Before the
FEDERAL COMMUNICATIONS COMMISSION
Washington, DC 20554

In the Matter of	)	
	)	IB Docket No. 11-109
Comment Sought on Ligado's	)	
Modification Applications	)	
	)	
To: The Commission	)	

REPLY COMMENTS OF LIGADO NETWORKS LLC

Gerard J. Waldron
Michael Beder
Dustin Cho
Ani Gevorkian
COVINGTON & BURLING LLP
One CityCenter
850 Tenth Street, NW
Washington, DC 20001
(202) 662-6000

Counsel for Ligado Networks LLC

June 6, 2016

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I. INTRODUCTION AND SUMMARY

The nineteen comments filed regarding the above-captioned license modification applications ("Modification Applications") reflect a consensus on a number of important issues. In particular, no party filed a petition to deny the Modification Applications, and commenters recognized that FCC action is important to make additional spectrum available for next generation wireless services.[1] Moreover, no commenter presented evidence indicating that a terrestrial network operating under the parameters set forth in the Modification Applications — which propose substantially reduced power and out-of-band emission ("OOBE") limits as per Ligado's constructive discussions and negotiations with key members of the GPS industry — would impact the performance of consumer-grade GPS devices. The comments also reflect that with respect to industrial GPS devices, those devices will experience no impact or can be remedied to ensure no impact.[2]

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[1] *See*, *e.g.*, Comments of Public Knowledge, New America's Open Technology Institute, and Common Cause, IB Docket No. 11-109, at 2-5 (filed May 23, 2016); Comments of Competitive Carriers Association, IB Docket No. 11-109, at 3 (filed May 23, 2016); Comments of ViaSat, Inc., IB Docket No. 11-109, at 3 (filed May 23, 2016).

[2] *See* Comments of Ligado Networks LLC, IB Docket No. 11-109, at 4 (filed May 23, 2016) ("Ligado Comments"); Comments of Topcon Positioning Systems, Inc. IB Docket Nos. 11-109 and 12-340, at 2 (filed May 23, 2016) (noting "Topcon and Ligado are engaged in productive (continued…)

Ligado files these Reply Comments to address certain questions raised by commenters regarding (1) how Ligado's operations would protect aviation-related GPS operations, and (2) the appropriate way to measure the impact of Ligado's operations on GPS devices generally. With respect to aviation, these Reply Comments provide additional detail on the role the FAA would play under the Modification Applications' "operational deference" proposal in the process of ensuring safe operations in the lower downlink (1526-1536 MHz). Some aviation commenters also raised questions regarding Ligado's proposed operations in the uplink bands (1627.5-1637.5 MHz and 1646.5-1656.5 MHz). This submission addresses those questions and, responding to the Public Notice's request for concrete data,[3] includes data that establishes that operations in the uplink bands on the right-hand side of the GPS signal allocation present no problems to certified or noncertified aviation devices at the power and OOBE levels specified in the Modification Applications. Lastly, some commenters proposed using a 1 dB change in the carrier-to-noise noise density ratio as a proxy for determining whether Ligado's proposed operations would cause harmful interference to GPS devices. However, as discussed below, that metric is not supported by theoretical or experimental analysis.

In short, the growing record in this proceeding establishes that grant of the Modification Applications filed in December 2015 will serve the public interest by cementing protections for

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discussions and working cooperatively to address Topcon's concerns"); Comments of Trimble Navigation Limited, IB Docket No. 11-109; IB Docket No. 12-340 at 2 (filed May 23, 2016) ("Trimble Comments") ("Taken as a whole, the Agreed Licensing Conditions represent a compromise which balances the competing public policy interests raised by Ligado's (and its predecessors') proposed use of their licensed spectrum. Given this compromise and balance, Trimble believes that it is in the public interest to grant the Modification Applications based upon the adoption of the Agreed Licensing Conditions as an integrated package."). Ligado remains in active discussions to address concerns raised by other stakeholders, such as NovAtel.

[3] *Comment Sought on Ligado's Modification Applications*, IB Docket Nos. 11-109 & 12-340, DA 16-442, at 8 (April 22, 2016) ("Public Notice").

the GPS community, guaranteeing a central role for the FAA in ensuring safe operations in the lower downlink, and promoting 5G and IoT deployment by freeing up greenfield mid-band spectrum for this important transition to next generation wireless service.[4]

II. THE PARAMETERS SET FORTH IN THE MODIFICATION APPLICATIONS ENSURE THAT LIGADO'S TERRESTRIAL NETWORK WILL BE COMPATIBLE WITH AVIATION SAFETY

A. The Modification Applications Establish a Vital Role for the FAA with Respect to Ligado's Operations in the Lower Downlink.

