National Advanced Spectrum and Communications Test Network

LTE Impacts on GPS
Test and Metrology Plan

July 22, 2016

Prepared by:

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

Contents

Preface 4
1 Background 5
2 Objective 5
3 Scope 6
4 Deliverable 7
5 Test Methods 7
5.1 Overview 7
5.2 Parameters 8
5.2.1 Device Under Test (DUT) Population 8
5.2.2 Global Positioning System (GPS) Satellites 11
5.2.3 Augmentation Signals 14
5.2.4 Long Term Evolution (LTE) Signaling Scenarios 14
5.3 Setup 15
5.3.1 Equipment 15
5.3.2 GPS Position Testbed 17
5.3.3 GPS Time Testbed 18
5.3.4 In-Band LTE Emulation 20
5.3.5 Out-of-Band Emissions (OOBE) LTE Emulation 23
5.3.6 Measurement Locations 24
5.4 Tests to Establish Data Collection Timing 24
5.5 Tests at Swept LTE Levels 26
5.5.1 Study LTE In-Band Coexistence Margins 27
5.5.2 Emulate swept range 27
5.6 Time to First Fix 28
5.7 Test Matrix 29
6 Statistical Considerations 30
6.1 Test Population 30
6.2 Relevant Experimental Variables and Sources of Uncertainty 30
6.3 Analysis Plan 31
6.3.1 Overview 31
6.3.2 Warm-up Time Assessment 31
6.3.3 Quantile Estimation 32

7 Outreach and Community Feedback 32
8 Data Management 32
9 Project Tasks 32
10 Safety 33
11 References 34
Appendix A. Estimating In-Situ Interference Response from Anechoic Measurement Results 35
A.1. Introduction. 35
A.2. Goal. 35
A.3. Interference Scenarios. 35
A.4. Systems Engineering Approach for Interference-Effects Measurement Studies 37
A.5. Impacts of Sharing a Single Transmit Antenna in Anechoic Tests 37
A.6. Applying the SIR to Predicted System Performance. 37
Appendix B. Specifications of Antenna and RF Front End 39
Appendix C. Procedures for Characterization and Calibration of Conducted Signals 39
C.1. Instrument Calibration 39
C.2. Characterization of In-Band LTE Signal Generation 41
C.3. Characterization Out-of-Band LTE Signal Generation 46
C.4. Characterization of L1 GPS Signal Generation 48
C.5. Uncertainty 49
Appendix D. Procedures for Characterization, Calibration, and Validation of Radiated Power 50
D.1. Calibration of Transmit Loss to Linear Polarization 50
D.2. Calibration of Radiated Power Levels 50
D.3. Validating radiated signal levels at the DUT 52
D.4. Uncertainty 53
Appendix E. Procedures and Considerations for Validating Calibrations 55
E.1. Intermodulation Effects between Test Signals 55

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 or semi-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 or semi-anechoic test method, but does not incorporate insight from any preliminary 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 conditions and 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 conditions and 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.

July 22, 2016

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 L1 GPS receivers in tracking and reacquisition modes. 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 conditional 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. In addition, testing was performed by National Space-Based Positioning, Navigation, and Timing Systems Engineering Forum (NPEF) in October 2011 to January 2012. 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 or fully define Key Performance Indicators such as pseudo range error or 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 in tracking and reacquisition modes. 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 10 MHz band with approximately 70% resource block allocation. 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 or semi-anechoic chamber. A representative subset of available devices will be tested in the anechoic or semi-anechoic chamber. As several comments solicited during the external review process have pointed out either directly or indirectly, there are tens of millions of GPS devices on the market. Testing a set of devices that represents the comprehensive market in a statistically complete manner is not practical in the timeframe of this testing. Details and descriptions in this test plan would allow testing of additional devices in an equivalent manner. The testing of devices representing different radio architectures e.g., narrow versus broadband, will be covered.

3 Scope

The purpose of the GPS receiver measurement project is to develop a rigorous (i.e., a repeatable, calibrated, and well-documented) 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 or semi-anechoic chamber setup. Specifically, LTE waveforms representing a downlink band will occupy 1526 MHz - 1536 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, the 1627.5 MHz - 1637.5 MHz uplink, the 1646.5 MHz – 1656.5 MHz uplink, and a waveform that includes simultaneous up and downlink activity. Time-to-first-fix (TTFF) with LTE activity in the 1526 MHz - 1536 MHz downlink and the 1627.5 MHz - 1637.5 MHz uplink will be tested.

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, loss-of-lock, etc. Emphasis is on real-world expected LTE signals. However, where practical, the LTE signal levels will cover a range of power levels that may 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 pair used for testing simultaneous LTE activity is 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 uplinks 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 location, high precision position, and high precision timing. Aviation, space-based, cellular, and DoD devices of all categories are not included. The test procedure may require modification to include those additional categories of devices, such as base station connectivity for cellular devices or verification of consistency with testing required for certified aviation requirements. While a device from each category mentioned above is not tested here, as pointed out during the feedback process and consistent with radio architectures in general, the previous TWG and NPEF testing appear to indicate that the basic receiver RF architecture is the distinguishing feature, e.g., a narrowband versus wideband receiver, in determining susceptibility to LTE activity outside of the GPS band.

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 the primary focus of this test. Time permitting and in cooperation with the manufacturers, such antennas may be considered.

The initial measurements will focus on stationary devices, with a moving satellite constellation. Testing with the DUT in simulated motion, which represents a useful use-case for consideration, is not included in these test primarily due to test time limitations. The testing does include a limited satellite exposure condition; there are certainly other limited satellite exposure conditions that could be tested.

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.

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 or semi-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 or semi-anechoic chamber tests will include atmospheric impairments in the GPS signal simulation. A key consideration in the use of either an anechoic or semi-anechoic environment is the shielding from external RF sources and the minimization of multipath contributions.

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 for each of the devices.

The highest priority devices include four general location and navigation, three precision timing, and four precision location devices. In addition, based on feedback, the list now includes additional high precision devices rather than several lower priority devices. 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 testing will focus on the highest priority devices, with testing on the lower priority devices on a time permitting basis.

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

General Location and Navigation						
Unit	**Antenna**	**PC interface**	**Data format(s)**	**Extra KPIs**	**Sub-type**	**Website**
Garmin eTrex H	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	Internal	USB	GPX	No	Hiking	https://buy.garmin.com/en-US/US/into-sports/handheld/etrex-30x/prod518048.html
Garmin GPSMAP 78	Internal	Serial	NMEA GPX	NMEA params	Hiking	https://buy.garmin.com/en-US/US/on-the-water/handhelds-wrist-worn/gpsmap-78/prod63601.html
Garmin Montana 680t	Internal	USB	GPX	No	Hiking	https://buy.garmin.com/en-US/US/into-sports/hiking/montana-680t/prod523677.html
Garmin Montana 650t	Internal	?			Hiking	

Table 2. High precision positioning devices identified for testing.

High Precision Positioning					
Unit	**Antenna**	**PC Interface**	**Data format(s)**	**Extra KPIs**	**Website**
Trimble NETR9	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 GR50	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
NovAtel FlexPak 628	NovAtel GPS-702-GGL	Ethernet USB RS232 Onboard	NMEA, RINEX, MDB, HATANAKA, CMR, CMR+, RTCM BINEX	all NMEA RINEX	http://www.novatel.com/products/gnss-receivers/enclosures/flexpak6/
NovAtel ProPak 6		Ethernet USB RS232	NMEA, RINEX, MDB, HATANAKA, CMR, CMR+, RTCM BINEX	all NMEA RINEX	http://www.novatel.com/products/gnss-receivers/enclosures/propak6/

		Onboard			

Table 3. Precision timing devices identified for testing

Precision Timing					
Unit	**Antenna**	**Accuracy**	**Ext. Oscillator Support**	**Lock state indicator**	**Website**
Arbiter 1088B GPS Satellite Clock (40ns)	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	Microsemi Kit	<15ns	Yes	Yes	http://www.microsemi.com/products/timing-synchronization-systems/time-frequency-distribution/network-appliances-servers/syncserver/syncserver-s650
Novatel ProPak (OEMV)	GPS-703-GGG			Yes	
MicroSemi TimeSource 3050	Microsemi Kit		Yes	Yes	http://www.microsemi.com/products/timing-synchronization-systems/time-frequency-references/telecom-primary-reference-sources/timesource-3050

5.2.2 Global Positioning System (GPS) Satellites

The configurations for the satellite constellation are based on a nominal and limited exposure setting, respectively. The emulated GPS signals will include the ionospheric and tropospheric propagation effects, as typically included in the Spirent simulated scenarios. Details for the constellation are listed in Table 5, with examples of the constellations shown below. Losses from the calibrated test signal radiation to the DUT will be verified according to Appendix D.3.

Table 4. Satellite constellation setup.

Nominal	
Number of generated satellites	11
GPS L1 C/A signal for each satellite	-128.5 dBm
Additional transmit signals	L1C pilot, Pseudo Y, and M-code
Time to First Fix	
Number of generated satellites	8 to 13
GPS L1 C/A signal for each satellite	-128.5 dBm
Additional transmit signals	L1C pilot, Pseudo Y, and M-code
Limited Exposure	
Number of generated satellites	8
GPS L1 C/A signal for 1st satellite	-128.5 dBm
GPS L1 C/A signal for 2nd satellite	-128.5 dBm
GPS L1 C/A signal for 3rd satellite	-133.5 dBm
GPS L1 C/A signal for 4th satellite	-133.5 dBm
GPS L1 C/A signal for 5th satellite	-138.5 dBm
GPS L1 C/A signal for 6th satellite	-138.5 dBm
GPS L1 C/A signal for 7th satellite	-143.5 dBm
GPS L1 C/A signal for 8th satellite	-143.5 dBm
Additional transmit signals	L1C pilot, Pseudo Y, and M-code
Augmentation signals	
Two WAAS satellites, W1 and W2	-128.5 dBm
GPS constellation power levels based on hypothetical power available from a 0 dBi antenna in the location of the DUT.	

