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Background and Timeline

- Covington and Burling retained Roberson and Associates (RAA) to conduct GPS device testing and analyze GPS device impacts under the proposed LTE emission levels agreed to by and between Ligado Networks and the three major GPS device manufacturers

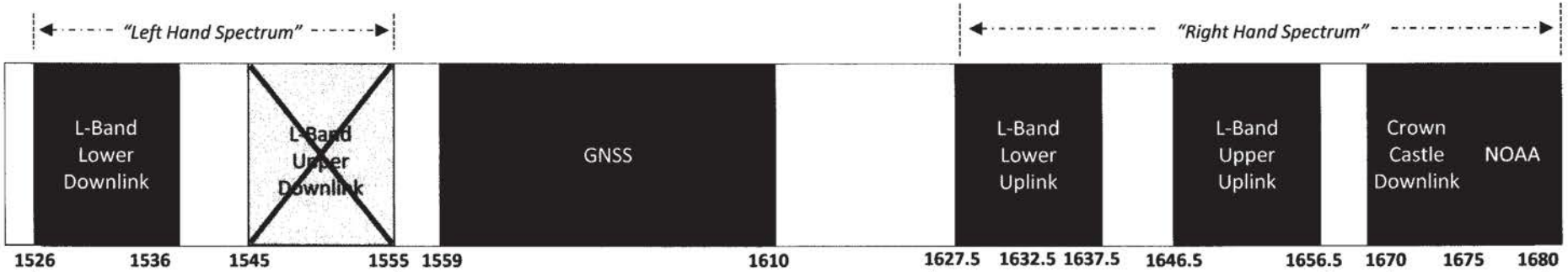
- Consistent with FCC policy on coexistence / interference, and to examine GPS impacts from Ligado's network deployment, GPS device testing focused on the potential impact of LTE on GPS user functional metrics (key performance indicators, KPIs)

- The preliminary Roberson GPS Test Plan was filed at the FCC in August 2015 with revisions initially filed in October 2015 and subsequently in February 2016
  - Stakeholder input provided in various forums incorporated into the Roberson GPS Test Plan

- Roberson and Associates presented an initial set of preliminary test results on February 5, 2016 to representatives of the DOT and other government agencies
  - Test results of multiple devices from a single device OEM and other selected devices
  - Materials for the February 5, 2016 briefing filed at the FCC on February 24, 2016

- Final Roberson Test Plan Results filed at the FCC on May 9, 2016
  - Over 250 pages of test results for 27 devices in the Cellular, GLN, High-Precision, and Non-Certified Aviation Device categories
  - Excel file for each device with KPI measurements by band by test condition
  - Summary document that provides overview of test method, conditions, and results

Ligado's FCC Proposal Based on New GPS Agreements



Lower Downlink

- Maximum power reduced from 42 dBW to 32 dBW EIRP
- 1526-1536 MHz power levels will be established in deference to the FAA to ensure compatibility with certified aviation GPS devices
- Out-of-Band Emission levels have been further reduced from previous limits
- Requested that the FCC remove the terrestrial rights of the 1545-1555 MHz downlink

Uplinks

- Maximum power reduced from 0 dBW to -7 dBW EIRP for uplink channels
- 1627.5-1632.5 MHz has an additional power limitation that ramps from -31 dBW to -7 dBW
  - This limitation expires at the end of 2020 at which time this segment will revert to -7 dBW across the band
- Out-of-Band Emission levels have been further reduced from previous limits

1670 - 1680 MHz Downlink

- 32 dBW EIRP level established for 1670-1680 MHz band

Consumer GPS Device Conclusions Under Ligado's Deployment

- RAA successfully tested GPS user performance metrics for four 10MHz bands
  - 1526-1536 MHz, 1627.5-1637.5 MHz, 1646.5-1656.5 MHz, and 1670-1680 MHz

- Study demonstrates feasibility of using Key Performance Indicators (KPIs) for GPS Devices
  - 2D Position Errors were captured
  - Testing included static and simulated motion of the device

- 16 Devices Successfully Tested*
  - Two Smartphones and One Tablet
  - Twelve General Location and Navigation (GLN) devices
  - One Non-Certified Aviation Device

  ** We were unable to obtain usable data for the iPad.*

- Comparing device performance with and without LTE to determine the difference, the RAA analysis demonstrates that GPS user performance shows:
  - No impact for Smartphone and Tablet devices
  - No impact for GLN devices in Open Sky conditions
  - No impact in 15 out of 16 use cases for GLN devices under Impaired GPS Signal test conditions
  - No impact for Non-Certified Aviation device

- 1 dB C/N_0 degradation does not predict impact of adjacent band signals on Consumer GPS device positioning performance

High Precision GPS Device Conclusions Under Ligado's Deployment

- RAA successfully tested GPS user performance metrics for four 10MHz bands
  - 1526-1536 MHz, 1627.5-1637.5 MHz, 1646.5-1656.5 MHz, and 1670-1680 MHz

- Study demonstrates feasibility of using Key Performance Indicators (KPIs) for GPS Devices
  - 3D Position Errors were captured

- 11 High Precision (HP) Devices Successfully Tested
  **We were unable to obtain useable data from the Deere Starfire 3000. Nonetheless, we understand that, in any case, Deere does not object to Ligado's proposed operations, subject to the license modifications Ligado has requested from the FCC.*

- Comparing device performance with and without LTE to determine the difference, the RAA analysis demonstrates that GPS user performance shows:
  - No impact on <u>four HP devices</u> from two different Device OEMs
  - One Device OEM that experienced no user impacts on three of its HP devices, did show impacts on some 10 MHz bands for <u>three other HP devices</u>. When each of these impacted HP devices, however, were re-tested using filtered antennae, all three HP devices showed no impact to user performance from LTE
  - <u>One HP device</u> manufactured by a separate Device OEM also showed impacts on some 10 MHz bands
  - This device is intended for maritime or agriculture use
  - <u>Three HP devices</u> manufactured by another Device OEM show performance impacts on just the lower downlink 1526-1536 MHz band, for which Ligado has agreed to operate at power levels consistent with FAA requirements

- 1 dB C/N_0 degradation does not predict impact of adjacent band signals on High Precision GPS device positioning performance

Five Test Procedures Used in RAA Testing

1. **Open Sky**. Spirent simulator created a moving constellation of GPS signals representative of a static location which were presented to devices along with LTE signals. This method was predominantly used for High Precision Devices.