Ligado's proposal for a terrestrial network robustly protects aviation by several means. *First,* Ligado has requested that the Commission remove Ligado's authority to conduct terrestrial operations in its upper 10 MHz downlink band at 1545-1555 MHz — the part of Ligado's spectrum that is closest to the GPS signal allocation — while proposing to reduce from 42 dBW to 32 dBW the equivalent isotropically radiated power ("EIRP") limit for Ligado's lower 10 MHz downlink band at 1526-1536 MHz.[5] *Second*, Ligado's revised operating parameters, which will apply to all of Ligado's terrestrial operations wherever they are conducted throughout the U.S. (including areas around airports as well as any other location in the country), ensure greater protection to all GPS devices, including non-certified aviation devices used by pilots, aircraft operators and airports.

Third, in addition to the proposed EIRP limits, Ligado would protect certified aviation devices by lowering the power of its terrestrial network operations in the 1526-1536 MHz band on a nationwide basis as necessary in deference to current and any future Minimum Operational Performance Standards ("MOPS") insofar as they are incorporated into active Technical

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[4] *See* Doug Smith, "Looking Forward to a 5G Future for the U.S. Wireless Industry," Ligado Networks Blog, http://ligado.com/blog/looking-forward-5g-future-u-s-wireless-industry/ (May 23, 2016) (discussing company's new business plan focusing on 5G and IoT).

[5] *See* Modification Applications, Description of Proposed Modification at 6.

Standard Orders ("TSOs") by the FAA and the industry-led RTCA Inc. ("RTCA").[6] The Modification Applications request that the Commission make adherence to these standards a condition of Ligado's licenses.[7] Ligado's proposal does not ask the FAA to mandate any changes in the equipment used by airlines or others in the aviation community. Nor, contrary to the potential misunderstanding of some commenters, does Ligado suggest that the FAA should establish some sort of special TSO governing Ligado's equipment.

Rather, under Ligado's proposal, the Commission's authorization for Ligado to conduct terrestrial operations in the 1526-1536 MHz band would be conditioned on Ligado lowering its power in that band to whatever level is necessary to ensure that Ligado's operations do not cause harmful interference to certified aviation GPS receivers that operate in accordance with current or future TSOs governing such receivers. Specifically, in its December 2015 filing, Ligado proposed that the FCC adopt a license condition requiring that Ligado "limit its power as necessary to achieve compatibility with current and any future MOPS insofar as they are incorporated into an active Technical Standard Order by the FAA."[8] Some comments indicated a partial misunderstanding of the meaning of this proposal.[9] The following discussion provides

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[6] As the RTCA's website states, "RTCA works in response to requests from the Federal Aviation Administration (FAA) to develop comprehensive, industry-vetted and endorsed recommendations for the Federal government on issues ranging from technical performance standards to operational concepts for air transportation. Our deliberations are open to the public and our products are developed by aviation community volunteers functioning in a consensus-based, collaborative, peer-reviewed environment." "About Us," RTCA, http://www.rtca.org/content.asp?pl=49&contentid=49 (last visited May 23, 2016).

[7] Modification Applications, Description of Proposed Modification at 7.

[8] Modification Applications, Description of Proposed Modification at 7.

[9] *See, e.g.*, Comments of Joint Aviation Parties, IB Docket Nos. 11-109 and 12-340, at 10, 13 (filed May 23, 2016) ("Joint Aviation Parties Comments").

additional details concerning each component of the condition proposed in the Modification Applications:

1. Ligado would bear responsibility for adjusting its power level. This means Ligado would be under a continuing obligation to adjust its power level to achieve compatibility with certified aviation GPS devices. Ligado's operational power levels thus would always be inferior to the requirements of certified aviation GPS devices (which Ligado has described as "operational deference"). Ligado's obligation would be imposed by the Commission as a license condition.

2. The standard to which Ligado would defer would be any current or future MOPS. Ligado recognizes that RTCA's development of MOPS is an ongoing process. Today, Ligado would be obligated to adjust its power level to ensure compatibility with existing MOPS. If RTCA were to adopt a new MOPS in the future, Ligado would be obligated to adjust its power level to ensure compatibility with the new standard.

3. Ligado's license condition would apply to any TSO that is active — that is, currently governing the use of deployed certified aviation GPS devices. This approach recognizes that MOPS become operative with respect to aviation GPS through the FAA's adoption of a TSO containing the MOPS, and that the FAA may choose to withdraw a TSO. This obligation would apply to Ligado for *any currently existing* TSO and *any future* TSO issued by the FAA, unless and until the TSO were withdrawn by the FAA. In short, for any active TSO now or in the future that includes a certified aviation GPS MOPS, Ligado would adjust its power levels to operate in a way that achieves compatibility with the MOPS.

4. Other applicable restrictions would continue to apply. Ligado's license condition would exist and be binding in addition to other restrictions designed to protect aviation GPS, such as tower siting restrictions near airports.