GPS emulator (Spirent GSS8000 GNSS Simulator) is configured to provide a satellite constellation with the following features:

- Frequency: (L1 only) 1575.42 MHz
- Stationary Location: N 31 degrees 35.893636 minutes; W 110 degrees 16.670841 minutes; height 1352.30m
- Satellite elevation mask angle of 5 degrees above horizon
- WAAS augmentation signals from two geostationary satellites: W1 (Intelsat Galaxy 15) at 133 degrees W longitude and W2 (Telesat Anik F1R) at 107 degrees, 18 seconds W longitude.
- Initial Satellite configuration corresponds to July 4, 2016 at UTC time 01:40:00 (UTC 1:40 am)

Nominal Satellite Coverage:

For a nominal satellite coverage case the power levels of all satellites is fixed (all satellites in view transmit the same power) to correspond to -128.5 dBm at plane of the DUT.

During a measurement power-level dwell period (on the order of 30 mins) the simulation provides 11 GPS L1 satellites in view.

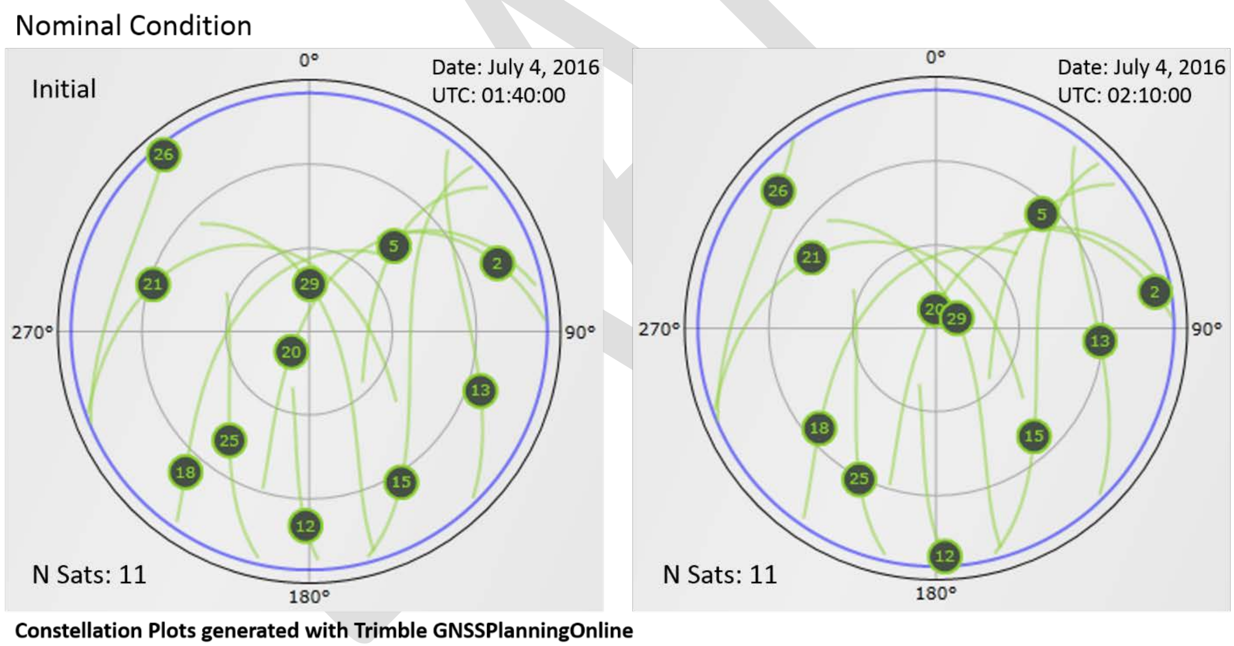


Figure 1. The Nominal satellite constellation. Initial GPS constellation (left), after 30mins (right). All satellites in view are configured to emit -128.5 dBm at the plane of the DUT assuming a 0 dBi receiving antenna.

Limited Satellite Coverage:

For a limited satellite coverage condition the number of satellites is reduced to 8 satellites at a range of power levels with the following constellation profile.

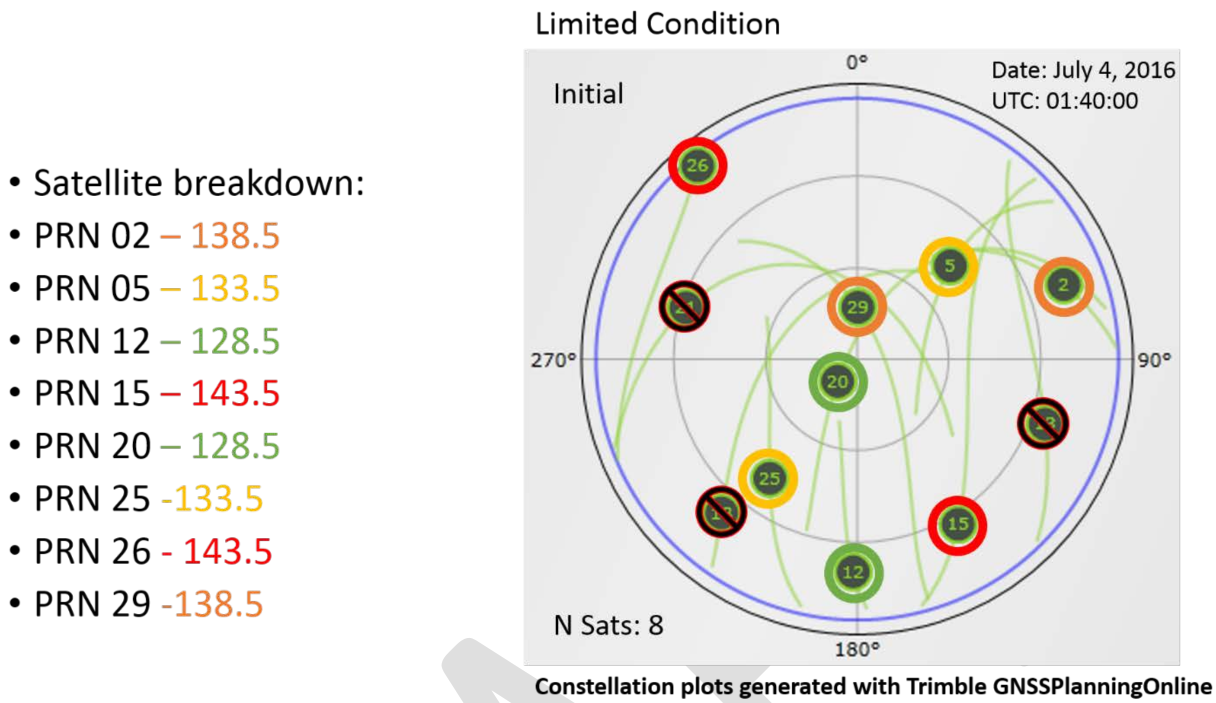


Figure 2. Limited satellite constellation. Initial GPS constellation (left), after 30 mins (right). Satellites in view will have a distribution of power levels at the plane of the receiver assuming a 0 dBi receiving antenna.

As the LTE power levels are incremented, the constellation is advanced by approximately 24 hours. A modified almanac was used to obtain similar geometries between the 24 hour intervals. Each DUT is tested using the same series of days.

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 to ensure that the impacts can be mapped to the GPS component of the receiver. Augmentation signals such as Wide Area Augmentation Signals (WAAS), Real Time Kinematic (RTK) solutions (e.g., signals from a secondary receiver), will be included as needed. Other navigation satellite constellations such as Galileo and Glonass are not considered and are not included in the GNSS simulation.

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 will not be generated during test since a cavity filter is not currently available with this passband.

Table 5. Up and downlink frequencies.

Number	LTE Link Direction	LTE Band (MHz)
1	Downlink	1526 - 1536
2	Uplink-1	1627.5 - 1637.5
3	Uplink-2	1646.5 - 1656.5
Not Tested	Downlink	1670 - 1680

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 3 in relation to GPS L1 and LTE operating bands under consideration.

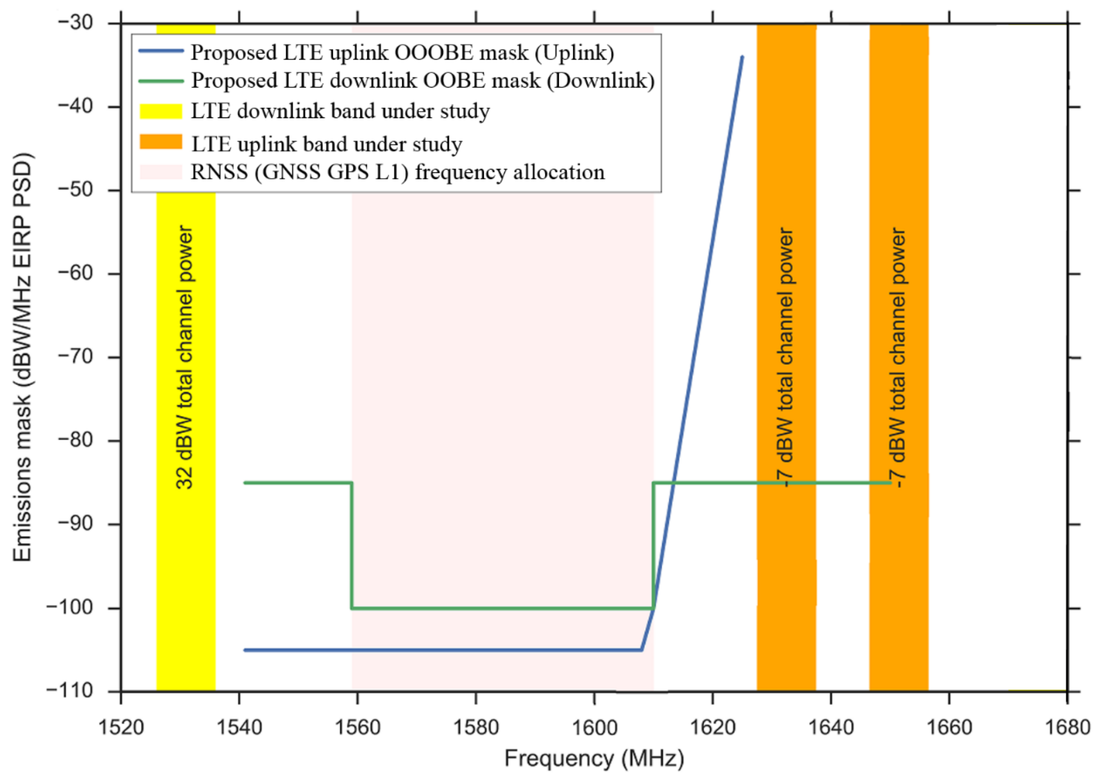


Figure 3. Proposed in-band and out-of-band LTE emission masks under study near the radio navigation satellite service (RNSS) allocation used by GPS L1.