2. **Open Sky with Motion**. Spirent simulator created a moving constellation of GPS signals representative of a moving vehicle, which were presented to devices along with LTE signals. This method was used for General Location and Navigation devices and the Samsung Tablet.

3. **Impaired GPS Signals with Motion**. Spirent simulator created a moving constellation of GPS signals at reduced GPS power levels representative of a moving vehicle which were presented to devices along with LTE signals. This method was used for General Location and Navigation devices.

4. **Live Sky**. A rooftop antenna captured GPS signals (and MSS augmentation signals in the case of some receivers) which were presented to devices along with LTE signals. This method was used for some of the High Precision devices.

5. **3GPP A-GPS Tests.** These are GPS conformance tests approved by 3GPP, the internationally recognized standards group for testing cellular devices. These methods were used for the Samsung S5 and S6.

Devices Tested

General Location and Navigation (GLN)	High Precision	Non-Certified Aviation	Cellular
Tested via Open Sky With Motion: Devices That Output NMEA Information	**Tested via Live Sky Method**	**Tested via Open Sky with Motion**	**Tested via 3GPP Methods**
Garmin 76 Garmin Montana 650t Garmin eTrex Garmin 78sc Motorola MW810 Trimble TM3000 Furuno GP32 Wabtec	Navcom SF-3050 Trimble R9 Trimble R8	Garmin GPSMAP 696	Samsung S5 Samsung S6
Tested via Open Sky With Motion: Devices That Do Not Output NMEA Information	**Tested via Open Sky Method**		**Tested via Open Sky***
Motorola APX 7000 Garmin nüvi 2495LMT Garmin nüvi 55 Garmin nüvi 2597LMT	Trimble AgGPS 542 Trimble SPS855 Topcon SGR-1 Topcon System 310 Trimble Geo 7x Trimble SPS985 Topcon HiPer V NovAtel SMART6		Samsung Tablet **Testing with 3GPP methods requires that the device can place a cellular call. The Samsung tablet provides data connectivity but did not support a phone call, therefore 3GPP testing was not possible.*

Measurement and Assessment Approach

1. Establish performance baseline for each device

- Measure position error without LTE
- Apply GPS signal for 2 hours

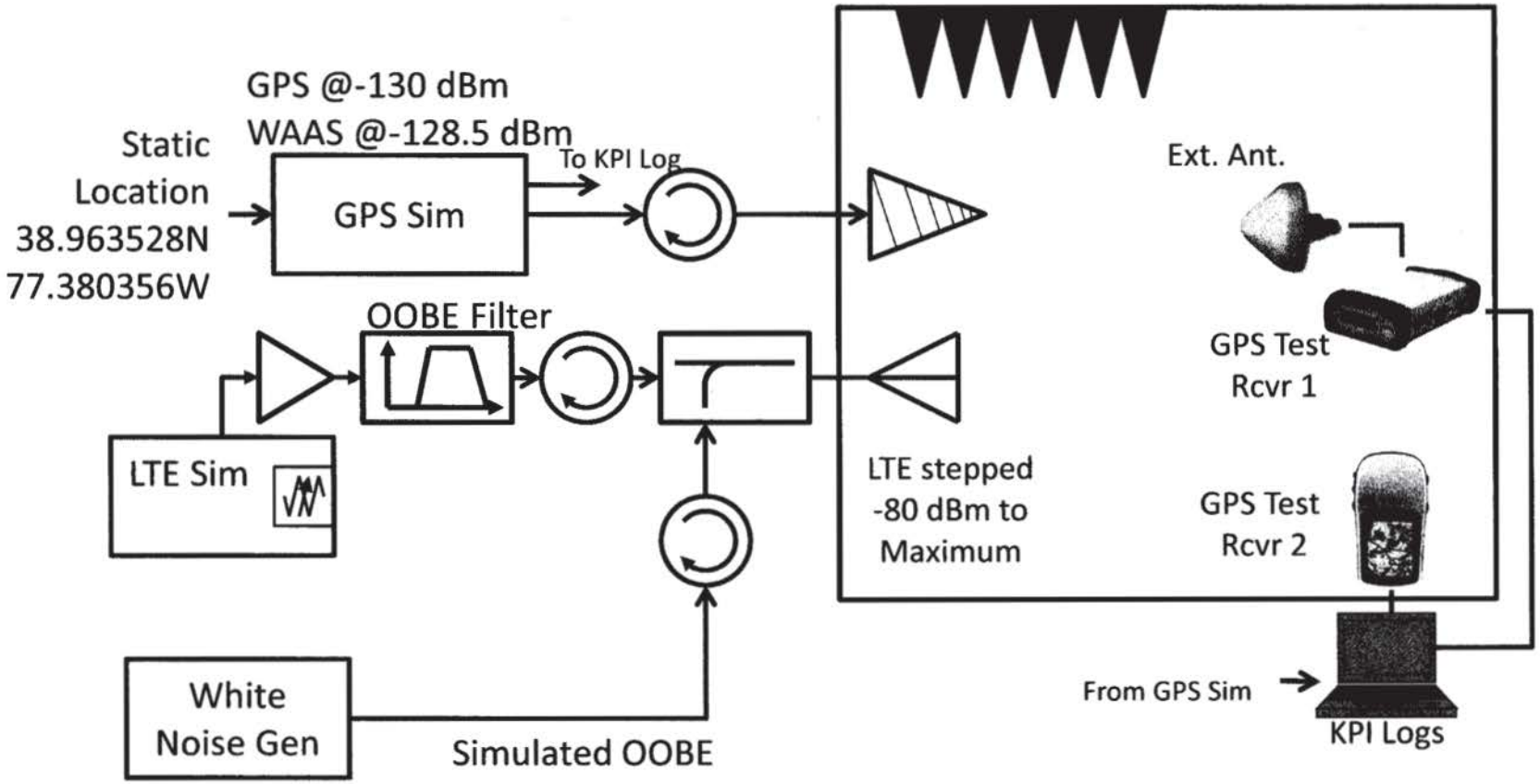
2. Measure performance with LTE

- Apply increasing LTE signal up to and beyond levels corresponding to the proposed Ligado power levels
- Test all four 10 MHz bands
- Test devices via Open Sky, Open Sky with Motion, Impaired GPS Signals with Motion, Live Sky, and 3GPP test condition methods

