing is used to determine the time for stability, t_s. During the portion of the test that includes LTE activity, an additional amount of time, t_{meas}, is added for the collection of data after reaching steady state. The total of the two times is called the capture time, t_c . As depicted in Figure 8, at each LTE power level, data are captured for a time duration of t_c .


Start
Baseline
-Set Conditions
-No LTE
Process data for stability (offline)
Stability?
Yes
No
Identify stability time
t_s
Estimate time to measure data
t_{meas}
Calculate time to collect data
$t_c=t_s + t_{meas}$
Stop
Check Experimental Setup
Ready?
Yes
No
Stop & Assess

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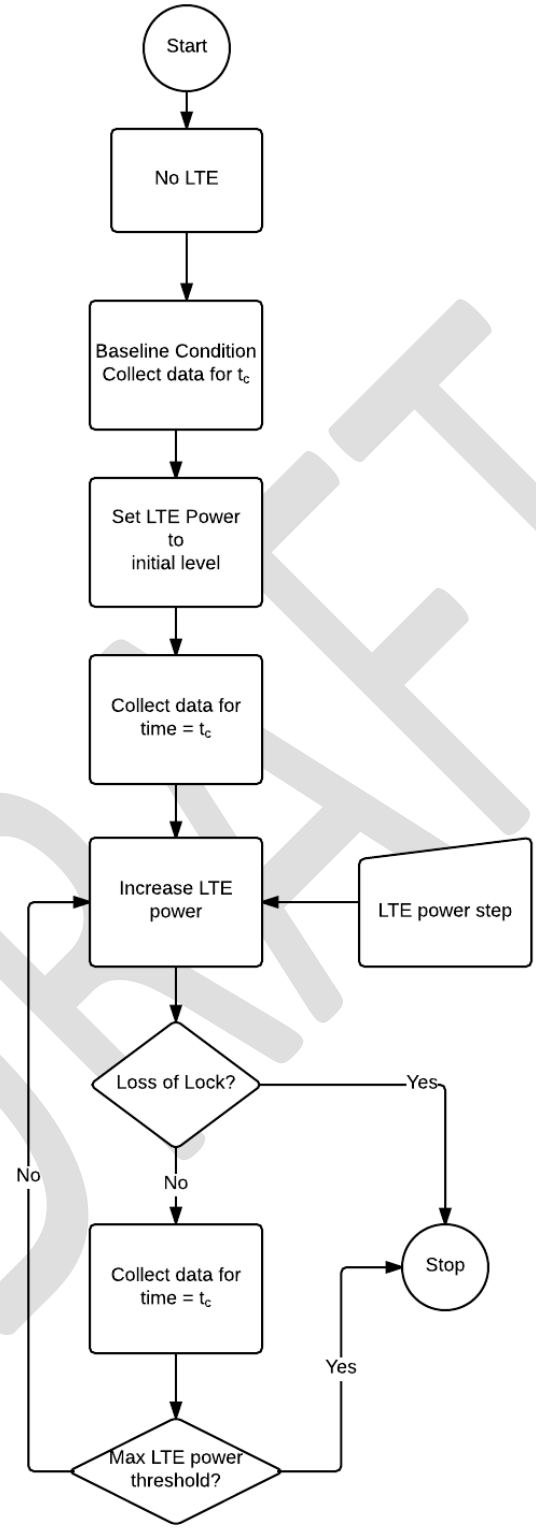
Start
No LTE
Baseline Condition
Collect data for t_c
Set LTE Power
to
initial level
Collect data for
time = t_c
Increase LTE
power
LTE power step
Loss of Lock?
Yes
No
No
Collect data for
time = t_c
Stop
Yes
Max LTE power
threshold?

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5.5 Tests at Swept LTE Levels

We propose here approaches of swept LTE power levels to study the impact of LTE waveforms on GPS receivers. While either test pattern may produce results that are useful for coexistence analysis, they are inherently linked when considering practical deployments. If time permits, both types of testing will be performed.

5.5.1 Emulate swept range

This test sweeps a path loss value that is approximately constant across the entire 1526 MHz - 1680 MHz range. This emulates slow fading path loss between LTE transmitter and the GPS receiver. The spectral shape of the emission mask (the ratio between in-band to out-of-band emission) of the LTE waveform is preserved, and simply shifted up and down.

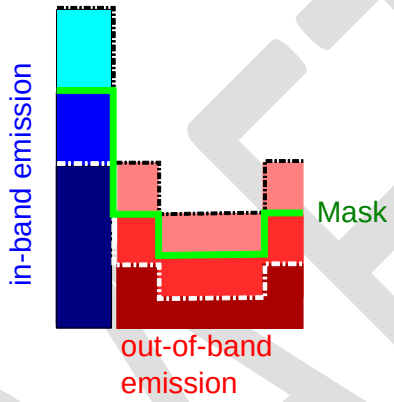

Figure 9. The in-band and out-of-band emission and the waveform mask for swept range emulation. The same losses apply to both in-band and out-of-band emissions.

This test aligns closely with propagation analysis through the Friis transmission equation. This, coupled with assumptions about noise levels inside the GPS receiver, connect transmitter and victim path loss and LTE impact on GPS receivers. The result may be to inform on spectral emission mask tolerances, LTE infrastructure design decisions, and to consider operating characteristics of GPS devices at various separation distances from LTE emitters near GPS L1.

5.5.2 Study LTE In-Band Coexistence Margins

This test fixes the power level of the out-of-band emission while varying the power level of the in-band emission as in Figure 10. The out-of-band emission power-spectral density is fixed to that of Figure 1, whereas the in-band emission is variable. In stepping through the power levels, the victim receiver is stressed with the maximum admissible out-of-band emission for specified distance (e.g. 3-meter separation) and observations inform on susceptibility to additional LTE in-band power. This test method evaluates the validity of the proposed emission mask shape, as well as gives LTE infrastructure designers guidelines on maximum in-band power levels while preserving the currently proposed out-of-band emission limits.

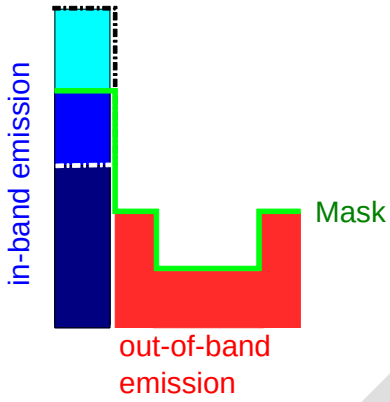

Figure 10. The in-band and out-of-band emission and the waveform mask for in-band LTE coexistence margin testing. Here, LTE out-of-band emission is held constant while LTE in-band emission is varied.