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.

Either a semi-anechoic or a fully anechoic chamber is appropriate for the test setup described here. The key considerations are the RF shielding from outside signals and the control of multipath contributions, i.e., reflections inside the chamber, at the location of the DUT. In addition, in a semi-anechoic chamber, the reflection off the floor, i.e., the “ground bounce”, should have minimal contribution at the DUT location. If necessary, adding RF absorber on the floor between the transmitting antenna and the DUT will help attenuate any floor reflections. D.4 describes the calibration process for ensuring the correct radiated power at the DUT and for verifying minimal multipath contribution at the DUT.

Table 6. Equipment for anechoic or semi-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	2
Isolator	Fairview Microwave SFI1020 (or similar)	1- 2 GHz Isolation > 19 dB	2
LTE amplifier	Varian Med S/N: 6459 TWTA: VZL6941K1	1-2 GHz, 20 W	1
LTE amplifier	EMPOWER Model: 2170-00	1000-3000 MHz, 1000 W	1
Programmable attenuator	Mini-Circuits RCDAT-6000-110 (or similar)	0.25 dB steps; 0.3 dB uncertainty	5
LTE downlink in-band OOB rejection filter	Custom S/N: 1103007 Model Name: RMC1531B10M01	1560 MHz-1610 MHz	1
Duplexer	Anatech 1542-1643D296	Separates an input into separate channels - LTE downlink bands and uplink bands	2
Antenna (RHCP for anechoic or semi-anechoic chamber)	ETS-Lindgren 3102	RHCP conical log spiral Nominal 1 GHz-10 GHz; use gain calibration @ 3m	1
Antenna (validation horn)	ETS Lindgren 3115 (or similar)	Nominal 1 GHz-18 GHz; use gain calibration @ 10m	1
Spectrum Analyzer	Rhode and Schwartz FSW26 ID: 1312.8000K26-103545-UQ	2 Hz -26.5 GHz	1
Network Analyzer	Agilent 8753ES	30 KHz – 3 GHz	1
Signal generator for LTE OOB emission	Rhode and Schwartz SMBV100A	9k kHz – 3.2 GHz, Requires ARB capability	1
Time Interval Counter	Keysight Technologies 53220A (or similar)	Single shot resolution 100 ps	1
Temperature monitor	Pyle Digital Hygrometer/Thermometer USB Data-Logger PTHDL170	-40 to 221° F	1
Band Pass Filter	K&L 4CP120-1651.7/E10.3-O/O	Custom OOBE filters	1
Band Pass Filter	K&L 4CP120-1632.7/E10.3-O/O	Custom OOBE filters	1

Air Dielectric Hybrid Coupler	H-3-CPUSE-N-Ai6	698-2700 MHz	3
High Power Amplifier	Minicircuits ZHL-4W-422+	500 to 4200 MHz, 4W,	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 4 depicts the setup in the anechoic or semi-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 10. 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 DUT will be reset to operate under the same conditions during LTE activity as the during the establishment of the baseline.

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.`

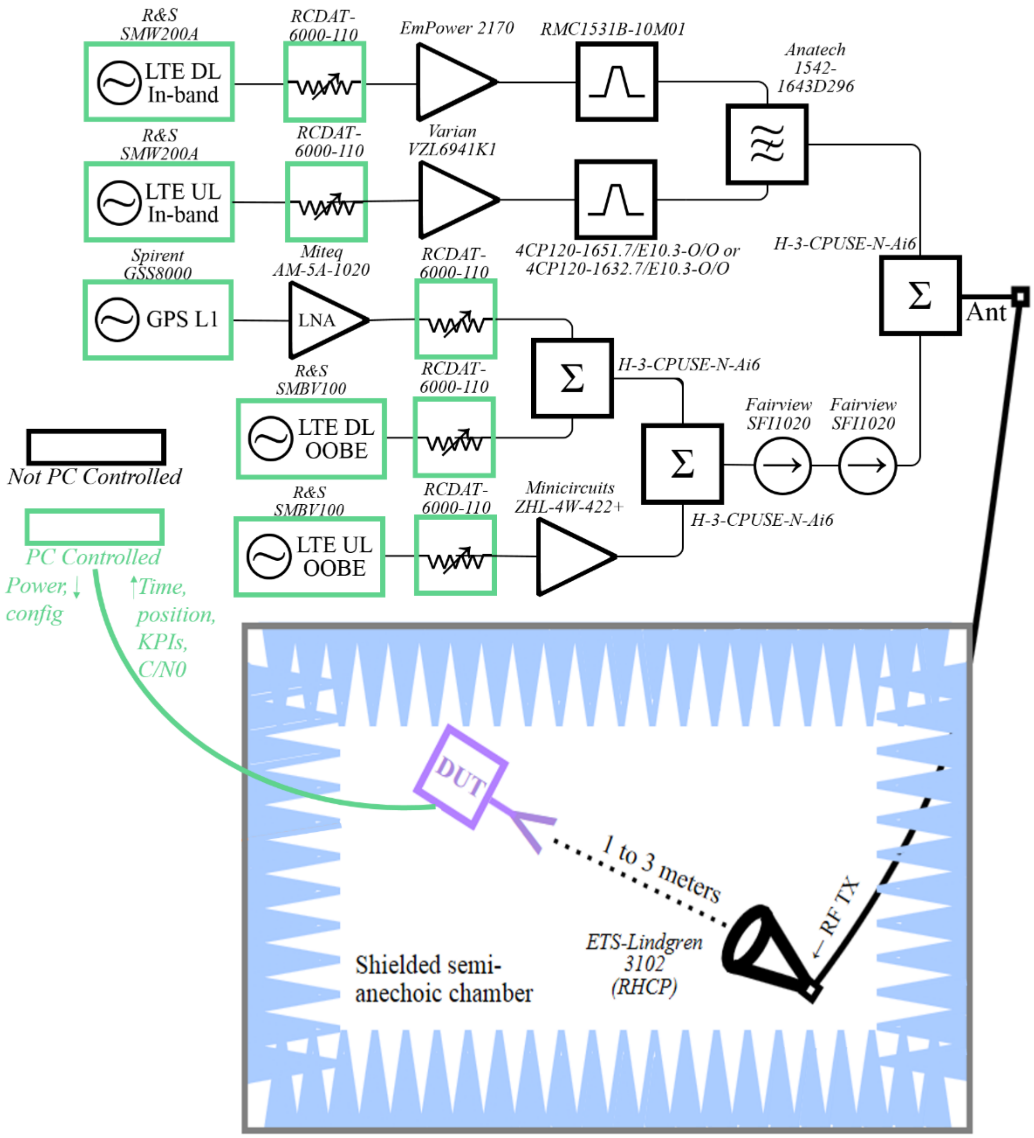


Figure 4. Setup for position measurements in the anechoic or semi-anechoic chamber.

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 5 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 10. Timing data are stored to allow determination of UTC accuracy and stability for the 1 PPS and, if available for each individual satellite.