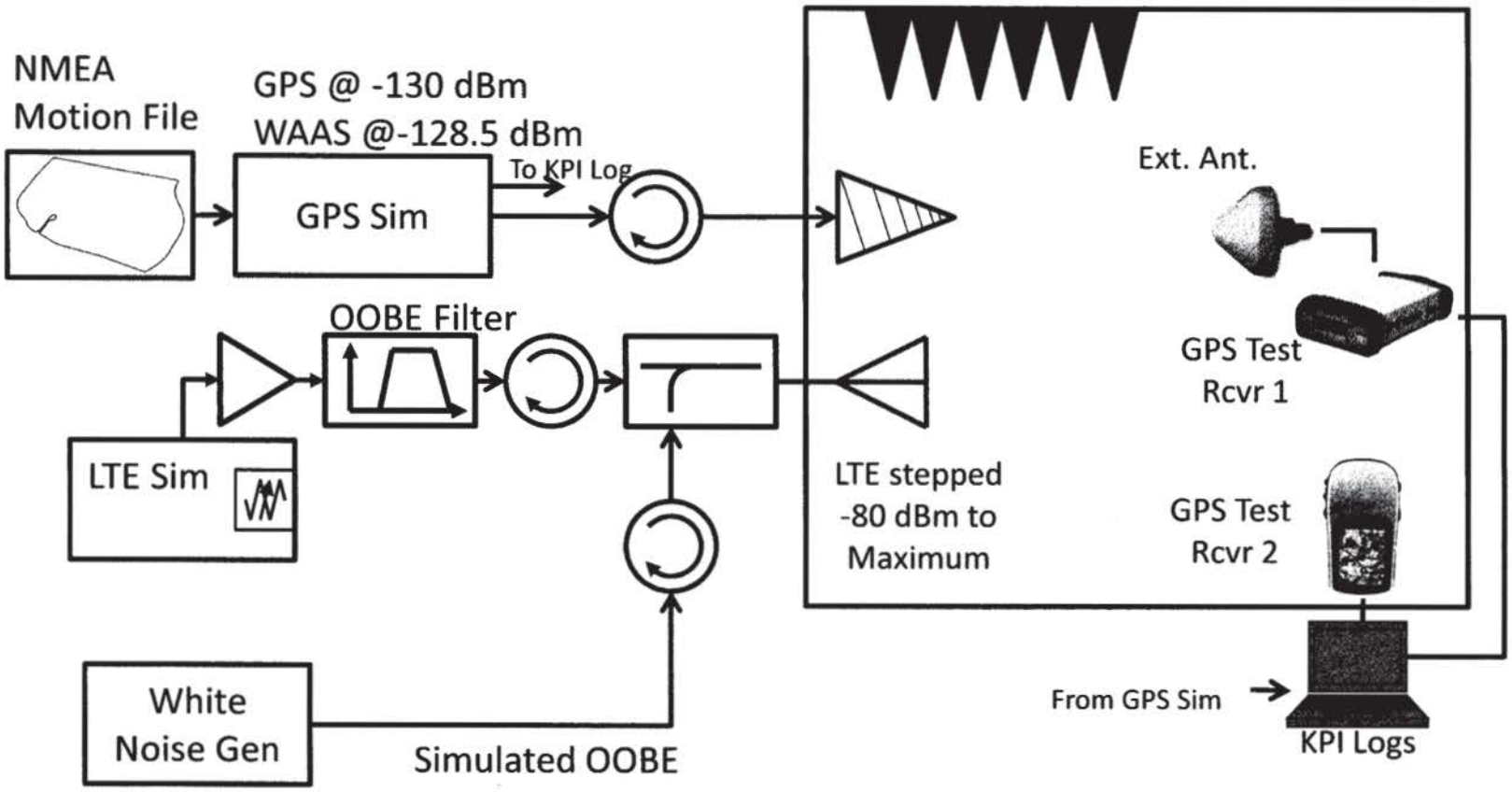
3. Compare device performance with and without LTE to determine the difference