Ligado and the FAA have been in active discussions since the December 2015 filing of the Modification Applications. These discussions are ongoing, but Ligado expects that, although Ligado's Commission authorization for terrestrial operations in the 1526-1536 MHz band would nominally permit such operations up to a power limit of 32 dBW, the power limit in that band required to satisfy the additional condition Ligado has proposed to protect certified aviation devices will be substantially lower to address the hardest use case of helicopters, and that level

could be in the range of 15 dBW.[10] The use case of helicopters would necessitate this substantially lower power limit on a nationwide basis until the helicopter situation was resolved. Fixed wing aircraft are required by FAA regulations to operate at least 500 feet from any obstruction (such as a radio tower), and often farther.[11] Helicopters in general have no minimum distance requirement, provided that the operator ensures there is no hazard to persons or property.[12] The effect of the distance of an aviation vehicle from the tower is magnified because the strength of a radio signal drops by approximately the square of the distance from the antenna. Consequently, a helicopter flying at 250 feet from the tower will experience approximately four times greater signal strength than the fixed wing aircraft would see at 500 feet. If Ligado were to resolve the helicopter use case, Ligado could consult anew with the FAA about the possibility of implementing a higher power limit.

Given the additional condition Ligado has proposed to ensure Ligado's power is limited to the level necessary to ensure compatibility even with these most difficult use cases, concerns based on testing the effects of a terrestrial network operating in this band at 32 dBW — such as the 2012 testing referred to by the Joint Aviation Parties[13] — have been superseded. In addition,

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[10] Under Ligado's proposal to defer to the FAA on the implementation of this condition, the Commission need not establish the specific power limits. Rather, these limits will be calculated by Ligado, in consultation with RTCA and subject to the FAA's concurrence with Ligado's calculations. As discussed above, Ligado will be under a continuing obligation to adjust its power level to achieve compatibility with certified aviation GPS. For the basis of comparison, were it not for the limiting helicopter use case, fixed wing aircraft — which operate at greater distances from antenna structures — would be compatible with Ligado base stations transmitting at a power of 26 dBW EIRP.

[11] 14 C.F.R. § 91.119 (requiring that aircraft operate at least 1,000 feet above the highest obstacle within 2,000 feet horizontally when over a congested area, 500 feet above the surface when not over a congested area, and not closer than 500 feet from any person, vessel, vehicle, or structure, except when necessary for takeoff or landing).

[12] *Id*.

[13] Joint Aviation Parties Comments at 8-9.

Ligado's discussions with the FAA are addressing not only the calculation of the necessary safe power limits but also the process by which the FAA can ensure Ligado's compliance without imposing undue burdens on the agency's staff, as well as how to ensure transparency and the involvement of all relevant stakeholder groups, such as manufacturers, airlines, and pilots, through RTCA's involvement in this process.

As explained in Ligado's comments, deferring to the FAA with the respect to the particular questions within that agency's expertise is consistent with the Commission's approach in other contexts where the Commission has found it appropriate to incorporate the specialized expertise of another agency or standards body into the Commission's own requirements.[14] This approach would allow the Commission to bring issues relating to the use of GNSS-adjacent spectrum to resolution, providing certainty to all stakeholders, while ensuring that the nation's aviation systems are fully protected.

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[14] *See, e.g.*, *Amendment of Parts 13 and 80 of the Commission's Rules Concerning Maritime Communications*, 2nd R&O, 6th R&O, and 2nd FNPRM, 19 FCC Rcd 3120, 3137 (2004) (authorizing use of INMARSAT-E emergency position indicating radiobeacons, subject to compliance with International Electro-technical Commission standard 61097-5); *Reassessment of Federal Communications Commission Radiofrequency Exposure Limits And Policies*, 1st R&O, FNPRM and NOI, 28 FCC Rcd 3498, 3515 (2013) (noting that classification of the outer ear as an extremity for purposes of human RF exposure guidelines is "supported by the expert determinations of the FDA and of the IEEE," and that "[t]he FDA in particular has statutory responsibility to carry out a program designed to protect public health and safety from electronic product radiation and we therefore place heavy reliance on its public health and safety determinations"); *Applications of Cellco Partnership d/b/a Verizon Wireless and SpectrumCo LLC and Cox TMI, LLC for Consent to Assign AWS-1 Licenses*, 27 FCC Rcd 10698, 10766 (2012) (conditioning foreign ownership authorization on licensee's continued compliance with agreement reached with U.S. Department of Defense, U.S. Department of Justice, FBI, and U.S. Department of Homeland Security); 47 C.F.R. § 64.1200(a)(2), (a)(3)(v) (exempting from certain telemarketing requirements calls governed by specified provisions of the HIPAA Privacy Rule promulgated by the U.S. Department of Health and Human Services).

B. Ligado's Proposed Terrestrial Uplink Operations are Compatible with Aviation Uses.

Outside of the 1526-1536 MHz band, Ligado's proposed operations will have no impact on certified aviation GPS devices. As noted above, Ligado has agreed to relinquish its terrestrial authority in the 1545-1555 MHz band. And contrary to the suggestion in some comments, there are no issues for aviation surrounding Ligado's use of the uplink bands. Specifically, Ligado's proposed terrestrial uplink operations in the right-hand spectrum have been shown, with additional evidence attached hereto, to pose no concerns for aviation.