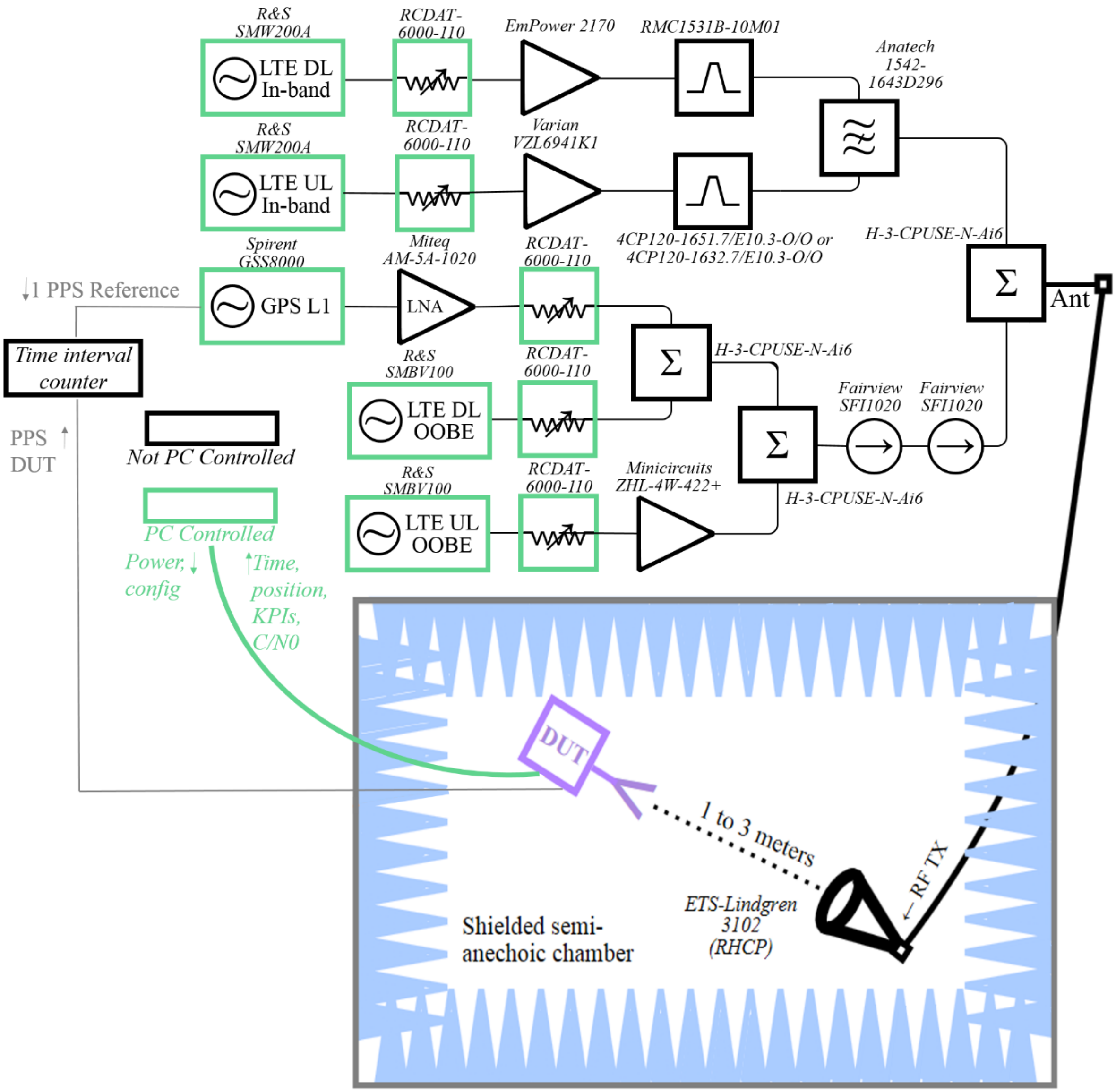


Figure 5 Setup for precision timing tests in the anechoic or semi-anechoic chamber.

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. There are two candidate channel configurations: 1) a single 10 MHz wide channel filling the full allocation, consisting of 50 available resource blocks (RBs), and 2) two 5 MHz channels to fill a full allocation, each consisting of 25 available RBs. The base station compensates for the weak link with fair scheduling, limiting the number of RBs allocated to our UE. For each channel configuration, we assume a relatively large 70% RB allocation (35 RBs for the single 10 MHz channel, or 18 RBs for each 5 MHz channel). The UE compensates for the weak link by transmitting the quadrature phase-shift keying (QPSK) at its maximum allowed EIRP following Figure 3. 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 6 and a spectrum like that in Figure 7. This uplink corresponds with 7 Mbps maximum data rate.

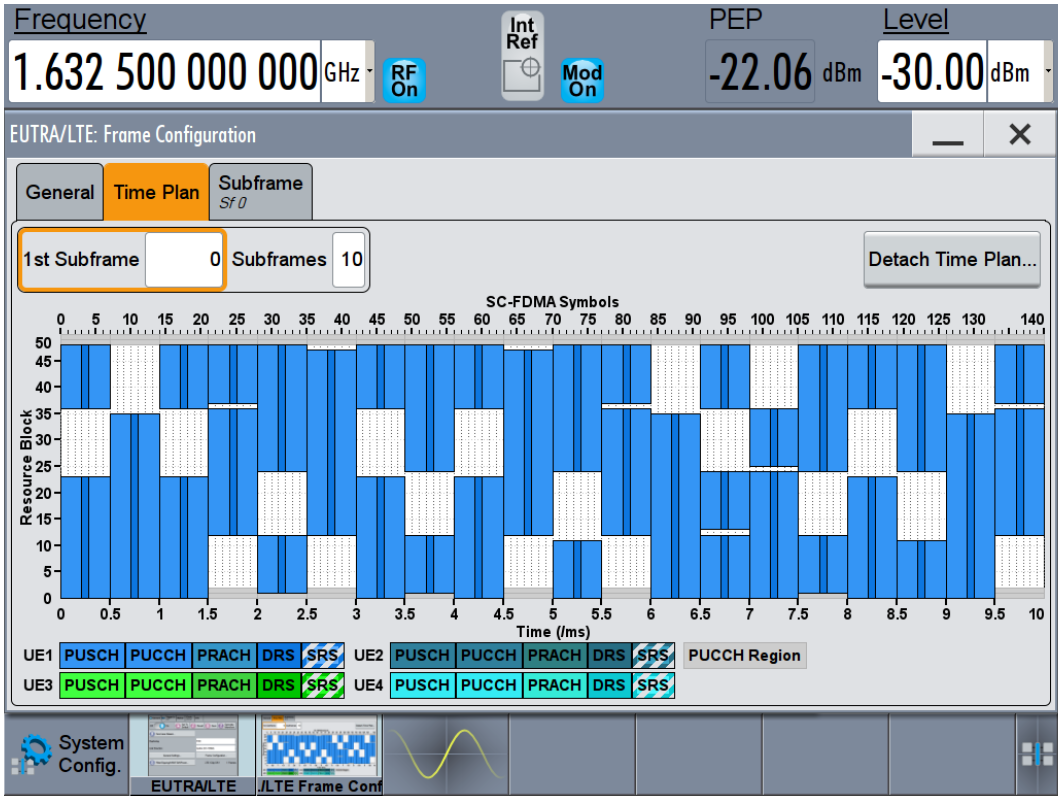


Figure 6. Example LTE uplink resource block allocation

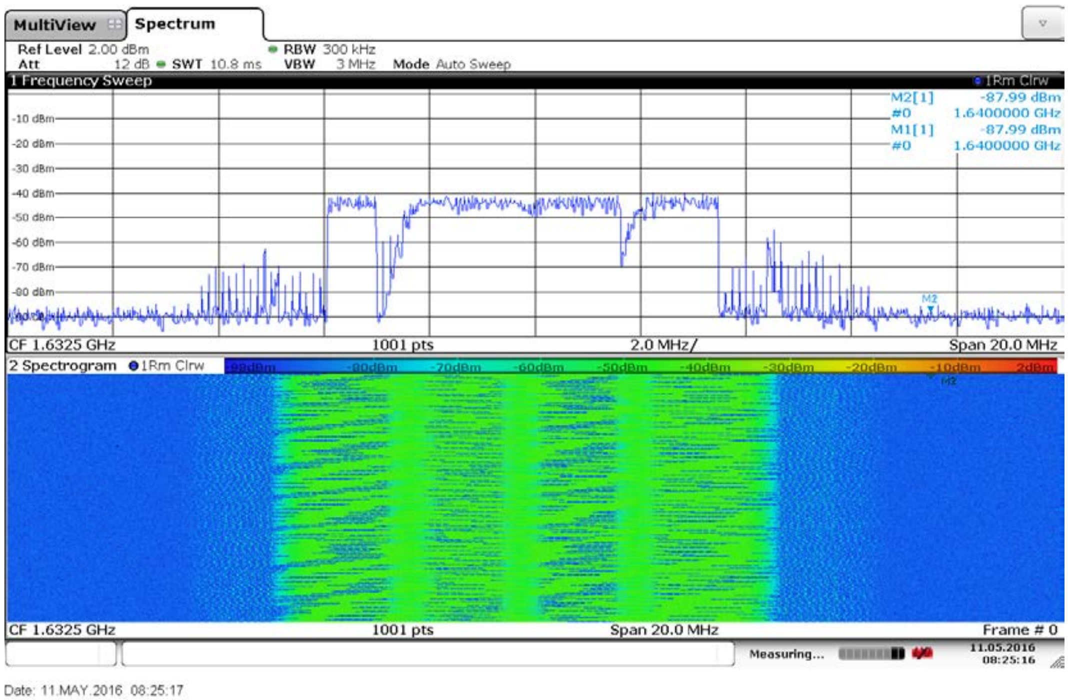


Figure 7. Example PSD measurement of a 10 MHz LTE uplink

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 represents a GPS unit located near is a fully-allocated downlink signal from a base station while a UE is also sending data to another base station on an uplink. 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 or semi-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 or semi-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 8 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.

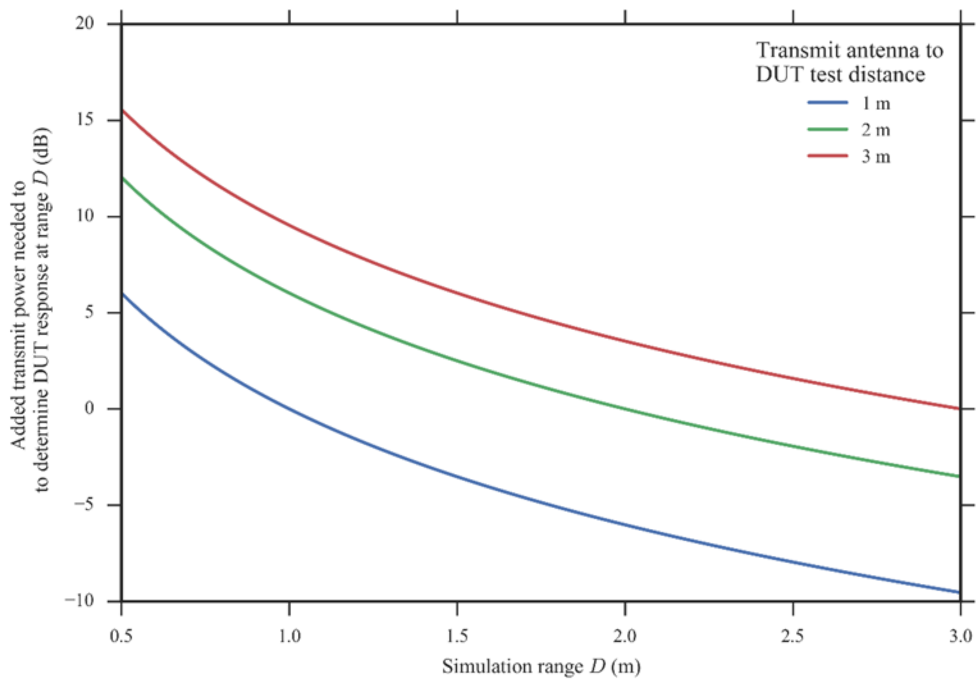


Figure 8. Path loss calculations based on the Friis transmission equation.