4. Analyze device performance under the proposed Ligado power levels

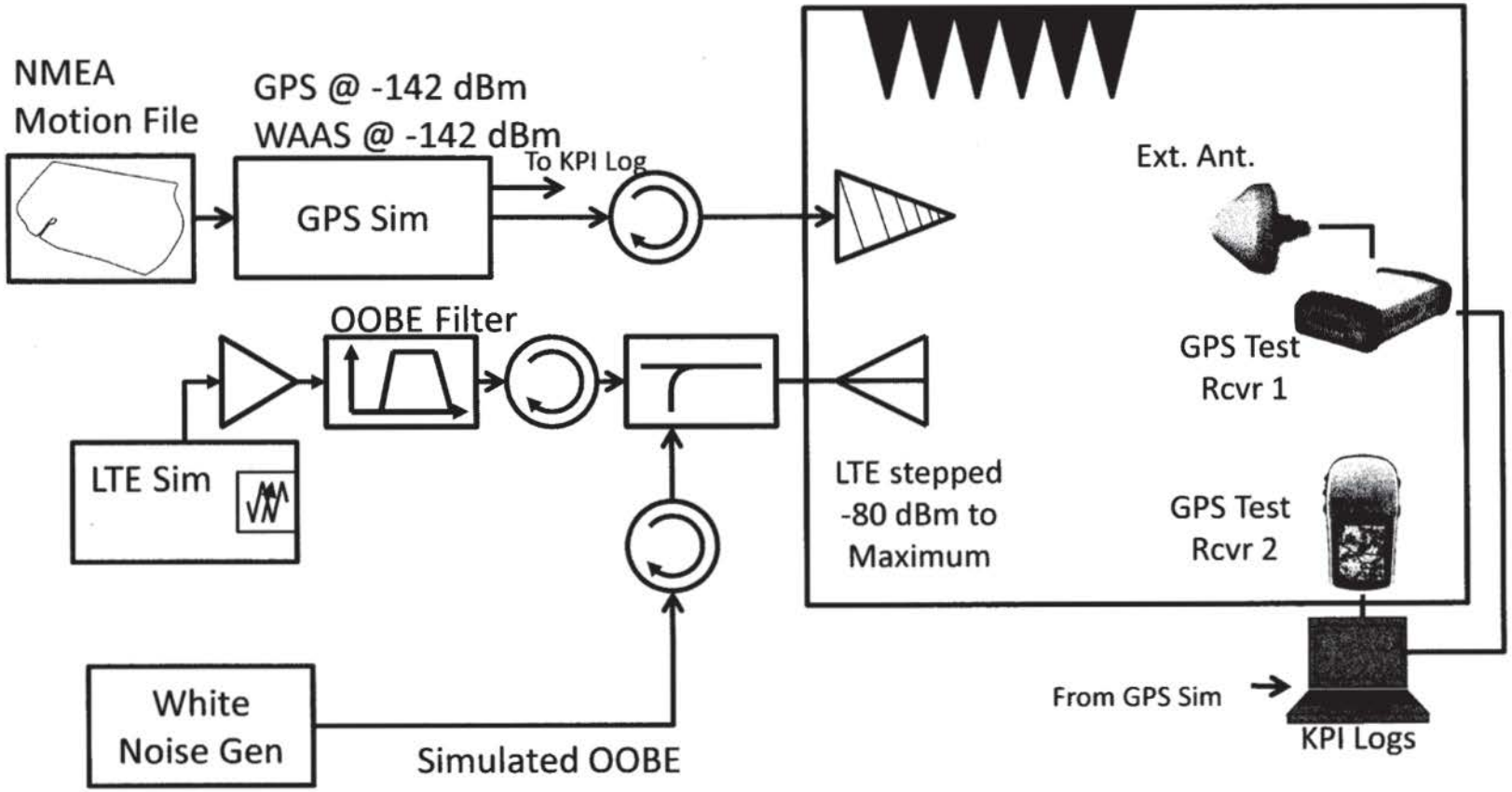
Open Sky Testing Chamber