6 Statistical Considerations

6.1 Test Population

GPS devices from the following classes will be tested:

- general location and navigation
- high precision
- timing
- development boards

A detailed enumeration of the GPS devices under test is provided in Table 1 through Table 4. The selection of devices chosen from each class will likely be driven by practical considerations, such as data accessibility. Moreover, only a single unit of each device will be tested to keep the test time and cost manageable.

Although the sample of test devices will be stratified according to class, it will not be randomized within each class. Therefore, there is a risk of selection bias in the test results. In addition, because only one unit of each device will be tested, variations in off-the-shelf performance will not be included in the test results. For these reasons, the conclusions that can be drawn from this test will be limited to the specific set of devices under test, and will not be rigorously generalizable to the population of all devices.

6.2 Relevant Experimental Variables and Sources of Uncertainty

- Response variables: GPS lock (binary outcome), once GPS lock is achieved, available device outputs, such as position, time, pseudo-range values, C/N_0, etc. will be recorded at regularly- spaced time intervals.
- Controlled variables:
    - GPS emulator parameters: number of satellites, satellite constellation, satellite signal-power levels, impairments (atmospheric effects, Doppler shift, multipath effects, satellite clock, and ephemeris errors)

- LTE emulator parameters: transmission band, power level, and resource block allocation
- Device position and orientation, start-up conditions, availability of augmentation, and indoor environmental conditions

- Uncontrolled variables: receiver antenna orientation (for embedded antennas)
- Sources of uncertainty: variations in LTE and GPS signal strength, structure of LTE signals, satellite constellation, GPS signal impairments, GPS processing algorithm, receiver antenna orientation, and indoor environmental conditions

6.3 Analysis Plan

6.3.1 Steady-State Assessment

The analysis of device outputs for the indoor testing is predicated on the assumption that the device is operating in a steady-state condition. Therefore, for each set of experimental conditions, stability of device outputs will be assessed as a function of time. The point at which transients are negligible will be identified with a pre-specified criterion. Subsequent analysis will be carried out on the steady-state portion of the data.

Note that the time required for the device under test to reach a steady-state condition will vary with the device as well as the test conditions. Therefore, an early phase of the testing will attempt to estimate the time required to reach steady-state. Such estimates will inform the subsequent experimental procedure.

A basic evaluation of steady-state performance will consist of applying a sliding time window to the data, and then estimating the mean and variance from the windowed data. For example, if the relative change of the mean and variance after a certain time is less than, e.g., 1%, then the time-series may be judged to be in a steady-state condition.

Additional metrics for assessing steady-state performance will be investigated in pre-testing with available GPS device output data. Moreover, pre-test investigations will inform the choice of a specific criterion for steady-state performance.

If the collected time series does not satisfy the pre-determined criteria for steady-state behavior, then alternative methods will be applied to derive a steady-state time series from the measurements. Specifically, techniques such as differencing and trend estimation will be used in an attempt to generate stationary data from the observed time series.

6.3.2 Estimation of Quantiles and Histograms

Assuming that the device under test has reached a steady-state condition, the steady-state distribution and associated quantiles, such as the median, 90%, 95%, and 99% percentiles will be estimated in a nonparametric manner for KPIs such as position error, pseudo-range error, and C/N_0. These estimates will enable comparison of the distribution for each KPI without LTE interference to that with LTE interference.

One difficulty in the statistical analysis stems from the fact that the time-series of device outputs is expected to be highly-correlated. Since classical statistical methods that are designed for independent samples break down for dependent samples, they are not applicable in this context, and special methods are required.

Point estimates and 95% confidence intervals for quantiles will be estimated with the averaged group quantile method of Heidelberger & Lewis [3], which is based on asymptotic theory for dependent sequences. In addition, depending on software availability, the more robust sequential estimation methods of either Chen & Kelton [4][5] or Alexopoulos et al. [6] will be applied.

The steady-state distribution will first be estimated with a conventional histogram, which will provide a simple means to compare distributions. It is well known that the histogram is an unbiased estimator of the probability mass in each bin as the bin size approaches zero, even for dependent data. However, because the classical histogram precision estimates are not valid for dependent data, it is challenging to estimate and control uncertainty in the histogram. To address this issue, if possible, the method of Chen & Kelton [5] will be applied to obtain histogram estimates with a specified precision.

7 Outreach and Community Feedback

NASCTN will solicit comments about the test plan from the engineering community within federal and non-federal groups and entities.

8 Data Management

The following measures will be taken to manage data.

- Measurements will be recorded on local storage at the measurement site and will be physically removed by NASCTN personnel at the end of the measurement period.

9 Project Tasks

The following are the major tasks of the project.

Develop and Write Test Plan
External Outreach and Test Plan Review
Comments received
Feedback Review info to Test Plan
Test Preparation
Preliminary Anechoic setup and baseline tests
Anechoic chamber test
Data Analysis and Report
NASCTN Data and Report Review Process (including Director)
Issue Report

10 Safety

The anechoic tests are indoor laboratory tests and subject to all the typical safety concerns associated with such environment.

11 References

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Appendix A. Estimating In-Situ Interference Response from Anechoic Measurement Results

A.1. Introduction.

A recurring question in the area of RF interference-effects measurements is whether such measurements can be better performed via radiation in propagation scenarios designed to be "realistic" versus measurands that seek to isolate minimize uncontrolled propagation effects. This problem is examined and supports extrapolating measurements to real-world deployments.

A.2. Goal.

The goal of RF interference-effects measurements on victim receivers is to help understand the circumstances under which interference between two or more radio systems will occur in real-world environments and conditional scenarios. Measurements typically do not completely answer this question, but measurements can (and do) provide definitive data points which can be integrated into models, simulations and analysis for validation or prediction.

A.3. Interference Scenarios.

Any real-world interference between two radio systems will involve radiation from one or more transmitter(s) through (usually) one or more transmitter antenna(s) with some combination of frequencies and polarizations. To the first order, potential interference impacts can be predicted by a comparison of aggregate power levels at the receiver. The radiated waves may propagate through space, over terrain, through vegetation, through one or more structural barriers and thence into a victim receiver via (usually) another antenna. The actual amount of interference coupled into the victim receiver will not only be affected by all of these identified factors, but will also be a function (in fact a ratio) of the bandwidth of the victim receiver to the bandwidth of the transmitter. For each interference source, this situation can be written mathematically (in decibels) as:

Equation 1. Link attenuation model for interference signal power at the victim receiver

$$P_{ri} = \mathrm{EIRP}_i - L_{pi} - L_{pol,i} + G_{ri} - L_{filt} - 10\log_{10}\left(\frac{B_r}{B_i}\right)$$

where:

P_{ri} = Interference power coupled into victim receiver;

EIRP_i = Effective isotropic radiated power radiated by the interferer in the direction of the victim receiver;

L_{pi} = Free-space propagation loss at a given separation distance between the interfering transmitter and the victim receiver;

$L_{pol,i}$ = Loss due to polarization mis-matches;

L_{filt} = Losses introduced by interference filtering (for example out-of-band rejection filters);

G_r = Gain of the receiver antenna *in the direction of the interference signal*;

B_r = Bandwidth of the victim receiver;

B_i = Bandwidth of the transmitted interference signal.