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 3. 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

The testing will take place at the National Test Systems (NTS) facility in Longmont, CO. The facility utilized will be a 10-meter, semi-anechoic chamber.

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 9, 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 10, at each LTE power level, data are captured for a time duration of t_c .

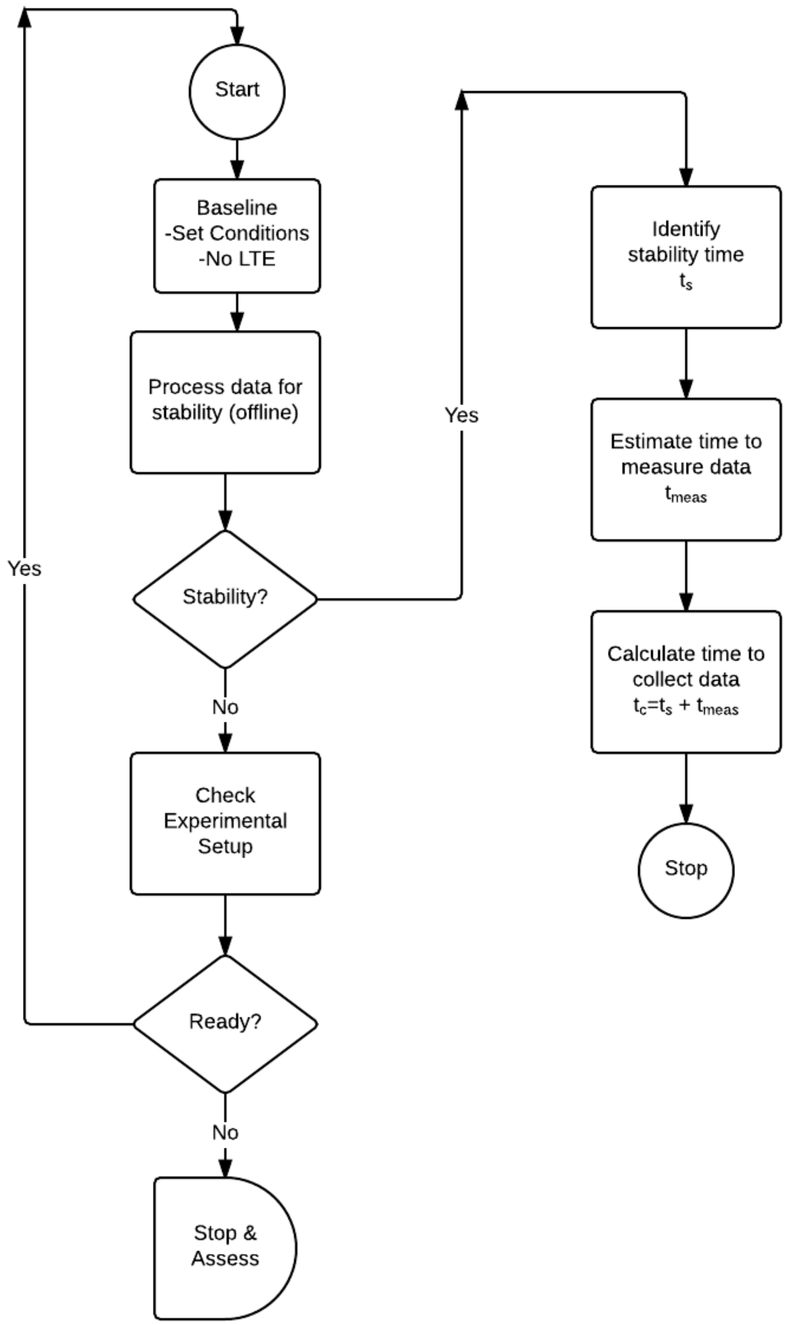


Figure 9. Process to establish data collection time for the DUT.

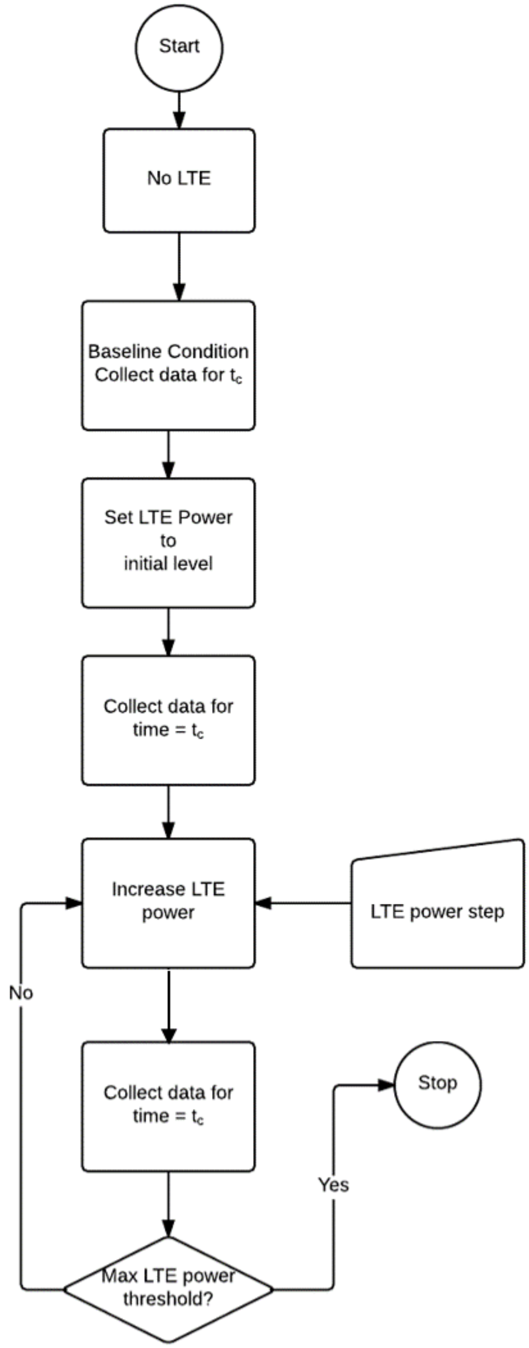


Figure 10. Process to increment LTE power for a specific waveform and collect data from the DUT.

5.5 Tests at Swept LTE Levels

We propose here two 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. The first approach assumes a fixed physical distance between the LTE signal and the DUT and will be given preference in the testing. The second approach assumes that the physical distance between the LTE source and the GPS device varies over a range. If time permits, both types of testing will be performed.

5.5.1 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 11. The out-of-band emission power-spectral density is fixed to that of Figure 3, 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.

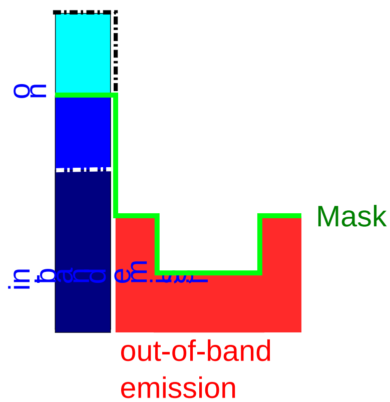


Figure 11. The in-band and out-of-band emission and the waveform mask for in-band LTE coexistence margin testing. Here, LTE out-of-band emission is held constant while LTE in-band emission is varied.

5.5.2 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. This scenario assumes changes in the fading channel between the DUT and the LTE transmitter due to factors such as changes in physical separation distances between the DUT and the LTE transmitter. 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.

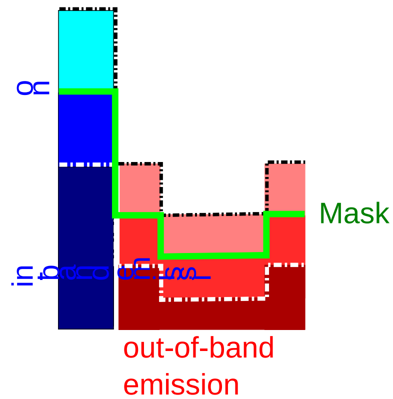


Figure 12. The in-band and out-of-band emission and the waveform mask for swept range emulation. The same losses apply to both in-band and out-of-band emissions.

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.

5.6 Time to First Fix

Time to first fix (TTFF) is the measure of the time a DUT takes to reacquire GPS lock after loss of signal through either a warm start or a cold start. In the warm start case, GPS signal is terminated for t_{reaq} seconds and then reintroduced. For a cold start, the GPS signal is held constant, however the DUT is sent a command to initialize a cold start as per manufacturer specification. It is important that t_{reaq} be chosen such that the DUT will have sufficient time to acquire or reacquire a lock on the GPS signal. Note that t_{reaq} is not necessarily equal to t_s discussed above.

The TTFF is being conducted in a nominal GPS satellite constellation and a fixed LTE power level, where the exact LTE power level will be determined during the Phase 1 testing of the devices. TTFF will be first tested with a downlink LTE waveform and subsequently an uplink LTE waveform. The warm/cold start cycling is performed a sufficient numbers of times to obtain sufficient data for meaningful statistical analysis.

The warm start sequence is described below:

1) GPS signal is turned on to nominal power level;
2) LTE signal is turned on to specific power level;
3) The DUT is started up and data collection begins;
4) After t_{reaq} seconds the GPS signal is attenuated such that the DUT loses lock;
5) Wait for t_{reaq} seconds;
6) Reintroduce GPS signal;
7) Repeat steps 4 – 6 until sufficient number of reacquisitions are achieved;

8) Stop data collection and turn off DUT.

Cold start sequence is described below:

1) GPS signal is turned on;
2) LTE signal is turned on;
3) The DUT is started up and data collection begins;
4) After t_{reaq} the cold-start command is sent to the DUT;
5) Wait for t_{reaq} seconds;
6) Repeat steps 4 – 6 until sufficient number of reacquisitions are achieved;
7) Stop data collection and turn off DUT.