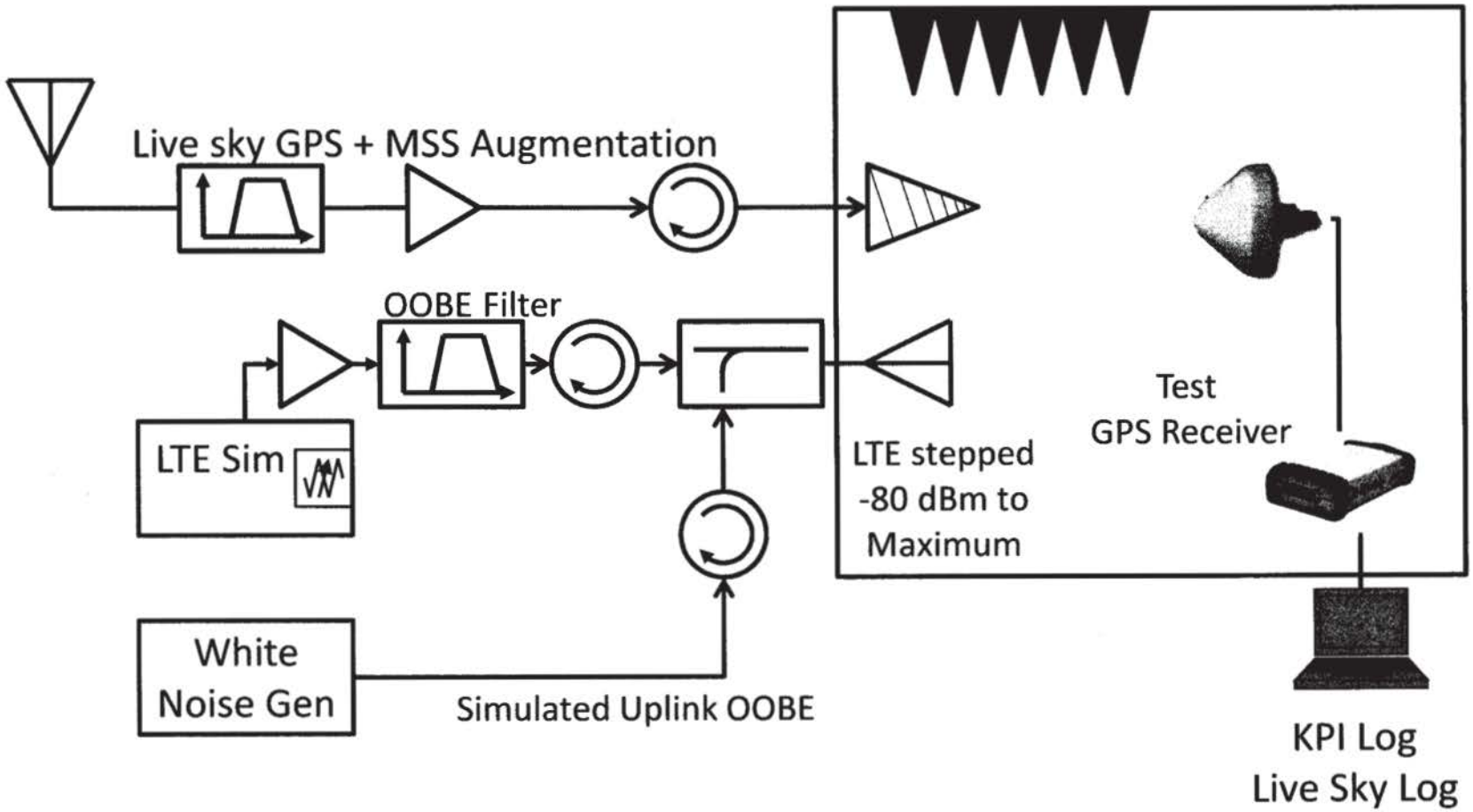
Open Sky with Motion Testing Chamber



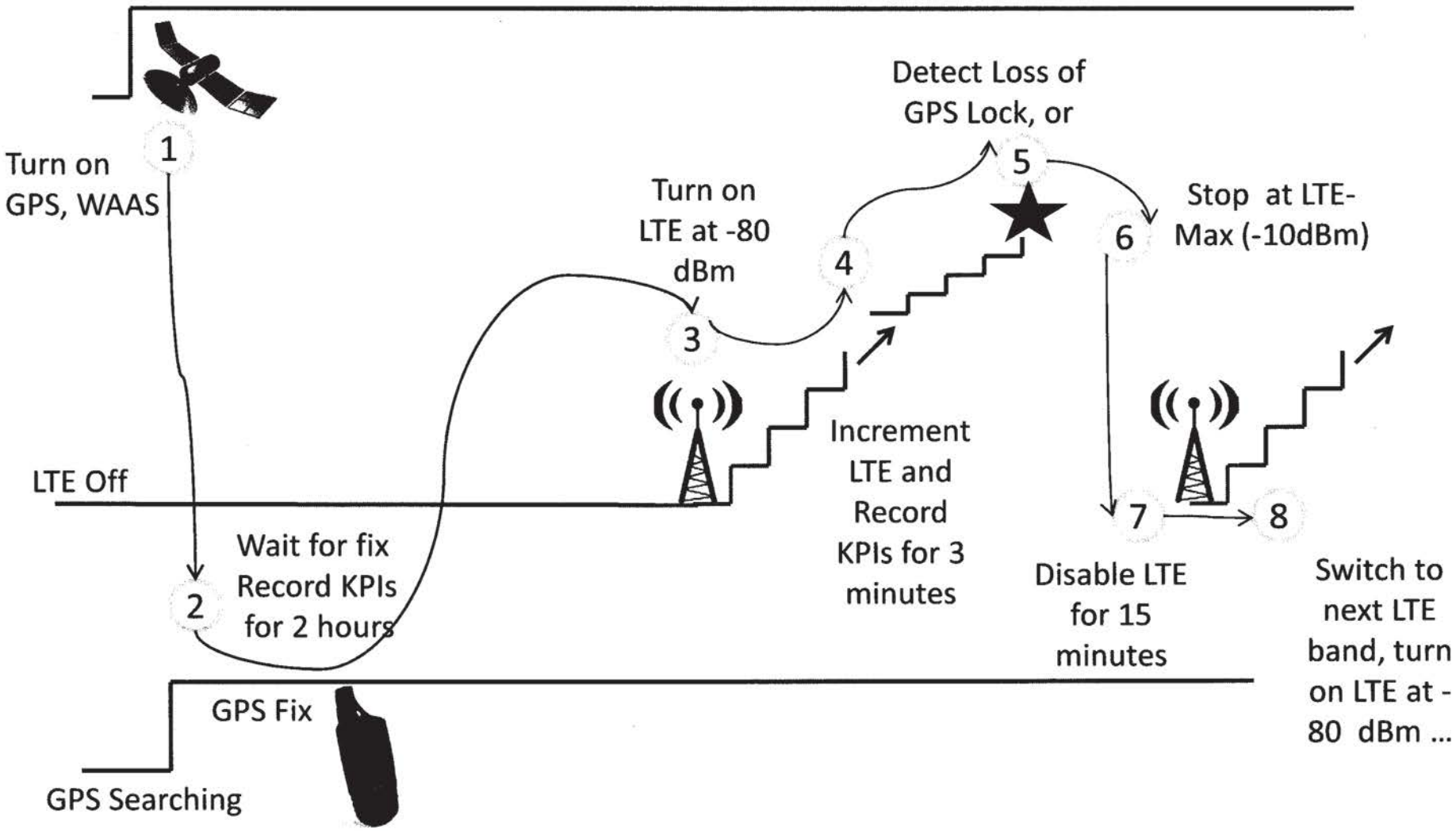
Impaired GPS Signals with Motion Testing Chamber