$10\log_{10}(B_r / B_i)$ is set to zero if $B_r > B_i$.

Similarly, the received ("non-interfering") signal that received by the victim device, this situation can be written mathematically (in decibels) as:

Equation 2. Link attenuation model for received (desired) signal power at the victim receiver

$$P_{rs} = \mathrm{EIRP}_s - L_{ps} - L_{pol,s} + G_{rs}$$

where:

P_{rs} = Desired power level of the signal the receiver is designed to detect;

$EIRP_s$ = Effective isotropic radiated power of the intended signal radiated in the direction of the victim receiver;

L_{ps} = Free-space propagation loss at a given separation distance between the transmitter radiating the desired signal and the victim receiver;

$L_{pol,s}$ = Loss due to polarization mismatches; and

G_{rs} = Gain of the receiver antenna in the direction of the transmitter of the desired signal;

Due to the wide range of potential values for the terms in the equation above, no practical set of end-to-end radiated measurements between a transmitter and a receiver can provide a comprehensive set that covers all possible permutations. In particular, for the wide range of potential propagation losses, radiated or not, any interference-effects assessment study will need to perform a range of independent evaluations of the following factors:

- Propagation losses of various sorts (see above), including time-variation studies of fading losses in L_{pi} and L_{ps}.
- Radiated power levels of the transmitters in the direction of the victim receiver;
- Gain of the victim receiver antenna in toward each of the desired signal and interfering transmitters;
- Polarization mismatch factors between both types of signal;
- Noise floor of the victim receiver.

The two equations above are used to compute the signal-to-interference (SIR), which is simply the difference between the power levels of the two signals above. Assuming that the filter losses, L_{filt}, are the same for both the desired and interfering signals, the SIR ratio at the receiver in decibels is:

Equation 3. General form of SIR equation for signal and interference originating from different sources, passing through unknown propagation attenuation

$$\mathrm{SIR} = P_{rs} - P_{ri} = (\mathrm{EIRP}_s - \mathrm{EIRP}_i) - (L_{ps} - L_{pi}) - (L_{pol,s} - L_{pol,}) + (G_{rs} - G_{ri}) + L_{filt} - 10\log_{10}\left(\frac{B_r}{B_i}\right)$$

A.4. Systems Engineering Approach for Interference-Effects Measurement Studies

A systematic engineering approach to the problem of radio interference-effects measurements will not, as pointed out above, attempt to simultaneously roll a dozen different factors into a single measurement scenario. Instead, a *systems-engineering approach* breaks this problem into discrete pieces, studying and evaluating each piece independently and then combining together for an overall interference-effects evaluation.

The first piece in this type of systems-engineering approach is the determination of the incident interference radiation amplitude at which interference effects occur at the victim receiver. To the extent possible, this evaluation should be performed without regard to the other factors in the interference equation. The various other factors in the interference equation should be added into the mix in the final engineering study, each factor itself being the result of detailed individual studies and evaluations.

A.5. Impacts of Sharing a Single Transmit Antenna in Anechoic Tests

Combining both types of signal into the same transmit antenna reduces the number of variables in the received SIR during measurements. The transmit signals share the same propagation loss ($L_{pol,s} - L_{pol,i} = 0$), polarization loss ($L_{rs} - L_{ri} = 0$), and victim receive antenna gain ($G_{rs} - G_{ri} = 0$), so the SIR ratio simplifies to

Equation 4. SIR in the test environment
NOTE: Only applies when sharing a single antenna

$$\mathrm{SIR}_{TEST} = P_{rs} - P_{ri} = (\mathrm{EIRP}_s - \mathrm{EIRP}_i) + L_{filt} - 10\log_{10}\left(\frac{B_r}{B_i}\right)$$

In other words, the test has been designed to control the SIR to a constant level determined by characteristics of the testbed transmitter (its EIRP and signal transmit bandwidth) and the victim receiver DUT (out-of-band filtering characteristics and receive bandwidth) instead of the environment. It is independent of orientation or multipath, and isolates a measurable parameter (SIR) from application-dependent environment variables, matching the systems engineering philosophy of the previous section.

A.6. Applying the SIR to Predicted System Performance.

The response of the victim receiver to interference are set by the SIR level and background noise (set in tests by room temperature thermal noise and receiver electronics). Estimating a victim receiver's response to the tested interference according to the equations here requires evaluating Equation 3, and translating the SIR to the victim receiver performance result.

The factors not tested in the lab need to be accounted for. In most deployment scenarios, the interferer and desired signals should be expected at different EIRP levels and to undergo different G_r, L_p, and L_{pol}.(Each term could be modeled as random variables for Monte Carlo analysis with each term consisting of a well-defined probability density function). Based on the SIR equation, what needs to be modeled is the difference between each term.

Here is an example case of how an SIR might be estimated from hypothetical link values. It requires estimates for each link parameter, which in turn depend on the deployment scenario and the technology in use.

1) The interferer radiates at a weaker level than the desired signal:
   $\mathrm{EIRP}_s - \mathrm{EIRP}_i = +10\ \mathrm{dB}$
2) Assume the interferer is much closer and undergoes substantially lower propagation loss:
   $L_{ps} - L_{pi} = -10\ \mathrm{dB}$
3) Now assume that the interferer has linear polarization, and the desired source is circularly polarized, resulting in a relative mismatch of 3 dB:
   $L_{pol,s} - L_{pol,i} = +3\ \mathrm{dB}$
4) Further, now assume that the interferer arrives nearer a sidelobe of the victim antenna pattern:
   $G_{rs} - G_{ri} = +2\ \mathrm{dB}$

The sum of these values gives SIR = +5 dB. The estimate for victim receive performance, based on measurement data, is the measurement result at the 5 dB SIR operating point. The result is valid assuming that temperature and background noise conditions are similar to test conditions, and that the structure of the input signal used in the test closely resembles that of the deployment under consideration.

Appendix B. Specifications of Antenna and RF Front End

Table 8. Specifications of antenna and system

Subsystem	Component	Anechoic
Antenna	Polarization	RHCP
	Boresight gain flatness across 1520 MHz – 1680 MHz	+/- 0.5 dB
	Maximum VSWR across 1520 MHz – 1680 MHz	1.5
	Manufacturer gain calibration	ANSI C63.5 or SAE ARP958, performed at 3m
System	GPS test signal power output range	TBD
	LTE test signal power output	TBD

Appendix C. Procedures for Characterization and Calibration of Conducted Signals

C.1. Instrument Calibration

A few baseline instrumentation calibration steps are illustrated in Figure 11. These should be taken after appropriate instrument warm-up time as specified by their manufacturers, respectively, and before characterizing the LTE and GPS signal generating paths. Procedures for these measurements are listed in Table 9.