In 2013, Ligado submitted to the Commission extensive data and analyses on the effect of using Ligado's authorized uplink channels in the 1626.5-1660.5 MHz band for uplinks from terrestrial wireless user terminals.[15] Ligado currently uses these bands for uplink transmissions from its customers' mobile earth terminals ("METs") to its geosynchronous satellites. These uplink channels have been in use since Ligado and its predecessor companies first began satellite operations in the mid-1990s.[16] This band also is currently used by Inmarsat for its customers' METs and other devices whose uplinks communicate with its L-Band satellite constellation.[17]

But even under the old and less-stringent limitations that Ligado proposed in 2013 for its terrestrial uplinks, the data and analyses showed that uplink emissions would have no impact on existing or emerging GNSS systems, based on the parameters established in existing FAA,

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[15] *See* Letter from John P. Janka, Counsel to LightSquared Subsidiary LLC, to Marlene H. Dortch, FCC Secretary, IB Docket No. 11-109 *et al*. (filed July 15, 2013) ("July 2013 *Ex Parte*"). Shortly after LightSquared emerged from bankruptcy in December 2015, the company's name was changed to Ligado Networks LLC; for consistency's sake the current name of the company is used throughout this filing to discuss submissions made earlier in the name of LightSquared.

[16] *Id*. at Attachment p. 1.

[17] *Id*.

RTCA, and International Civil Aviation Organization (ICAO) standards for aviation GPS.[18] To assess Ligado's operations in the uplink bands at the reduced power levels and OOBE limits in the Modification Applications, Ligado undertook an analysis using the proposed FAA work plan that was submitted to RTCA ("WG-6 Response") and approved by the Plenary Session of SC-159 on March 20, 2015.[19] Specifically, Ligado assessed the following use cases as called for in the WG-6 Response: (i) the impact of numerous Ligado devices operating at ground level on aircraft in flight overhead, (ii) passengers using Ligado inside an aircraft that is taxiing, (iii) the operation of a Ligado device at the top of the stairs leading from the tarmac to an aircraft, (iv) numerous Ligado devices operating simultaneously near an aircraft parked at the gate, and (v) the impact of numerous Ligado devices operating at ground level on low-flying aircraft utilizing terrain awareness and warning systems.[20] In each use case, even using worst-case assumptions, the attached analyses confirm that emissions from Ligado's proposed handheld devices would not affect aviation GPS operations.[21] Thus, Ligado's proposed uplink operations are fully compatible with existing standards for the protection of certified aviation GPS operations.[22]

Given this record and the absence of any evidence that any of the right-hand spectrum is relevant to aviation issues, the aviation focused modification of the lower downlink should suffice to address the concerns of the aviation sector.

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[18] *Id*. at Attachment p. 13.

[19] *See* Ligado Report on Compatibility of Ligado Networks' Uplink Emissions with FAA Requirements for Certified Aviation GPS Receivers, attached hereto as Attachment A, at p.1.

[20] *Id*. at 2, 7, 10, 13, and 16.

[21] *Id*. at 1.

[22] *Id*.

III. KEY PERFORMANCE INDICATORS ARE THE APPROPRIATE MEASURE OF WHETHER LIGADO'S PROPOSAL WOULD CAUSE HARMFUL INTERFERENCE TO CONSUMER AND INDUSTRIAL GPS DEVICES

The recent study conducted by Roberson and Associates ("RAA") conclusively showed that the GPS firms protected their customers' GPS devices by obtaining Ligado's assent to power and OOBE reductions.[23] In its study, RAA tested 27 GPS devices, including general location and navigation, cellular, non-certified aviation, and high precision devices. The study yielded over 250 pages of test results, all of which led RAA to conclude that there is

> no meaningful correlation between 1 dB change in C/N_0 and GPS device's KPI performance. Indeed, average C/N_0 values reported by the receiver (averaged over all GPS satellites) showed random variations in excess of 1 dB in the absence of any adjacent band signals, and such variations did not accurately predict a device's position accuracy.[24]

The RAA test results repeatedly show that, across different devices (and types of devices) operating in different conditions, a substantial change in the carrier to noise density ratio (C/N_0) may be accompanied by a decrease, an increase, or no meaningful change in the device's position error.[25]

This experimental evidence is consistent with the theoretical analysis performed by Mark A. Sturza.[26] His white paper demonstrates two reasons why a 1 dB change in C/N_0 is the

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[23] Roberson and Associates, LLC, "Results of GPS and Adjacent Band Co-Existence Study," IB Docket No. 11-109, at 13 (filed May 11, 2016) ("Roberson Results Report").

[24] *Id.* at 13.

[25] This phenomenon is evident throughout the RAA data, *see* Roberson Results Report *supra* note 24, but is most obvious in the following slides: App'x A at 36 (Garmin eTrex, Open Sky with Motion, 1627.5-1637.5 MHz LTE [Uplink]); App'x C at 15 (Trimble R9, Live Sky, 1627.5-1637 MHz LTE [Uplink]); App'x D at 8 (Trimble AgGPS 542 [Zephyr Antenna], Open Sky, 1526-1536 MHz LTE [Downlink]); App'x D at 56 (Trimble SPS985, Open Sky, 1627-1637.5 MHz LTE [Uplink]).