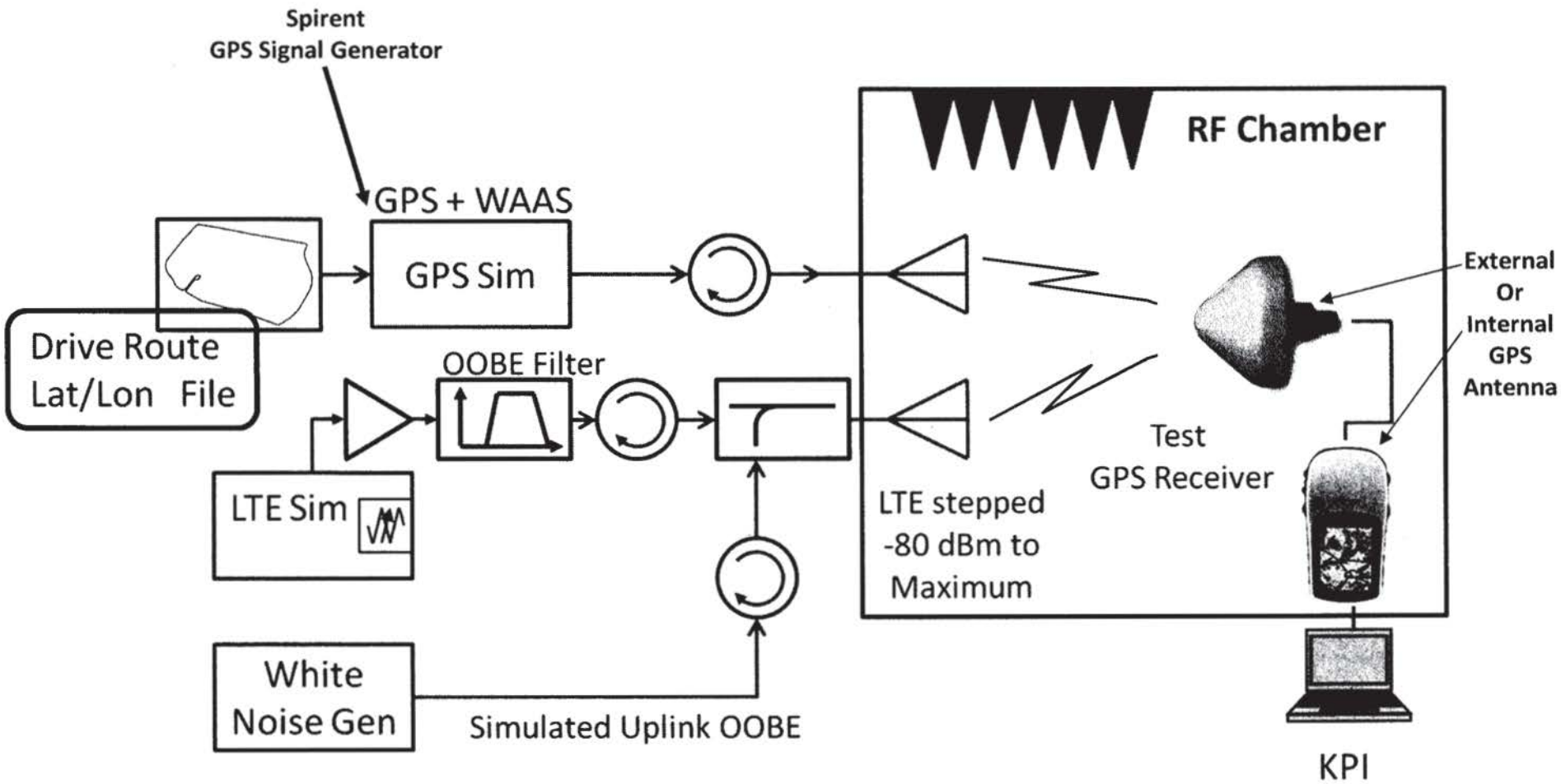
Live Sky Testing Chamber



Basic KPI (Position Error) Measurement Sequence: All Devices Except A-GPS Cellular



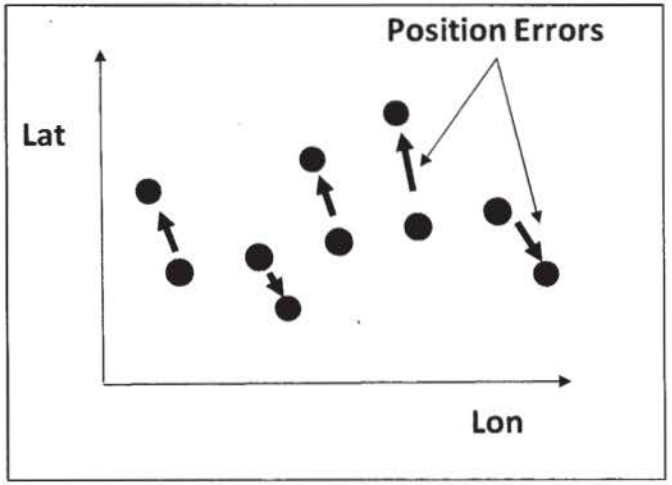
Motion Testing and Test Set Up



LTE simulated with all 50 Resource Blocks populated for both uplink and downlink

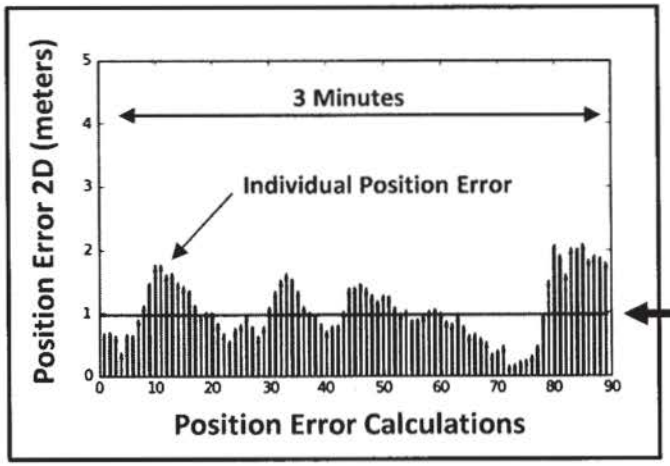
Calculating and Plotting 2D Position Error of GPS Devices

I. Calculate Position Errors: Compare Device Position Measurements with True Positions



- True Positions from GPS Generator
- Position Measurements from Device

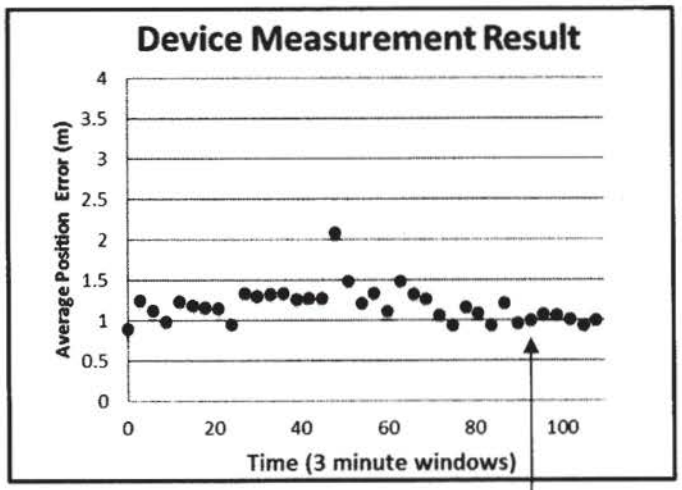
II. Calculate Average Position Error Over Three Minutes*