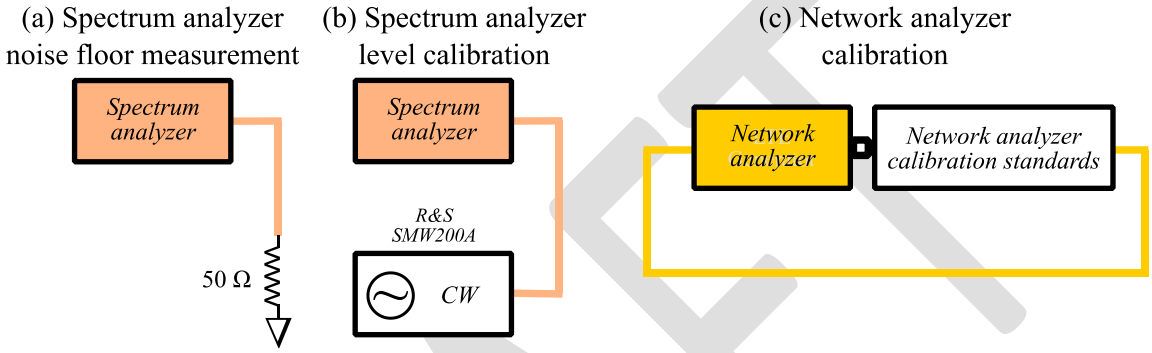

Figure 11. Instrument calibration signal paths

Table 9. Calibration equipment setup.

Test	Input source	Output measurement
Spectrum Analyzer CW Calibration Sweep	CW source ✓CW stepped frequency sweep 1500 – 1660 MHz 1601 points, 10 ms per point Power level (P_{ref}[1] - 10 dB)	Spectrum analyzer (at GPS emulator) ✓PSD (max hold) 1500 MHz – 1660 MHz 1601 points Ref Level P_{ref}[1]
Spectrum Analyzer Noise Floor	Matched termination	Spectrum analyzer (at GPS emulator) ✓PSD 1500 MHz – 1660 MHz 1601 points
Network Analyzer Calibration	Network analyzer, port 1 (according to manufacturer operating manual)	Network analyzer, port 2

[1] Set the reference level, P_{ref}, to the highest power level that leads to 0 dB input attenuation, with the spectrum analyzer set to automatic input attenuation leveling.

Table 10. Instrument calibration measurements

Calibration	Calculation and application
Spectrum Analyzer Trace Level	Apply trace math as follows (point by point across frequency band): Corrected trace PSD = Pref (dBm) - 10 (dB) - Spectrum Analyzer CW Calibration Sweep (dB) Record this PSD for remaining tests. Do not change input attenuation setting, number of points, or frequency span.
Network Analyzer Two-Port Calibration	Perform a full two-port calibration on the instrument according to instrument operating instructions. Leave calibration on in remaining tests. Do not change resolution bandwidth, number of points, or frequency bounds.

C.2. Characterization of In-Band LTE Signal Generation

The purpose of generating the LTE in-band signal is to populate only the downlink (1526 MHz - 1536 MHz) and/or one of the uplink bands (1627.5 MHz – 1637.5 MHz, 1646.5 MHz – 1656.5 MHz). The in-band signal generation path needs to be characterized across the full calibration bandwidth (1500 MHz – 1660 MHz) to include its contribution in the conducted power output into the antenna.

The test setup is illustrated in Figure 12. The signal path is broken between the power amplifier output and the upstream isolator. A signal analyzer characterizes the power spectral density output by of the amplifier, and a network analyzer characterizes the loss between the amplifier and the input to the antenna. It is necessary to split the signal path measurements into two because the out-of-band emissions level is too weak compared to the signal analyzer noise floor.

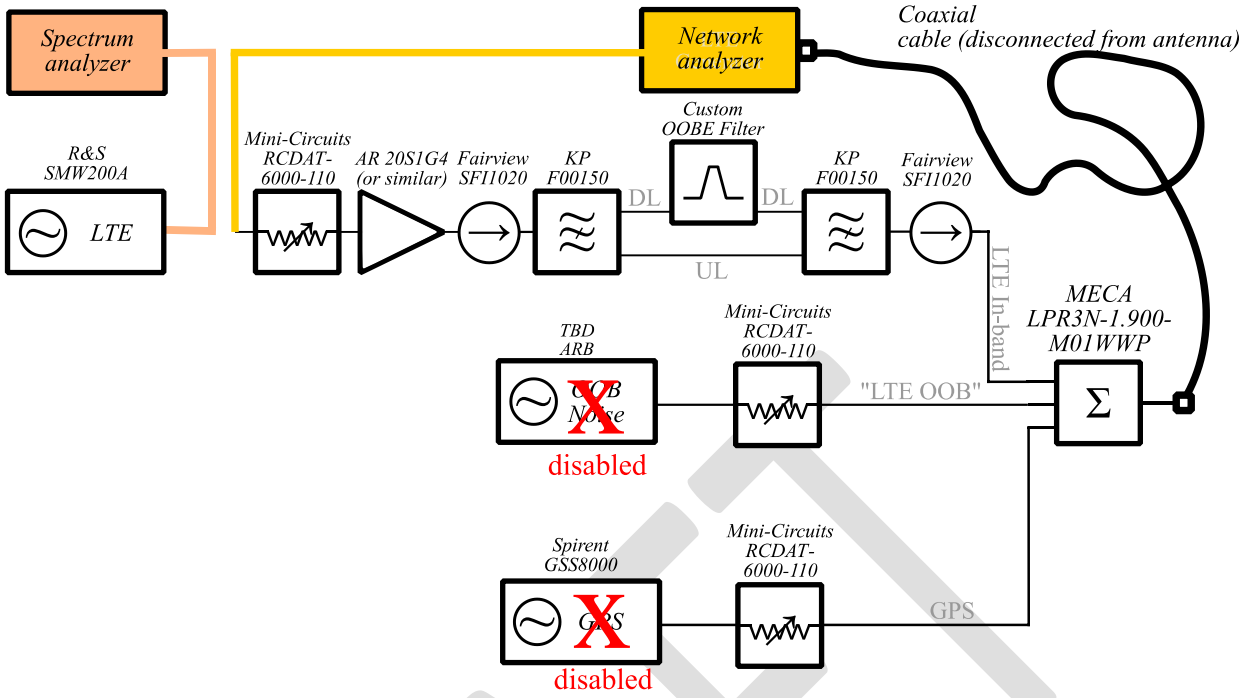

Figure 12. LTE in-band signal generation path conducted measurements for calibrations

The calibration measurements necessary to characterize the LTE in-band signal generation path are listed in Table 12. The correction computations based on these measurements are listed in Table 13.