[26] Mark A. Sturza, "Changes in C/N0 Are Not a Reliable Indicator of KPI Impact" at 3, attached hereto as Attachment B.

incorrect metric for a meaningful study. First, GPS devices in the ordinary course of their operation experience changes in the noise floor of significantly greater than 1 dB in C/N_0 and yet still function smoothly.[27] These changes in C/N_0 values may be caused by any number of sources, including:

- Antenna gain. Depending on the nature of the device's antenna, the orientation of the device, and the device's proximity to people or objects and nearby conductive surfaces, the ability of the device to receive signals will differ.[28]

- Trees. When foliage obstructs the signal path between GPS satellites and the device, the foliage attenuates the signal. Average signal loss due to blockage by trees ranges from 2.5 dB to 20.1 dB, with a mean of 11 dB.[29]

- Ionospheric scintillation. Amplitude scintillation caused by electron density irregularities in the ionosphere affects C/N_0 values. These effects are seasonal, and associated with high levels of solar and geomagnetic activities.[30]

- Urban canyons. When a GPS satellite signal reflects off a building or the ground before reaching the device, the signal fades. This multipath fading is especially dramatic when there is no direct path between a satellite and a device, and only the reflected signal reaches the device's receiver. As only a portion of the signal is reflected, the device receives it with significant loss, especially when it is reflected multiple times.[31]

Second, most of the errors in commercial GPS devices are caused predominately by elements completely independent of C/N_0.[32] These factors include:

- Errors that can be attributed to GPS satellites and GPS ground control system;

- Multipath fading; and,

- The delay in the signal's path from satellite to receiver caused by changes in the ionosphere and troposphere, with such delays changing due to many factors, such as

[27] *Id.* at 3-6.

[28] *Id.* at 3-5.

[29] *Id.* at 5-6.

[30] *Id.* at 6.

[31] *Id.*

[32] *Id.* at 10-11.

> geographic location, solar activity, time of day, temperature, pressure, and humidity.[33]

Because a 1 dB change in C/N_0 is not a reliable indicator of any degradation in the performance of a GPS device, the Commission should not credit studies that conclude a GPS device has suffered harmful interference based solely on such a 1 dB change in C/N_0. In the last century, parties in spectrum discussions often based their analysis on a 1 dB change in the carrier-to-noise density ratio because such changes were easy to measure with the testing equipment then available, not because evidence showed such changes were a reliable metric of device performance. But to rely on this outdated, and flawed, metric, which has no correlation with actual performance of the GPS device, is misguided when modern tools are available to measure what counts: whether interference causes the GPS device to deliver faulty position or timing information to end users. Accordingly, the Commission should credit studies that evaluate interference to GPS devices by using the performance measures that matter to users.

Nonetheless, Ligado agrees with the comments of Trimble Navigation Limited that granting the Modification Applications does not necessarily require the Commission to rule definitively on whether measuring KPIs or a 1 dB change in C/N_0 is the appropriate method for determining harmful interference in all cases.[34] In this case, the separate Co-Existence Agreements Ligado reached with Garmin, Trimble, and Deere — which, along with the RAA test results, form the basis of the parameters under which Ligado now seeks to operate — are strong evidence that Ligado's proposed terrestrial deployment will not harm GPS devices. This conclusion is bolstered by the coordination agreement Ligado recently reached with the

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[33] *Id.* at 10.

[34] *See* Comments of Trimble Navigation Limited, IB Docket No. 11-109; IB Docket No. 12-340 at 4 (May 23, 2016).

Aerospace and Flight Test Radio Coordinating Council with respect to protections for aeronautical mobile telemetry.[35] These agreements provide the Commission with a sufficient basis to conclude that the parameters proposed in the Modification Applications will protect GPS operations from harmful interference, regardless of whether the Commission measures harmful interference on the basis of KPIs or on changes in the carrier to noise density ratio.

[35] Letter from Dan Robinson, President, AFTRCC, and Jeffrey Carlisle, Executive Vice President for Regulatory Affairs, Ligado Networks LLC, to Marlene H. Dortch, Secretary, FCC, IB Docket Nos. 11-109 & 12-340 (filed May 23, 2016).

CONCLUSION

The record in this proceeding provides the Commission with substantial factual and legal support to modify Ligado's licenses as requested ─ and finally enable this vital mid-band spectrum to support the transition to 5G services and next-generation IoT and meet the American people's growing demand for wireless broadband service. For the reasons set forth herein, the above-captioned Modification Applications should be granted.