5.7 Test Matrix

The table below lists the test phases. The satellite constellations are described in Section 5.2.2. An initial stepped LTE power test will determine the delta between LTE power steps. The time spent at each power step will be long enough to collect sufficient data for the accompanying the data analysis discussed below.

Table 7. Matrix for the three phases of testing. The satellite constellation descriptions are provided in Table 5 and the uplink and downlink frequencies are given in Table 6. The stepped LTE is described in Section 5.5.

Phase 1							
#	Device	Satellite Constellation	LTE Waveform				LTE Power
			Downlink	Uplink-1	Uplink-2	Downlink + uplink-1	
1	Garmin GPSMAP 78	Nominal	x	x	x	x	Stepped
2	Garmin 2 Etrex 30x	Nominal	x	x	x	x	Stepped
3	Garmin 3 Montana 680T	Nominal	x	x	x	x	Stepped
4	Garmin 4 Etrex H	Nominal	x	x	x	x	Stepped
5	Trimble NetR9	Nominal	x	x	x	x	Stepped
6	Leica GR30	Nominal	x	x	x	x	Stepped
7	NovAtel Propak 6	Nominal	x	x	x	x	Stepped
8	NovAtel FlexPak 628	Nominal	x	x	x	x	Stepped
9	Arbiter Timing	Nominal	x	x	x	x	Stepped
10	MicroSemi Symmetricom SyncServer S650	Nominal	x	x	x	x	Stepped
11	MicroSemi TimeSource 3050	Nominal	x	x	x	x	Stepped
Phase 2 Time to First Fix (TTFF)							
1	Garmin GPSMAP 78	Nominal	x	x			Fixed
2	Garmin 2 Etrex 30x	Nominal	x	x			Fixed
3	Garmin 3 Montana 680T	Nominal	x	x			Fixed
4	Garmin 4 Etrex H	Nominal	x	x			Fixed
5	Trimble NetR9	Nominal	x	x			Fixed
6	Leica GR30	Nominal	x	x			Fixed
7	NovAtel Propak 6	Nominal	x	x			Fixed

8	NovAtel FlexPak 628	Nominal	x	x			Fixed
9	Arbiter Timing	Nominal	x	x			Fixed
10	MicroSemi Symmetricom SyncServer S650	Nominal	x	x			Fixed
11	MicroSemi TimeSource 3050	Nominal	x	x			Fixed
Phase 3 Limited Exposure							
1	Garmin GPSMAP 78	Limited	x	x			Stepped
2	Garmin 2 Etrex 30x	Limited	x	x			Stepped
3	Garmin 3 Montana 680T	Limited	x	x			Stepped
4	Garmin 4 Etrex H	Limited	x	x			Stepped
5	Trimble NetR9	Limited	x	x			Stepped
6	Leica GR30	Limited	x	x			Stepped
7	NovAtel Propak 6	Limited	x	x			Stepped
8	NovAtel FlexPak 628	Limited	x	x			Stepped
9	Arbiter Timing	Limited	x	x			Stepped
10	MicroSemi Symmetricom SyncServer S650	Limited	x	x			Stepped
11	MicroSemi TimeSource 3050	Limited	x	x			Stepped

6 Statistical Considerations

6.1 Test Population

GPS devices from the following categories will be tested:

- general location and navigation
- high precision
- timing

A detailed enumeration of the GPS devices under test is provided in Table 1 through Table 4. To keep the test time and cost manageable, only a single unit of each device will be tested.

Although the sample of test devices will be stratified according to category, it will not be randomized within each category. 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. Also, for a limited number of conditions, time to first fix (TTFF) will be evaluated. Note that the response variables will be device dependent.
- 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), start-up device state (for devices without an accessible reset option)
- Sources of uncertainty: variations in LTE and GPS signal strength, structure of LTE signals, satellite constellation, GPS signal impairments, GPS processing algorithm, start-up device state, receiver antenna orientation, and indoor environmental conditions

6.3 Analysis Plan

6.3.1 Overview

The analysis aims to compare the steady-state distribution of each device output with LTE interference to the steady-state distribution of the device output without LTE interference (the "baseline"). Key steps of the analysis are as follows:

- Each time-series is first processed by estimating a warm-up period, which includes transients due to start-up or sudden changes in conditions. Subsequent analysis discards data from the warm-up period.
- Steady-state distributions are compared by evaluating quantiles, e.g., median, 90th and 95th percentiles, capturing differences in both typical and extreme behavior

6.3.2 Warm-up Time Assessment

The analysis of device outputs is predicated on the assumption that the device is operating in a steady-state condition. Non-steady-state behavior is expected at start-up or when the device is experiences a sudden change in conditions. Since the GPS simulator will be set-up so as to minimize sudden changes in the satellite constellation, transient effects are expected to be present only when the device is first exposed to a new test condition.

The time at which transients are negligible, called the warm-up time, will be estimated with the approach of Alexopoulos et al.[3]. This procedure starts by dividing the time-series into non-overlapping batches of equal length and then estimates a specified quantile, e.g., the median, for each batch. Next, the von Neumann randomness test is applied to check if the batch quantiles are statistically independent. The procedure iteratively increases the batch size while decreasing the significance level, until the test is passed. Lastly, the final batch size is taken to be the warm-up time. In a nutshell, this method requires the warm-up time to be sufficiently large so that data from the initial warm-up period is independent of the remaining time-series.

Once the warm-up time is estimated, all subsequent analysis will be carried out on the steady-state portion of the data that follows. Note that because 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, the warm-up time must be estimated for each device and test condition.

6.3.3 Quantile Estimation

Quantiles of the steady-state distribution, such as the median, 90th, and 95th 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 baseline distribution for each KPI without LTE interference to that with LTE interference. Statistical precision of the measurements will be evaluated by estimating confidence intervals for each quantile.

One difficulty in the statistical analysis stems from the fact that the time-series of device outputs is expected to be highly-correlated. Classical statistical estimators of confidence intervals for quantiles are designed for independent samples, and they break down for dependent samples. Consequently, special methods designed for dependent sequences are required. Point estimates and confidence intervals for quantiles will be estimated with the averaged group quantile method of Heidelberger & Lewis [4], which is based on asymptotic theory for dependent sequences.

To compare a given quantile for the baseline and LTE interference conditions, a confidence interval for the difference of quantiles will be formed from the respective quantile confidence intervals. A conservative coverage probability for the difference confidence interval can be justified with the Bonferroni inequality. The results for each KPI at a specified quantile will be presented by plotting the difference of quantiles versus LTE power level.

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 Semi-anechoic setup and baseline tests
Semi-anechoic chamber test
Data Analysis and Report
NASCTN Data and Report Review Process (including Director)
Issue Report

10 Safety

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

11 References

[1] http://www.nist.gov/ctl/nasctn/nasctn_moa2015.cfm

[2] M. A. Weiss, F. G. Ascarrunz, T. E. Parker, V. Zhang, and X. Gao, "Effects of Antenna Cables on GPS Timing Receivers," Proc. 1999 Joint Mtg. IEEE Intl. Freq. Cont. Symp. And EFTF Conf., pp. 259-262, 1999. http://tf.boulder.nist.gov/general/pdf/1384.pdf

[3] C. Alexopoulos, D. Goldsman, A. Mokashi, K-W. Tien, and J. R. Wilson, "SEQUEM: estimating extreme steady-state quantiles via the maximum transformation, Proc. 2015 Winter Simulation Conf., pp. 562-574., Dec. 2015

[4] P. Heidelberger and P. A. W. Lewis, "Quantile estimation in dependent sequences," Operations Research, vol. 32, no. 1, pp. 185-208, Jan-Feb, 1984.

[5] J.C. Perdo, N.B. Carvalho, "Intermodulation Distortion in Microwave and Wireless Circuits." Boston: Artech House, 2003, p. 17.

[6] Federal Communications Commission, "Comment Sought on Ligado's Modification Applications," Report no. DA 16-442. April 22, 2016. Online: http://transition.fcc.gov/Daily_Releases/Daily_Business/2016/db0422/DA-16-442A1.pdf

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); this term is also known as the Off-Frequency Rejection (OFR) component of the Frequency-Dependent Rejection (FDR) term;

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 $B_r > B_i$. In addition, this term is known as the On-Tune Rejection (OTR) component of the FDR, and is typically set to zero when considering adjacent-channel interactions with a noise-like emission source.

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

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 or semi-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 13. 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 10.

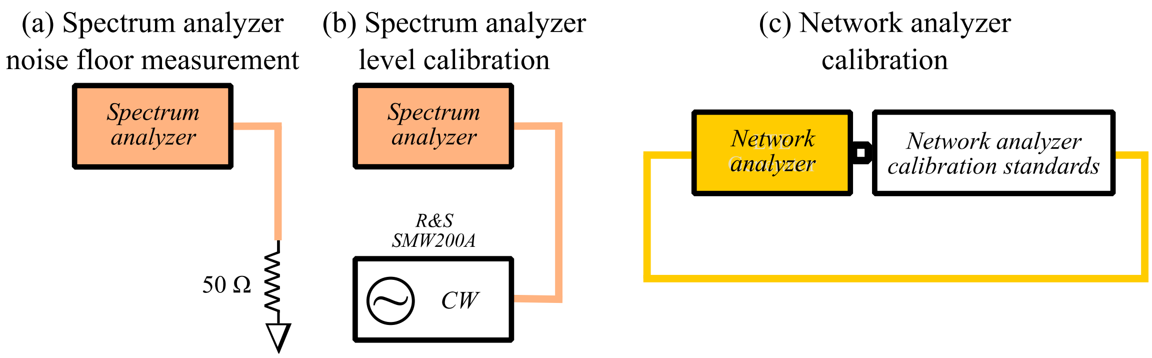


Figure 13. Instrument calibration signal paths

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 14. 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.