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Table 11. Instrument calibrations.

Signal	Test	Input source	Output measurement
LTE DL	**LTE in-band path S-parameters**	Network analyzer Port 1 – output of input (upstream) isolator	Network analyzer Port 2 - Cable output (antenna side) ✓2-port S-parameters: 1500 MHz – 1660 MHz 1601 points Narrow IF bandwidth
	LTE DL PSD input	LTE emulator 1526 – 1536 MHz	Spectrum analyzer (at GPS emulator) ✓PSD: 1500 MHz – 1660 MHz 1601 points
LTE UL1	**LTE in-band path S-parameters**	(reuse the S-parameter measurement result from LTE DL tests)	
	LTE UL1 PSD input	LTE emulator 1627.5 – 1637.5 MHz	Spectrum analyzer (at LTE emulator) ✓PSD: 1500 MHz – 1660 MHz 1601 points
LTE UL2	**LTE in-band path S-parameters**	(reuse the S-parameter measurement result from LTE DL tests)	
	LTE UL2 PSD input	LTE emulator 1646.5 – 1656.5 MHz	Spectrum analyzer (at LTE emulator) ✓PSD: 1500 MHz – 1660 MHz 1601 points

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Table 12. In-band signal generation path calibration measurements

Calibration	Calculation and application
LTE DL in-band PSD maximum output	The LTE downlink out-of-band power spectral density is that available to a 50 Ohm matched antenna. It is computed from measurements of Table 14 at each frequency point as LTE In-Band DL PSD input (dBm/Hz) - |LTE in-band path S-parameters, S_{21}| (dB) This expression shall be evaluated by trace math on the spectrum analyzer.
LTE DL in-band PSD output	The actual conducted power level includes the path attenuator setting, LTE OOB DL PSD maximum output (dB) - LTE OOB signal path attenuator setting (dB)
LTE UL in-band PSD maximum output	The LTE uplink out-of-band power spectral density is that available to a 50 Ohm matched antenna. It is computed from measurements of Table 16 at each frequency point as LTE OOB UL PSD input (dBm/Hz) - LTE OOB path loss (dB) This expression shall be evaluated by trace math on the spectrum analyzer and may be reevaluated in different units.
LTE UL in-band PSD output	The actual conducted power level includes the path attenuator setting at each PSD frequency point as LTE OOB UL PSD maximum output (dB) - LTE OOB signal path attenuator setting (dB) This value may be computed in the PC since the attenuator setting may not be available inside the spectrum analyzer.

Table 13. In-band signal generation path calibration corrections.

Signal	Test	Input source	Output measurement
LTE OOB signal	LTE OOB path S-parameters	Network analyzer Port 1 – OOBE attenuator input	Network analyzer Port 2 – Cable output (antenna side) ✓2-port S-parameters: 1500 MHz – 1660 MHz 1601 points Narrow RBW
	LTE OOB DL PSD input	OOBE noise emulator (noise to DL spectral mask) ✓1526 – 1650 MHz	Spectrum analyzer ✓PSD: 1500 MHz – 1660 MHz 1601 points
	LTE OOB UL PSD input	OOBE noise emulator (noise to UL spectral mask) ✓1526 – 1650 MHz	Spectrum analyzer ✓PSD: 1500 MHz – 1660 MHz 1601 points

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C.3. Characterization Out-of-Band LTE Signal Generation

The purpose of generating the LTE out-of-band (OOB) signal is to fill the range 1526 MHz – 1680 MHz with noise at the power density limit defined by an LTE spectral mask.

There are two spectral masks: one for the LTE downlink (DL) band at 1526 MHz – 1536 MHz and another that applies identically to operation of either uplink band (UL1 1627.5 MHz – 1637.5 MHz, UL2 1646.5 MHz – 1656.5 MHz). Each is generated by a pre-stored waveform to be played back as OOB noise.

The test setup is illustrated in Figure 13. The signal path is broken between the ARB output and the corresponding downstream variable attenuator. A spectrum analyzer characterizes the power spectral density output by of the noise generator, and a network analyzer characterizes the loss between the amplifier and the input to the antenna. It is necessary to split the signal path measurements into two because the out-of-band emissions noise is too weak compared to the spectrum analyzer noise floor.

The instrumentation configuration for the LTE OOB signal characterization is shown in Figure 13. The intended OOB signal levels are weak, so the spectral density measurement is at the generator output, where the signal is more powerful. S-parameter measurements give the remaining attenuation to the antenna input. The calibration measurements in this setup to characterize the LTE in-band signal generation path are listed in Table 14.

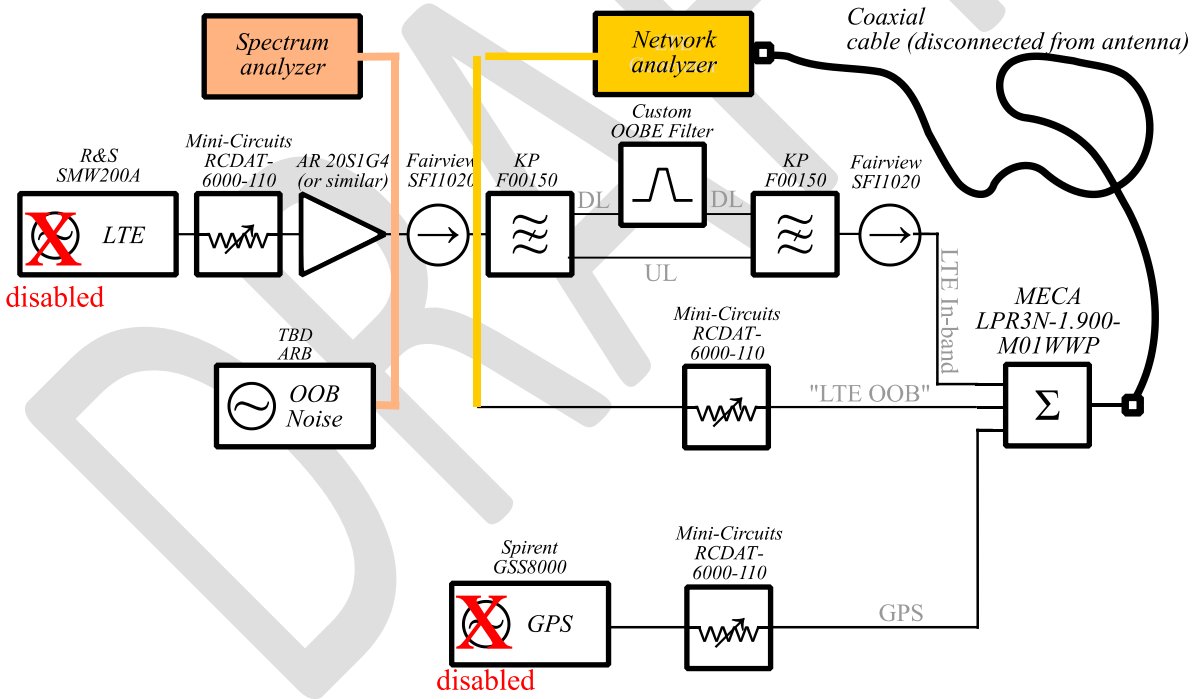

Figure 13. Conducted measurement setup for calibrating LTE out-of-band signal generation