Respectfully submitted,

/s/ Gerard J. Waldron

Gerard J. Waldron
Michael Beder
Dustin Cho
Ani Gevorkian
COVINGTON & BURLING LLP
One CityCenter
850 Tenth Street, NW
Washington, DC 20001
(202) 662-6000

Counsel for Ligado Networks LLC

Attachments

June 6, 2016

Attachment A

Ligado Report on Compatibility of Ligado Networks' Uplink Emissions with FAA Requirements for Certified Aviation GPS Receivers

Ligado Report on Compatibility of Ligado Networks' Uplink Emissions with FAA Requirements for Certified Aviation GPS Receivers

June 6, 2016

1.0 Background and Summary

On October 7, 2014, the FAA, in a letter to RTCA ("FAA Letter"), submitted questions to elicit input to the FAA's analysis of commercial spectrum bands adjacent to spectrum used by GPS. The FAA Letter proposed use cases and compliance methods that would be used to determine if uplink emissions from handsets (referred to here as "User Equipment", or "UE") using bands such as those licensed to Ligado Networks, would cause harm to the operation of certified aviation GPS receivers.

On March 19, 2015 the summary response to the FAA questions, as well as new edits to the proposed FAA work plan (together, the "WG-6 Response"), were presented to WG-6 which approved the documents. The WG-6 Response was then approved by the Plenary Session of SC-159 on March 20, 2015.[1]

This report analyzes the compatibility of Ligado's proposed uplinks in accordance with the recommendations in the WG-6 Response.

The only exceptions are with respect to certain propagation models where Ligado has made simplifying assumptions that make the models *more conservative*. The need for this simplification arose because a certain input parameter (the mean out of band emissions ("OOBE") power spectral density ("PSD") of legacy UEs at the GPS receiver, for use cases where the aircraft is on the ground) is required to run the new interference models defined by the FAA. That information is controlled by the FAA and thus was not available to Ligado as it developed the analysis, and so a more conservative assumption was used instead.[2] Ligado has shared the models described below with the FAA in the process of developing the present work.

This report concludes that Ligado's operations in the uplink bands (1627.5-1637.5 and 1646.5-1656.5) are compliant with applicable FAA requirements for each of the use cases identified by the FAA – while utilizing highly conservative assumptions that further assure aviation safety is not compromised in any way.

[1] Ligado Networks (then LightSquared) had reservations about certain aspects of the RTCA's recommendations in the WG-6 Response, and proposed alternatives in a companion report filed on April 3, 2015.

[2] FAA is the owner of the aggregate legacy UE PSD model and provided the subject information for heights other than ground level in DO-327 and in the Letter.

2.0 Use Cases[3]

2.1 Inflight Aircraft / Ground-based Handset Cases

This use case is designed to demonstrate the potential effects of thousands of ground-based handsets on an aircraft that is flying overhead.

Excerpt from FAA Letter[4]:

> The FAF WP case is also used to represent airborne terminal area operations, while the other 2 cases represent limiting cases on aircraft precision approaches. The ground-based handsets in these cases are assumed to have a 1.8 meter antenna height. Their random locations are assumed to be uniformly distributed to the radio horizon except where excluded, as noted, from annular sector zones. Besides the basic parameters for the aircraft receive antenna height, radio horizon, and exclusion zone, Table 1 also lists important breakpoint radii for the blended path loss model. For example, the "Mid-range Inner Radius" is the breakpoint between the 2-Ray short range path loss model and the mid-range model.

Table 1 Key Geometric Parameters for the Inflight Aircraft / Ground-based Handset Source Cases

Parameter	FAF WP Case	Cat. I DH Case	Cat. II DH Case
Receive Antenna. Ht. (m)	535.2	53.34	25.94
Std. Dev. Inner Radius, r_s (m)	533.4	51.54	24.14
Mid-range Inner Rad. R_1 (m)	1054.237	111.149	99.3811
Mid-range Outer Rad. R_2 (m)	7502.3	11227.6	2475.381
Excl. Zone Half-angle (deg)	0.0	17	25
Excl. Zone Inner Rad. (m)	N/A	488.0	44.93
Excl. Zone Outer Rad. (m)	N/A	5830.0	2842
Radio Horizon Radius (km)	100.941	35.653	26.537

Assumptions

In the past, the FAA had evaluated the compliance of the uplink Out Of Band Emissions (OOBE) from UEs using a new band, such as Ligado's, by comparing the composite power spectral density (PSD) of the emissions from UEs in the new band with the existing emitters[5], to a maximum mean threshold of -146.5 dBW/MHz. This is also referred to as the Environmental Limit.[6]

The Environmental Limit was derived by adding 6 dB of safety margin to the absolute maximum threshold of tolerable RFI of -140.5 dBW/MHz. This threshold is the testing threshold for the RTCA Minimum Operational Performance Standards ("MOPS") (referred to herein as the "MOPS Threshold").