Individual Position Errors

Average Position Error

III. Plot Average Position Errors



Power Limits on Transmitter Under Proposed Ligado GPS Plan Translate to Received Power at the Device

- RAA's Test Plan measures the effect of LTE power levels measured at the GPS device antenna
- For its downlink spectrum, Ligado's FCC proposal to modify its licenses places restrictions on the transmit emissions from the LTE base station antenna
- For its uplink spectrum, Ligado's FCC proposal to modify its licenses places restrictions on the emissions from the LTE device antenna
- It is necessary to convert from the emitted power levels to received power levels at the GPS receiver to determine impact on the GPS devices
  - For the downlink bands (1526-1536 MHz and 1670-1680 MHz), the power at the receiving GPS device will be less than -20dBm at least 99% of the time.[1] Power could be significantly reduced on the 1526-1536 MHz band to meet FAA requirements.
  - For the uplink bands (1627.5-1637.5 MHz, 1646.5-1656.5 MHz), the power at the receiving GPS device will be less than -19dBm at least 99% of the time.[2] Power will be significantly reduced in the 1627.5-1632.5 MHz portion of the uplink band in the five-year transition period proposed by Ligado in its license modification applications.

[1] Based on 2011 TWG Las Vegas Measurements

[2] Based on CSMAC LTE Device Power CDF

GLN Devices with NMEA Data
Condition: Open Sky with Motion

Test Performance under the Ligado GPS Proposal

Device	Test	Antenna	1526-1536 MHz Downlink	1627.5-1637.5 MHz Uplink	1646.5-1656.5 MHz Uplink	1670-1680 MHz Downlink
Garmin GPSMAP 76CSx	Open Sky with Motion	Internal	**No Impact**	**No Impact**	**No Impact**	**No Impact**
Garmin eTrex	Open Sky with Motion	Internal	**No Impact**	**No Impact**	**No Impact**	**No Impact**
Garmin GPSMAP 78sc	Open Sky with Motion	Internal	**No Impact**	**No Impact**	**No Impact**	**No Impact**
Motorola MW810	Open Sky with Motion	External	**No Impact**	**No Impact**	**No Impact**	**No Impact**
Trimble TM3000	Open Sky with Motion	Internal	**No Impact**	**No Impact**	**No Impact**	**No Impact**
Furuno GP32	Open Sky with Motion	External	**No Impact**	**No Impact**	**No Impact**	**No Impact**
Garmin Montana 650t	Open Sky with Motion	Internal	**No Impact**	**No Impact**	**No Impact**	**No Impact**
Garmin Montana 650t	Open Sky (Static)	Internal	**No Impact**	**No Impact**	**No Impact**	**No Impact**

"No Impact" means that, with LTE received powers corresponding to the transmit power levels under the Ligado GPS proposal, there was no impact on the device performance compared to those KPI measurements with GPS alone.

GLN Devices with NMEA Data
Condition: Impaired GPS Signal with Motion

Test Performance under the Ligado GPS Proposal

Device	Test	Antenna	1526-1536 MHz Downlink	1627.5-1637.5 MHz Uplink	1646.5-1656.5 MHz Uplink	1670-1680 MHz Downlink
Garmin eTrex	Impaired GPS Signal with Motion	Internal	**No Impact**	**-30 dBm***	**No Impact**	**No Impact**
Garmin GPSMAP 78sc	Impaired GPS Signal with Motion	Internal	**No Impact**	**No Impact**	**No Impact**	**No Impact**
Motorola MW810	Impaired GPS Signal with Motion	External	**No Impact**	**No Impact**	**No Impact**	**No Impact**
Trimble TM3000	Impaired GPS Signal with Motion	Internal	**No Impact**	**No Impact**	**No Impact**	**No Impact**
Garmin Montana 650t	Impaired GPS Signal with Motion	Internal	**No Impact**	**No Impact**	**No Impact**	**No Impact**

"No Impact" means that, with LTE received powers corresponding to the transmit power levels under the Ligado GPS proposal, there was no impact on the device performance compared to those KPI measurements with GPS alone.

* The Garmin eTrex was compatible with the 1627.5-1637.5 MHz band with up to -30 dBm of LTE power when tested with an impaired GPS signal with motion.

GLN Devices with NMEA Data
Condition: Impaired GPS Signal with Various Antennae

Test Performance under the Ligado GPS Proposal

Device	Test	Antenna	1526-1536 MHz Downlink	1627.5-1637.5 MHz Uplink	1646.5-1656.5 MHz Uplink	1670-1680 MHz Downlink
Wabtec	Impaired GPS Signal with Motion	Gilsson	**No Impact**	**No Impact**	**No Impact**	**No Impact**
		PCTEL	**No Impact**	**No Impact**	**No Impact**	**No Impact**

"No Impact" means that, with LTE received powers corresponding to the transmit power levels under the Ligado GPS proposal, there was no impact on the device performance compared to those KPI measurements with GPS alone.

GLN Devices Without NMEA Data Conditions: Open Sky Static and with Motion

Test Performance under the Ligado GPS Proposal

Device	Test	Antenna	1526-1536 MHz Downlink	1627.5-1637.5 MHz Uplink	1646.5-1656.5 MHz Uplink	1670-1680 MHz Downlink
Motorola APX 7000	Open Sky with Motion	Internal	**No Impact**	**No Impact**	**No Impact**	**No Impact**
Motorola APX 7000	Open Sky (Static)	Internal	**No Impact**	**No Impact**	**No Impact**	**No Impact**
Garmin nüvi 2495LMT	Open Sky with Motion	Internal	**No Impact**	**No Impact**	**No Impact**	**No Impact**
Garmin nüvi 55	Open Sky with Motion	Internal	**No Impact**	**No Impact**	**No Impact**	**No Impact**
Garmin nüvi 2597LMT	Open Sky with Motion	Internal	**No Impact**	**No Impact**	**No Impact**	**No Impact**

"No Impact" means that, with LTE received powers corresponding to the transmit power levels under the Ligado GPS proposal, there was no impact on the device performance compared to those KPI measurements with GPS alone.