Table 14. Measurements of the out-of-band signal generation path for calibration

Calibration	Calculation and application
LTE OOB DL PSD maximum output	The LTE downlink out-of-band power spectral density is that available to a 50 Ohm matched antenna. It is computed from measurements of Table 14 at each frequency point as LTE OOB DL PSD input (dBm/Hz) - |LTE OOB path S-parameters, S_{21}| (dB) This expression shall be evaluated by trace math on the spectrum analyzer.
LTE OOB DL PSD output	The actual conducted power level includes the path attenuator setting, LTE OOB DL PSD maximum output (dB) - LTE OOB signal path attenuator setting (dB)
LTE OOB UL PSD maximum output	The LTE uplink out-of-band power spectral density is that available to a 50 Ohm matched antenna. It is computed from measurements of Table 16 at each frequency point as LTE OOB UL PSD input (dBm/Hz) - LTE OOB path loss (dB) This expression shall be evaluated by trace math on the spectrum analyzer and may be reevaluated in different units.
LTE OOB UL PSD output	The actual conducted power level includes the path attenuator setting at each PSD frequency point as LTE OOB UL PSD maximum output (dB) - LTE OOB signal path attenuator setting (dB) This value may be computed in post-processing since the attenuator setting may not be available on the spectrum analyzer.

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Table 15. LTE out-of-band conducted power calibration corrections.

Signal	Measurement	Input source	Output measurement
GPS L1 signal	GPS signal path loss (dB)	Network analyzer Port 1 – GPS L1 path attenuator input (0 dB attenuation setting)	Network analyzer Port 2 – Cable output (antenna side) ✓2-port S-parameters: 1500 MHz – 1660 MHz 1601 points Narrow RBW
	Input power spectral density (dBm/Hz)	GPS emulator ✓L1: 1563.42– 1587.42 MHz	Spectrum analyzer (at GPS emulator) ✓PSD: 1500 MHz – 1660 MHz 1601 points

C.4. Characterization of L1 GPS Signal Generation

The purpose of generating the L1 GPS signal is to provide GPS satellites to test the response of GPS receiver DUTs.

The test setup is illustrated in Figure 14. The signal path is broken between the GPS emulator and its corresponding downstream variable attenuator. A signal analyzer characterizes the power spectral density output by of the amplifier, and a network analyzer characterizes the loss between the amplifier and the input to the antenna. Loss through the path needs to be measured separately because the L1 GPS level is weak compared to the signal analyzer noise floor.

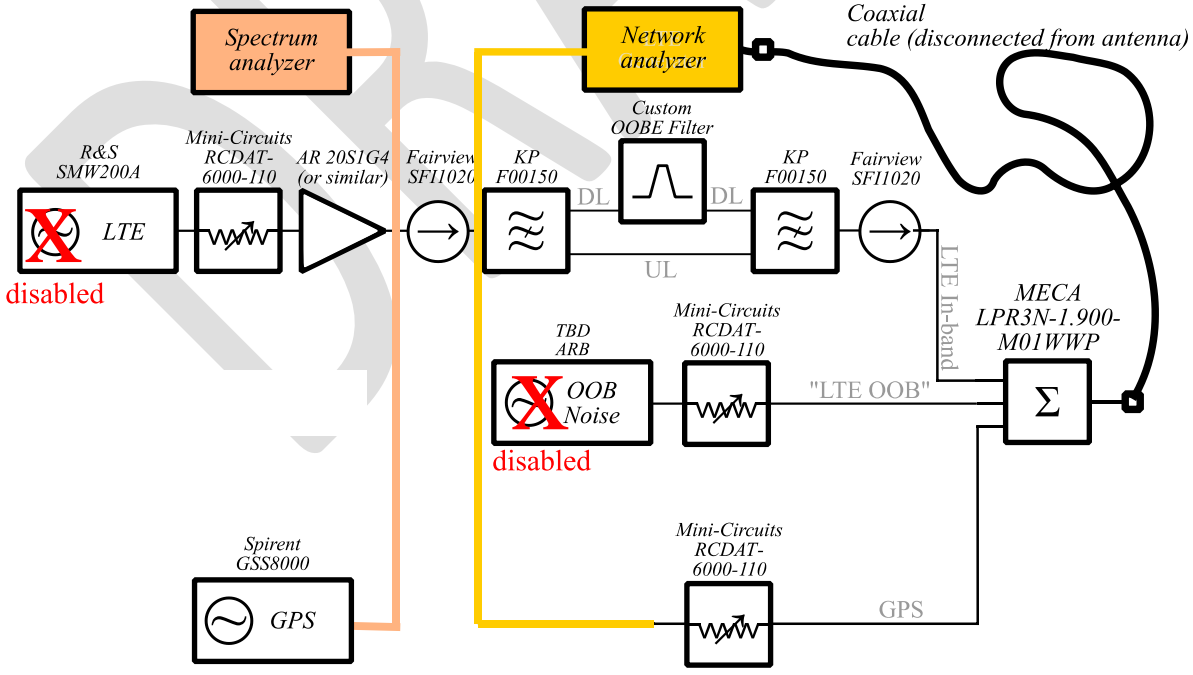

Figure 14. GPS L1 signal generation path conducted measurements for calibrations

The instrumentation configuration for the GPS L1 signal characterization is shown in Figure 13. The intended OOB signal levels are weak, so the spectral density measurement is at the generator output, where the signal is more powerful. S-parameter measurements give the remaining attenuation to the antenna input. The calibration measurements in this setup to characterize the GPS L1 signal generation path are listed in Table 16.

Table 16. GPS L1 signal generation path conducted measurements for calibrations

Calibration	Calculation and application
GPS L1 output PSD	The GPS L1 signal power is the power available to a 50 Ohm matched antenna. It is computed from measurements of Table 16 at each frequency as PSD_{TX} (dBm/Hz) = Input power spectral density (dBm/Hz) - GPS L1 signal path loss (dB) - GPS L1 signal path attenuator setting (dB) This expression should be evaluated by trace math on the spectrum analyzer if possible.
GPS L1 conducted transmit power	The average GPS L1 conducted transmit power available to a 50 Ohm matched antenna is P_{TX} (dBm) = GPS L1 output PSD, band power 1563.42 – 1587.42 MHz This expression should be evaluated by trace math on the spectrum analyzer if possible.