The FAA Letter set forth a new methodology which it described as follows: [7]

> Recent studies ([3], [5]) have shown that an existing baseline environment[8] results in an aggregate received RFI whose probability distribution tail essentially comes up to the operational probability limit for precision

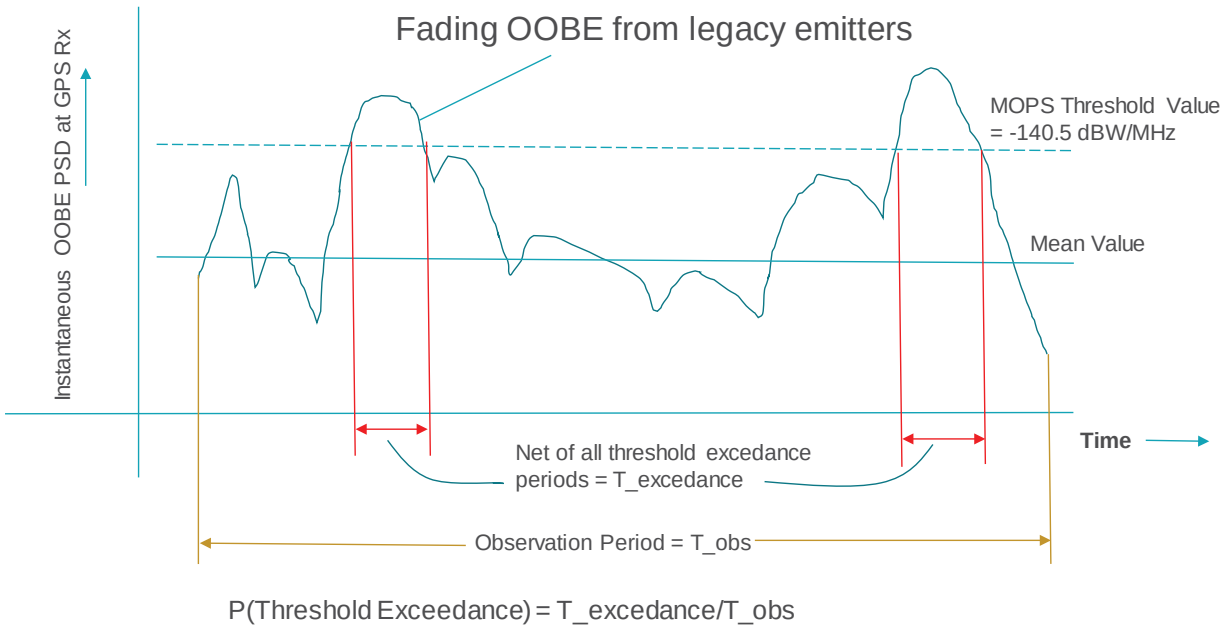
[3] These use cases have been defined by the FAA and thus form the focus of this report.
[4] FAA Letter, Section 3.1.1.
[5] Model defined in RTCA DO-235B
[6] RTCA DO-327, Section 6.2.3.3
[7] Id. Section 2.1.1.2

approach. As such any additional aggregate impact from new broadband wireless source unwanted emission will need to be kept well below that of the baseline environment. The limit for the short duration study is the aggregate effect from additional in-band RFI shall not increase the exceedance probability by more than 6%.

The FAA adopted this new approach because it acknowledged that certain variations of the environmental OOBE level exist currently due to the randomness in the clustering of legacy UEs on the ground and normal variations in propagation paths between UEs and GPS receivers.

A theoretical example of the physical implication of this new methodology is illustrated in Figure 1. This demonstrates the types of random variation cited above that exist today, which at times exceed the MOPS threshold value of -140.5 dBW/MHz.

Figure 1 Description of OOBE compliance requirement introduced by FAA Letter



The FAA's methodology requires the creation of probability distribution of the OOBE from legacy UEs in the current environment. The FAA has specified in [1], [2] the method it wishes to apply to determine the probability distribution function (PDF) of the legacy UEs for all aircraft heights in Table 1 and, from them, to calculate the exceedance probability, shown as P(Threshold Exceedance) in Figure 1. The addition of Ligado devices is not permitted to increase the Exceedance Probability by more than 6%.[9] Ligado has used the FAA's methodology to obtain the results below.

[8] Accumulation of unwanted emissions from cellular mobile handsets, unlicensed wireless network interface infrastructure (U-NII) emitters and unintentional emissions from FCC Part 15 Class B digital devices.

[9] As mentioned, this model is not specified for the case of the aircraft on the ground but the "6% exceedance requirement" applies only to aircraft when they are airborne – specifically at the heights in Table 1 in the FAA Letter. Therefore the lack of this data was not a barrier to performing the present calculations.

2.1.1 Results and Discussion

The calculations by RTCA [1] show that the worst case mean aggregate PSD of -152.67 dBW/MHz from the legacy devices on the ground is generated at the GPS receiver at an altitude of 25.9 m AGL (which is the Category II Decision Height for a landing aircraft). The statistical behavior of the aggregate RFI is shown in table 4 of [1] and is represented in Figure 2 as a plot of cumulative probability distribution of the mean RFI PSD versus the probability of Threshold Crossing.

Here, the threshold value is the MOPS Threshold of -140.5 dBW/MHz and is referred to as 0 dB reference on the X axis. The probability of crossing this threshold is shown on the Y axis as a function of mean RFI level relative to the MOPS Threshold.