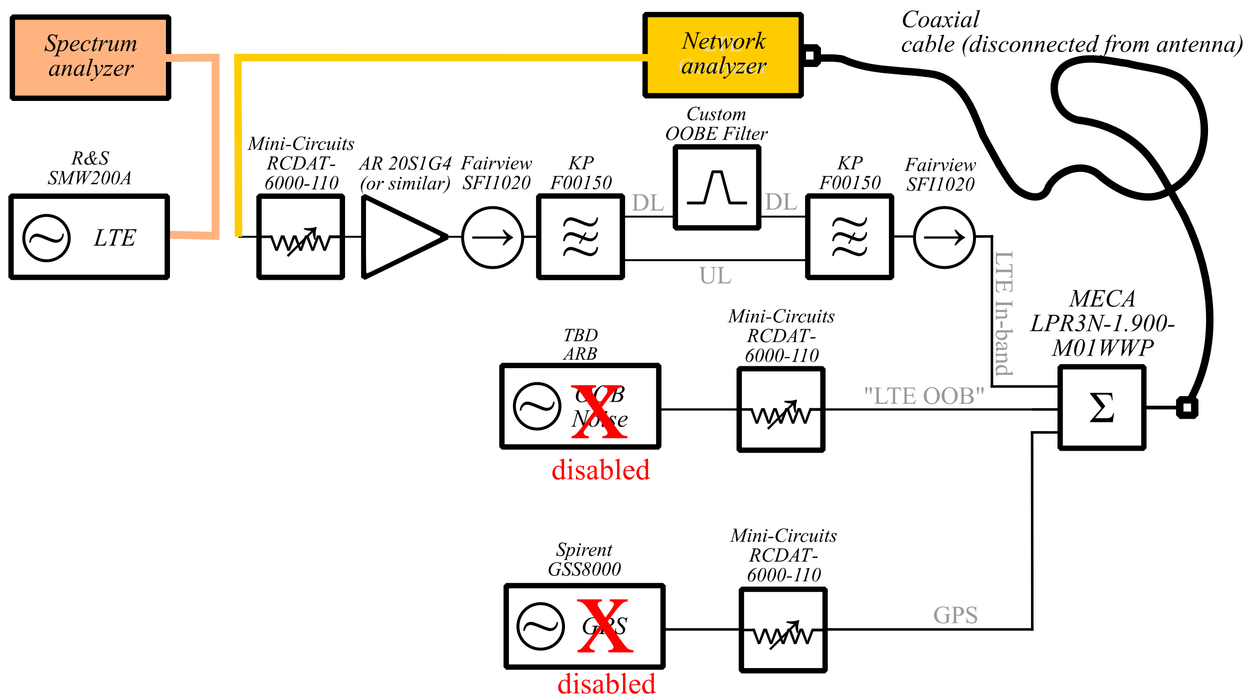


Figure 14. LTE in-band signal generation path conducted measurements for calibrations

The calibration measurements necessary to characterize the LTE in-band signal generation path are listed in Table 13. The correction computations based on these measurements are listed in Table 14.

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

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 15 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 17 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

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 15. 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 15. 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 15.

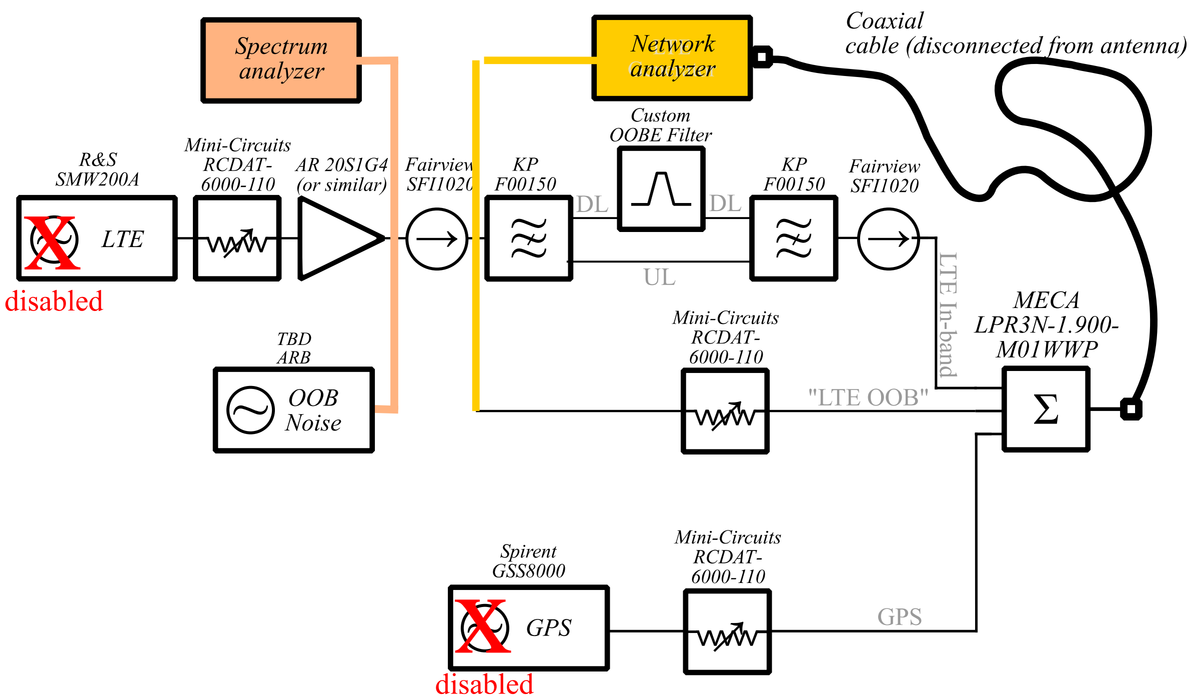


Figure 15. Conducted measurement setup for calibrating LTE out-of-band signal generation

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 15 at each frequency point as LTE OOB DL PSD input (dBm/Hz) - $\lvert$LTE OOB path S-parameters, $S_{21}\rvert$ (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 17 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.

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 16. 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.

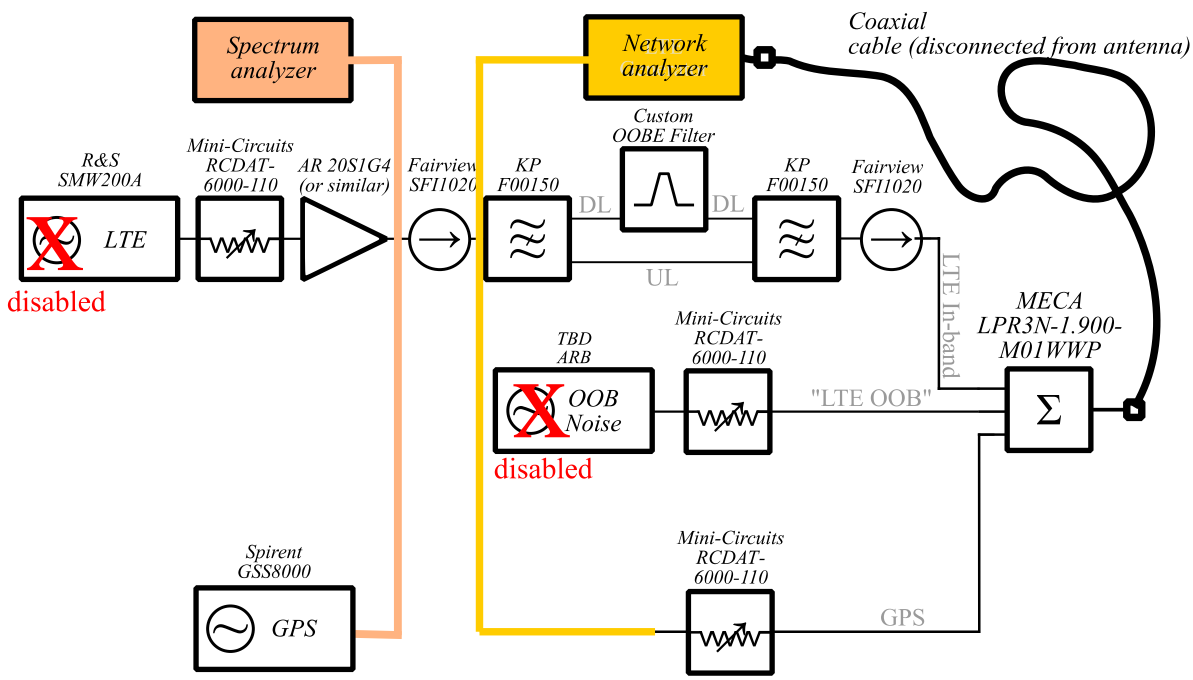


Figure 16. GPS L1 signal generation path conducted measurements for calibrations

The instrumentation configuration for the GPS L1 signal characterization is shown in Figure 15. 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 17.