C.5. Uncertainty

Signal power uncertainty estimates will be provided where feasible based on tests, noise levels, and procedures provided by instrument manufacturers.

Appendix D. Procedures for Characterization, Calibration, and Validation of Radiated Power

D.1. Calibration of Transmit Loss to Linear Polarization

The LTE radiated emission spectral masks are specified for linear polarization, but the transmit antenna is designed for linear polarization. If the transmit antenna radiates true RHCP, then the linear component corresponding to the LTE spectral mask is 3 dB weaker (3 dB of polarization loss).

Table 17 . GPS L1 signal generation calibrations

	Calculation and application
Transmit Polarization Loss to Linear	A test for the circular polarization purity is to measure the transmit power from a RHCP antenna with a linear-polarized horn at two orthogonal angles. The received power out of the horn antenna should be approximately the same at each angle. The ratio of these, in dB, is the transmit antenna's axial ratio (AR). The measured estimate of the polarization loss is related to the AR as L_{pol} = AR + 3 dB = Received power H-pol (dB) – Received power V-pol (dB) + 3 dB

D.2. Calibration of Radiated Power Levels

The radiated power computations here combine conducted signal power levels (calibrated in Appendix C) and antenna gain (calibrated by the antenna manufacturer). The radiated power that is the result of this computation is therefore also taken to be calibrated.

Table 18. Radiated power level calibrations

Calibration	Calculation and application
EIRP (GPS L1, right-hand circular polarization)	The EIRP of the testbed antenna at boresight, given the RHCP partial gain of the transmit antenna, *G*, is EIRP (in dBm) = P_{TX} (dBm) + *G* (dBi) – L_{pol} (dB) + 3 or EIRP (in dBm/Hz) = P_{TX} (dBm/Hz) + *G* (dBi) – L_{pol} (dB) + 3 This conducted transmit power PTX should be taken from the measurement "GPS L1 conducted transmit power" in Table 16.
EIRP (LTE in-band or OOB, vertical polarization)	The calibrated EIRP of the testbed antenna at boresight, given the total gain of the RHCP transmit antenna, G, is

	EIRP (in dBm) = PTX (dBm) + G (dBi) - Lpol (dB) or EIRP (in dBW/MHz) = PTX (dBW/MHz) + G (dBi) - Lpol (dB) This expression applies to the uplink or downlink, and in-band or out-of-band. The appropriate choice of conducted transmit power PTX comes from the desired choice among "LTE UL in-band PSD output" or "LTE DL in-band PSD output" in *Table 13*, or "LTE OOB DL PSD output" or "LTE OOB UL PSD output" in *Table 15*.
3GPP GPS Power Level	3GPP conformance test standard TS 37.571-1 defines a power level operating point for over-the-air tests of GPS receivers in cellular industry tests. The power level is defined as the incident field strength (or power density) equivalent to $\underline{P}_{RX}$ = -130 dBm received with an antenna that has gain $\underline{G}_{RX}$ = 0 dBi in the location of the DUT. The calibration here assumes this receive antenna gain is the RHCP partial gain as defined in the IEEE dictionary of standard terms for antennas. The Friis transmission equation relates these to the EIRP and test zone geometry: P_{RX} (in dBm) = EIRP (in dBm) + $\underline{G}_{RX}$ – 20 $\log_{10}$ ($4\pi r/\lambda_0$) where r = 3 meters is the separation distance between the DUT and test antennas and λ_0 is the wavelength, approximately 0.19 meters. EIRP must be calculated with the "GPS L1, in-band" calibrated transmit power. Inserting these numbers the EIRP necessary to fulfill the 3GPP standard becomes $EIRP_{3GPP}$ = -84.0 dB at test antenna boresight. Measurements at the levels specified in TS 37.571-1 are achievable by adjusting the LTE in-band attenuator to bring EIRP to this level (and adjusting the LTE OOB attenuator to maintain desired relative levels).

D.3. Validating radiated signal levels at the DUT

In order to validate the expected anechoic propagation behavior (Figure 6) and the calibrated gain level of the testbed transmit antenna, we perform an additional check on the propagation attenuation between the calibrated source antenna and a second calibrated validation antenna. The test setup is illustrated in Figure 15.

For each LTE downlink (in-band and OOB), LTE uplink (in-band and OOB), and GPS L1 signal, conducted power will be measured 1) at the calibrated testbed output and 2) out of the validation antenna. These are the “source” and “through” measurements in Figure 15. The ratio of each power measurement expressed in decibels, will be taken the difference between these two signals (in decibels) for each signal. This ratio will be reported as the propagation attenuation.

The anticipated gain of these antennas, and their separation, will be used to compute the expected loss according to the Friis transmission equation. This expected value will be compared against the measured loss.