GLN Devices Without NMEA Data
Condition: Impaired GPS Signal with Motion

Test Performance under the Ligado GPS Proposal

Device	Test	Antenna	1526-1536 MHz Downlink	1627.5-1637.5 MHz Uplink	1646.5-1656.5 MHz Uplink	1670-1680 MHz Downlink
Motorola APX 7000	Impaired GPS Signal with Motion	Internal	**No Impact**	**No Impact**	**No Impact**	**No Impact**
Garmin nüvi 2495LMT	Impaired GPS Signal with Motion	Internal	**No Impact**	**No Impact**	**No Impact**	**No Impact**
Garmin nüvi 2597LMT	Impaired GPS Signal with Motion	Internal	**No Impact**	**No Impact**	**No Impact**	**No Impact**

"No Impact" means that, with LTE received powers corresponding to the transmit power levels under the Ligado GPS proposal, there was no impact on the device performance compared to those KPI measurements with GPS alone.

High Precision Devices
Condition: Open Sky with Various Antennae

Test Performance under the Ligado GPS Proposal

Device	Test	Antenna	1526-1536 MHz Downlink	1627.5-1637.5 MHz Uplink	1646.5-1656.5 MHz Uplink	1670-1680 MHz Downlink
Trimble AgGPS 542	Open Sky	Zephyr	**-34 dBm***	**-38 dBm***	**No Impact**	**No Impact**
		Filtered	**No Impact**	**No Impact**	**No Impact**	**No Impact**
Trimble SPS855	Open Sky	GA30	**-38 dBm†**	**No Impact**	**No Impact**	**No Impact**
		Filtered	**No Impact**	**No Impact**	**No Impact**	**No Impact**

"No Impact" means that, with LTE received powers corresponding to the transmit power levels under the Ligado GPS proposal, there was no impact on the device performance compared to those KPI measurements with GPS alone.

* The Trimble AgGPS 542 with the Zephyr antenna was compatible with the 1526-1536 MHz band with up to -34 dBm of LTE power, and with the 1627.5-1637.5 MHz band with up to -38 dBm of LTE power. When retested with a filtered antenna, the Trimble AgGPS 542 was compatible with the proposed LTE emissions.

† The Trimble SPS855 with the GA30 antenna was compatible with the 1526-1536 MHz band with up to -38 dBm of LTE power. When retested with a filtered antenna, the Trimble SPS855 was compatible with the proposed LTE emissions.

High Precision Devices
Condition: Open Sky

Test Performance under the Ligado GPS Proposal

Device	Test	Antenna	1526-1536 MHz Downlink	1627.5-1637.5 MHz Uplink	1646.5-1656.5 MHz Uplink	1670-1680 MHz Downlink
Topcon SGR-1	Open Sky	Internal	**-24 dBm***	**No Impact**	**No Impact**	**No Impact**
Topcon System 310	Open Sky	Stock	**-34 dBm†**	**No Impact**	**No Impact**	**No Impact**
Trimble Geo 7X	Open Sky	Internal	**No Impact**	**No Impact**	**No Impact**	**No Impact**
Trimble SPS985	Open Sky	Internal	**No Impact**	**No Impact**	**No Impact**	**No Impact**
Topcon HiPer V	Open Sky	Internal	**-32 dBm‡**	**No Impact**	**No Impact**	**No Impact**
NovAtel SMART6	Open Sky	Internal	**-55 dBm§**	**-34 dBm§**	**No Impact**	**No Impact**

"No Impact" means that, with LTE received powers corresponding to the transmit power levels under the Ligado GPS proposal, there was no impact on the device performance compared to those KPI measurements with GPS alone.

* The Topcon SGR-1 was compatible with the 1526-1536 MHz band with up to -24 dBm of LTE power.

† The Topcon System 310 was compatible with the 1526-1536 MHz band with up to -34 dBm of LTE power.

‡ The Topcon HiPer V was compatible with the 1526-1536 MHz band with up to -32 dBm of LTE power.

§ The NovAtel SMART6 was compatible with the 1526-1536 MHz band with up to -55 dBm of LTE power, and with the 1627.5-1637.5 MHz band with up to -34 dBm of LTE power.

High Precision Devices
Condition: Live Sky

Test Performance under the Ligado GPS Proposal

Device	Test	Antenna	1526-1536 MHz Downlink	1627.5-1637.5 MHz Uplink	1646.5-1656.5 MHz Uplink	1670-1680 MHz Downlink
NavCom SF-3050	Live Sky	Internal	**No Impact**	**No Impact**	**No Impact**	**No Impact**
Trimble R9	Live Sky	GA30 Filtered	**-55 dBm*** **No Impact**	**-24 dBm*** **No Impact**	**No Impact** **No Impact**	**No Impact** **No Impact**
Trimble R8	Live Sky	Internal	**No Impact**	**No Impact**	**No Impact**	**No Impact**

"No Impact" means that, with LTE received powers corresponding to the transmit power levels under the Ligado GPS proposal, there was no impact on the device performance compared to those KPI measurements with GPS alone.

* The Trimble R9 with the GA30 antenna was compatible with the 1526-1536 MHz band with up to -55 dBm of LTE power, and with the 1627.5-1637.5 MHz band with up to -24 dBm of LTE power. When retested with a filtered antenna, the Trimble R9 was compatible with the proposed LTE emissions.

Cellular Devices
Condition: Open Sky with Motion

Test Performance under the Ligado GPS Proposal

Device	Test	Antenna	1526-1536 MHz Downlink	1627.5-1637.5 MHz Uplink	1646.5-1656.5 MHz Uplink	1670-1680 MHz Downlink
Samsung Tablet	Open Sky with Motion	Internal	**No Impact**	**No Impact**	**No Impact**	**No Impact**

"No Impact" means that, with LTE received powers corresponding to the transmit power levels under the Ligado GPS proposal, there was no impact on the device performance compared to those KPI measurements with GPS alone.