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 17 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 circular 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 17.
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

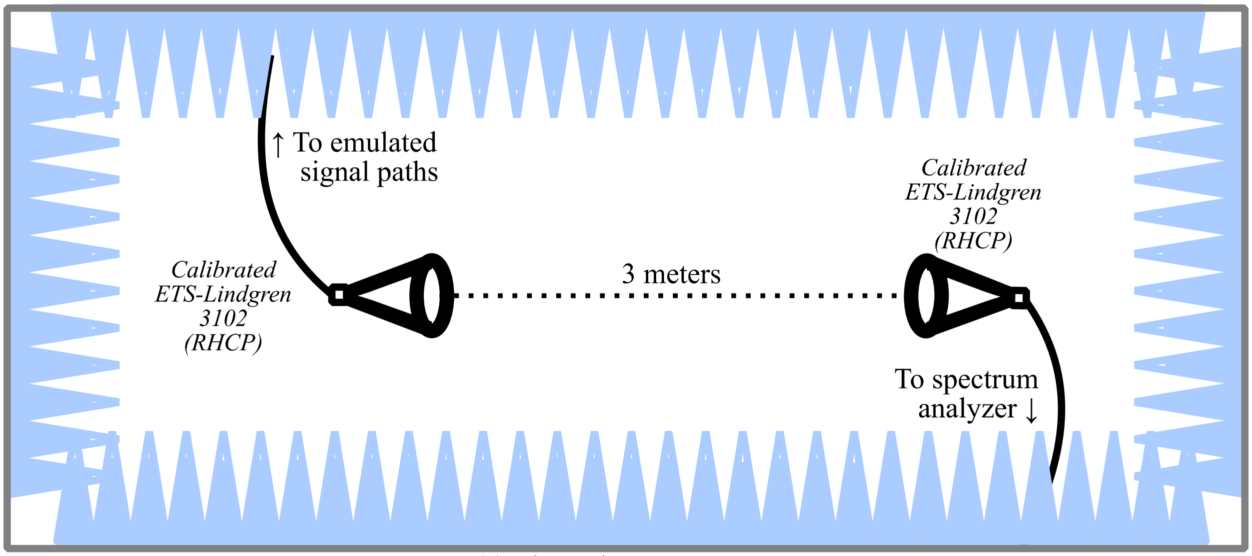
	EIRP (in dBm) = PTX (dBm) + G (dBi) - Lpol (dB) or EIRP (in dBW/MHz) = PTX (dBW/MHz) + G (dBi) - Lpol (dB) This expression applies to the uplink or downlink, and in-band or out-of-band. The appropriate choice of conducted transmit power PTX comes from the desired choice among "LTE UL in-band PSD output" or "LTE DL in-band PSD output" in *Table 14*, or "LTE OOB DL PSD output" or "LTE OOB UL PSD output" in *Table 16*.
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 dBm 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

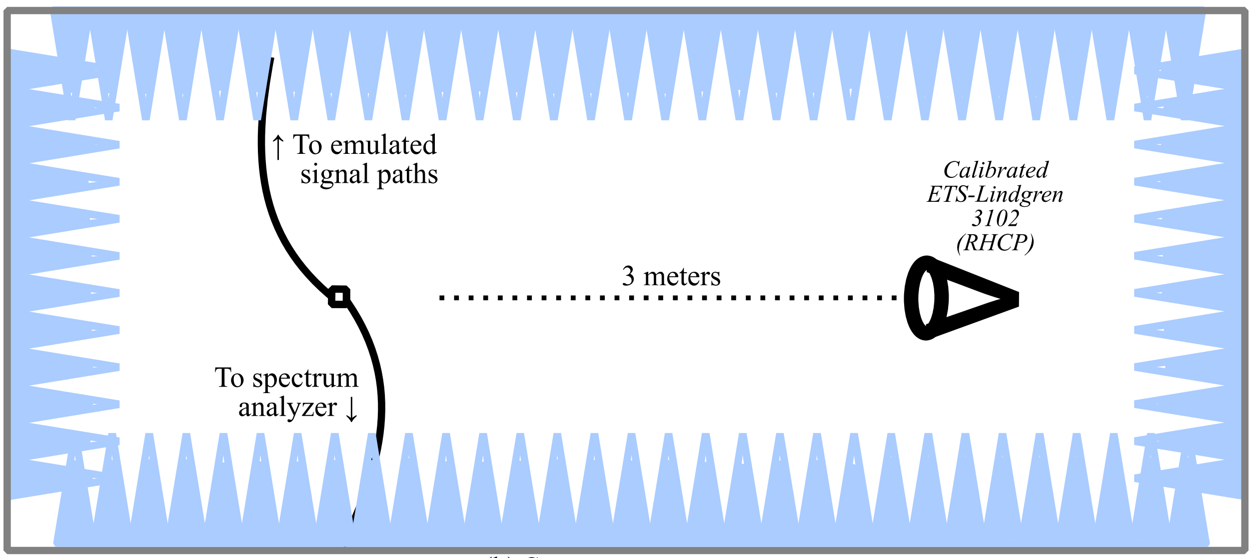
In order to validate the expected anechoic or semi-anechoic propagation behavior (Figure 8) and the calibrated gain level of the testbed transmit antenna, we perform an additional check on the propagation attenuation between the calibrated source antenna and a second calibrated validation antenna. The test setup is illustrated in Figure 17.

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 17. 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.



(a) Through measurement



(b) Source measurement

Figure 17. Validation procedures for radiated signal levels

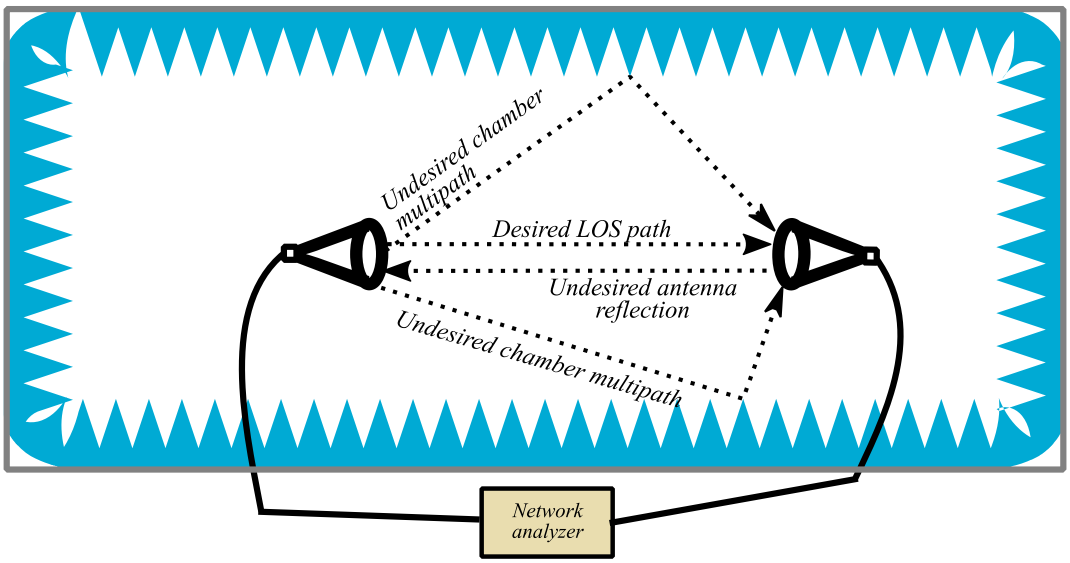
D.4. Chamber Validation Tests

This test plan depends received DUT power attenuating smoothly with r^2 (the square of the distance to the transmit antenna). Any actual test zone includes error ripples caused by multiple reflections between the antennas and the environment, and reflections between the transmit antenna and the DUT. It is therefore crucial to ensure the error components that produce these ripples are small.

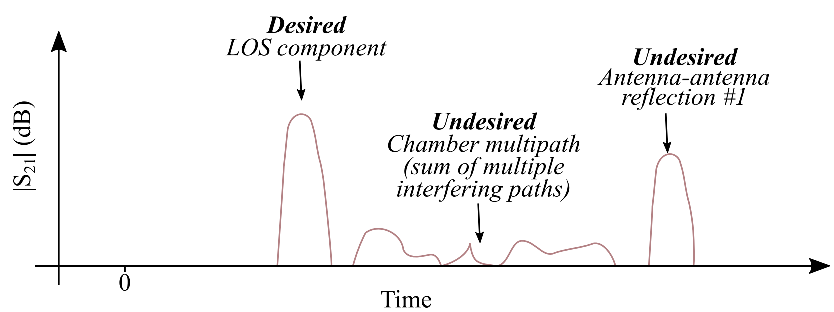
The environmental reflections will be made worse if the test environment is a semi-anechoic chamber with a reflective floor. In this case, adding absorber on the floor between the transmit antenna and the DUT mitigates these reflections.

Field uniformity and multipath tests validate the that minimal contributions from reflections are preset in the test zone. The goal is to ensure that undesired reflections have a substantially lower magnitude than that of the desired LOS path. One approach is shown in the figure below. A network analyzer connects to the transmit antenna and the calibration antenna (or other test antenna) and performs scattering parameter “through” (S21) measurements, then transforms into the time domain. If the calibration (or test) antenna does not match the specific gain pattern of the DUT, a minimally directive calibration antenna is desirable so as to capture any potential multipath contributions arriving from different angles at the DUT test location.

The plot of the resulting test data shows the power distribution over time as it arrives at the receiving antenna. If initial tests show that additional absorber is necessary to dampen reflections in the test chamber, follow-up tests should be able to confirm that less power arrives as undesired, time-delayed reflection components.



(a) Calibration antenna field uniformity check setup



(b) Example field uniformity check by checking power levels in trainsformed "thru" measurements

Figure 18. Setup to validate minimal multipath contribution at the location of the DUT.

D.5. 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 18. Intermodulation products come from the mixing product frequencies f_{mn} = m f_1 + n f_2, = (m+n) f_1 + n Δf [5], 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

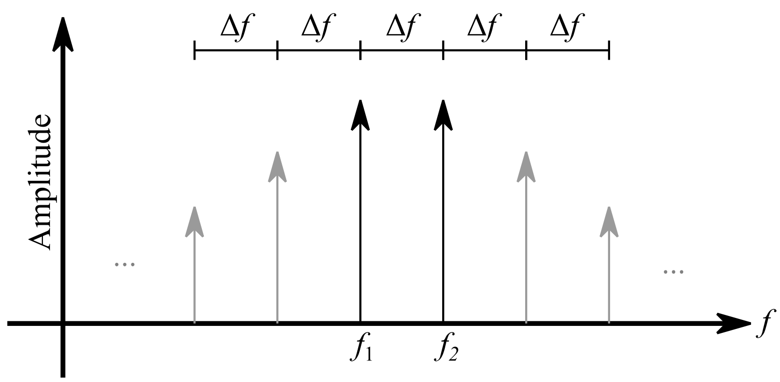


Figure 19. Center frequencies of intermodulation products

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

Like the illustration in Figure 18, 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