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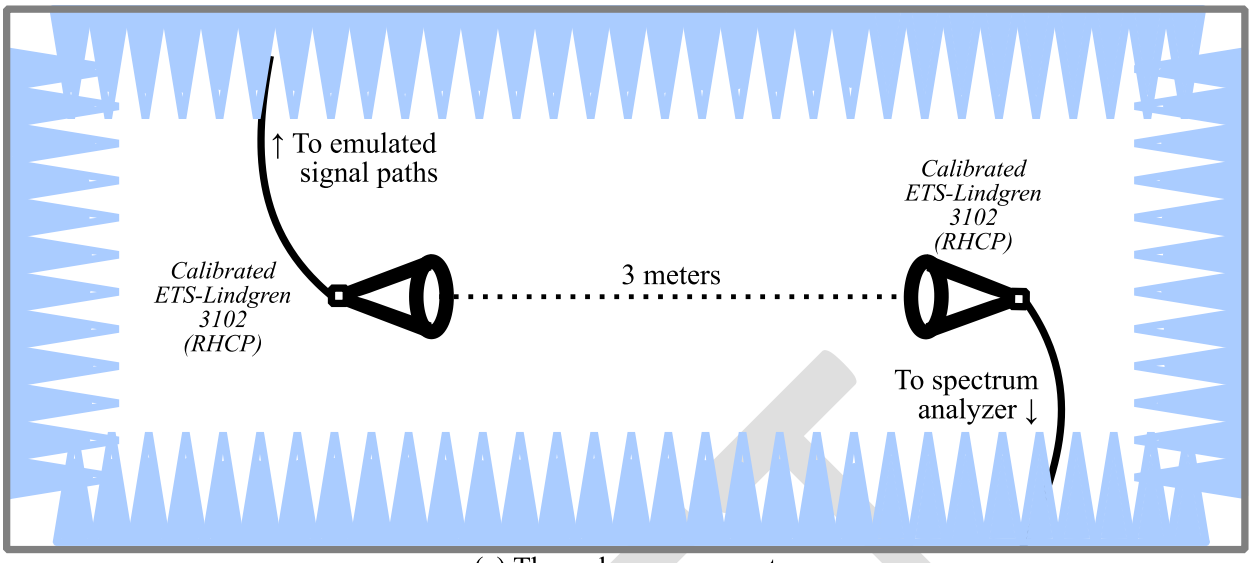
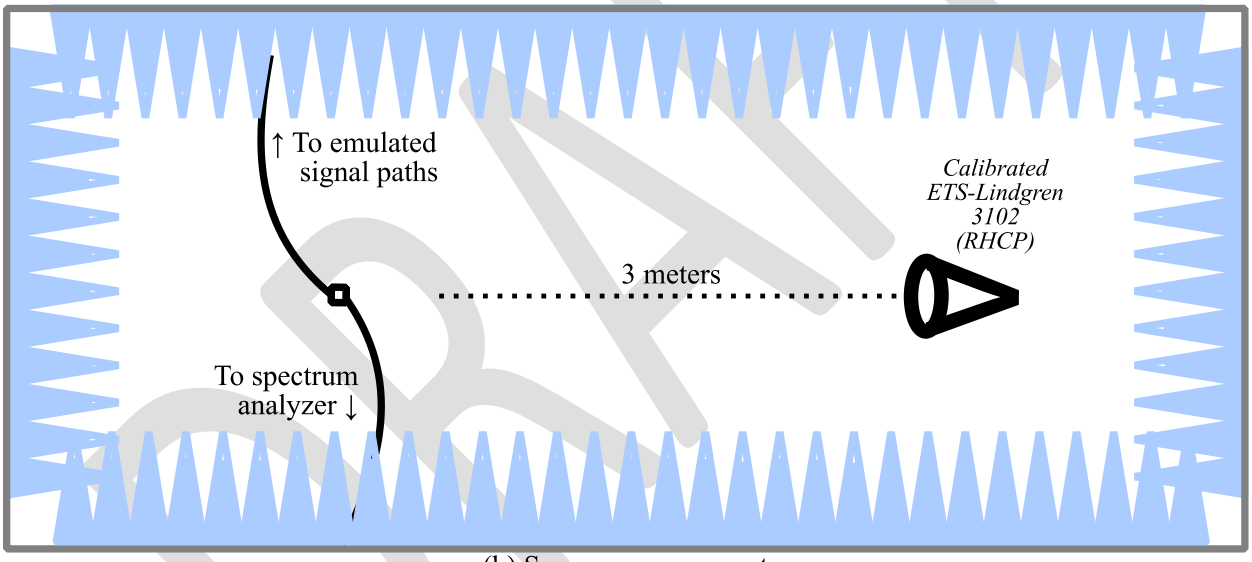


(a) Through measurement



(b) Source measurement

Figure 15. Validation procedures for radiated signal levels

D.4. Uncertainty

When possible, signal level uncertainty statements and analysis will be provided based on best practices from NIST and instrument manufacturers.

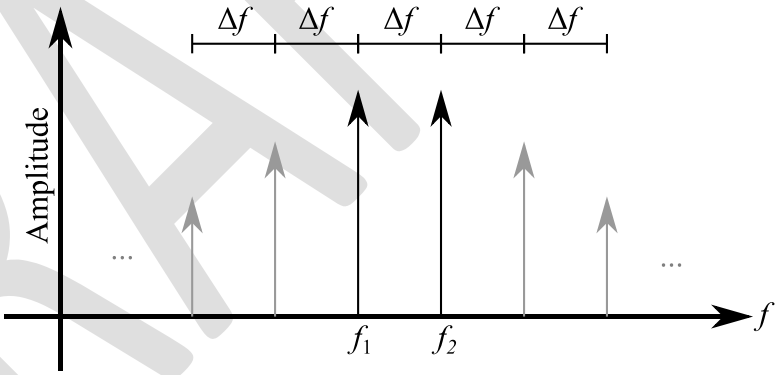
Appendix E. Procedures and Considerations for Validating Calibrations

E.1. Intermodulation Effects between Test Signals

This test plan prescribes signals that may have components at more than one (or all) of the LTE downlink, LTE uplink, and GPS L1 bands. Node voltages with these waveforms at nonlinear components of active system blocks (like amplifiers, receivers, and signal generators) may produce measurable signal components at new frequencies. Signals at these new frequencies are the intermodulation distortion (IMD) products. In passive devices like the combiner, connections between different metals form weakly nonlinear p-n diode junctions, which producing signal content at new frequencies but at weak levels that may be difficult to measure. This phenomenon is called passive intermodulation distortion (PIM), which is a form of IMD expected to have weaker amplitude than expected in active devices.

The impacts of IMD are a concern in testing LTE interference effects upon GPS L1 if the distortion alters the test results. The relatively powerful LTE waveforms "bookend" the interference sources, so we take IMD products to be important only if they are fall between LTE uplink and downlink frequencies: 1536 MHz – 1627.5 MHz. Within this frequency span, IMD products are negligible if they can be confirmed to be weak relative to the OOBE noise floor.

In general, the center frequency of each IMD product for two input signal bands is determined by their signal band center frequencies, f_1 and f_2, as in Figure 16. Intermodulation products come from the mixing product frequencies $f_{mn} = m f_1 + n f_2$, $= (m+n) f_1 + n \Delta f$ [7], where m and n can be any integer, and Δf is the spacing between the band center frequencies. The intermodulation products that we are concerned about happen near the fundamental frequencies. For these frequencies, m + n = 1, so each n^{th} intermodulation center frequency is



$$f_{imd} = f_1 + n \Delta f.$$

Like the illustration in Figure 16, none of the intermodulation frequencies are located between f_1 and f_2.

Intermodulation frequencies are listed for each pair of generated band centers in the table below. Only the combination of LTE downlink and GPS L1 signals produce IMD products in the test band, covering 1590.84 MHz – 1633.84 MHz (centered at 1619.84 MHz). Therefore, IMD will need to be tested with signals covering the LTE downlink and GPS L1 bands to ensure the IMD products are below the noise floor.

Table 19. Nearest high and low intermodulation frequencies produced by each pair of bands. Intermodulation products that need to be tested in the calibration process are shown in red.

Band 1, center frequency	Band 2, center frequency	Nearest IMD center frequency (below)	Nearest IMD center frequency (above)
LTE downlink, 1531 MHz	LTE uplink 1, 1632.5 MHz	1429.5 MHz	1734 MHz
LTE downlink, 1531 MHz	LTE uplink 2, 1651.5 MHz	1410.5 MHz	1772 MHz
LTE downlink, 1531 MHz	GPS L1, 1575.42 MHz	1486.58 MHz	1619.84 MHz
GPS L1, 1575.42 MHz	LTE uplink 1, 1632.5 MHz	1518.34 MHz	1689.58 MHz
GPS L1, 1575.42 MHz	LTE uplink 2, 1651.5 MHz	1499.34 MHz	1727.58 MHz

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