As an example, for a mean RFI PSD level of -152.67 dBW/MHz, the analysis is as follows:

1) Calculate the level relative to the reference line, which is: -140.5 - (-152.67 dBW/MHz) = 12.17 dB.
2) Read the probability of exceeding threshold on Y axis as 3.0 x10^-4.

With an equal number of Ligado devices as legacy devices in the same area and with the same user densities, the calculation shows (Table -2) that the new aggregate RFI PSD will be -152.65 dBW/MHz, an increase in noise floor of 0.02 dB. (Level relative to 0 dB reference line: 12.15 dB).

Note that the probability of exceeding the threshold is increased to 3.1 x10^-4. The increase in the exceedance probability is calculated as:

(3.1 x10^-4) – (3.0 x10^-4) / (3.0 x10^-4) = 3.33%

Figure 2 Cumulative Probability Distribution of RFI PSD versus Probability of Threshold Crossing

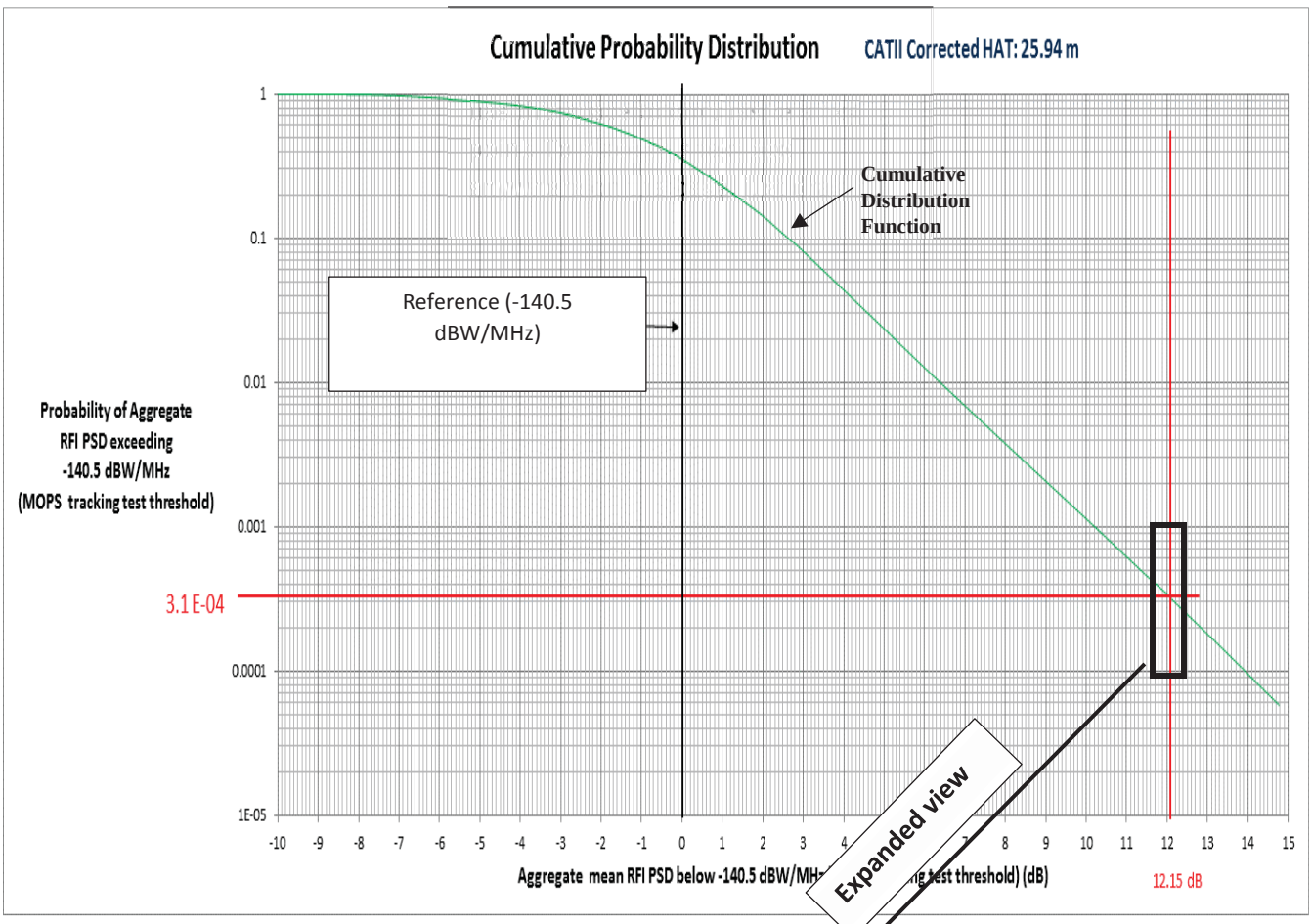


Figure 3 – Magnified view at Aggregate mean RFI PSD below -140.5 dBW/MHz at 12 dB

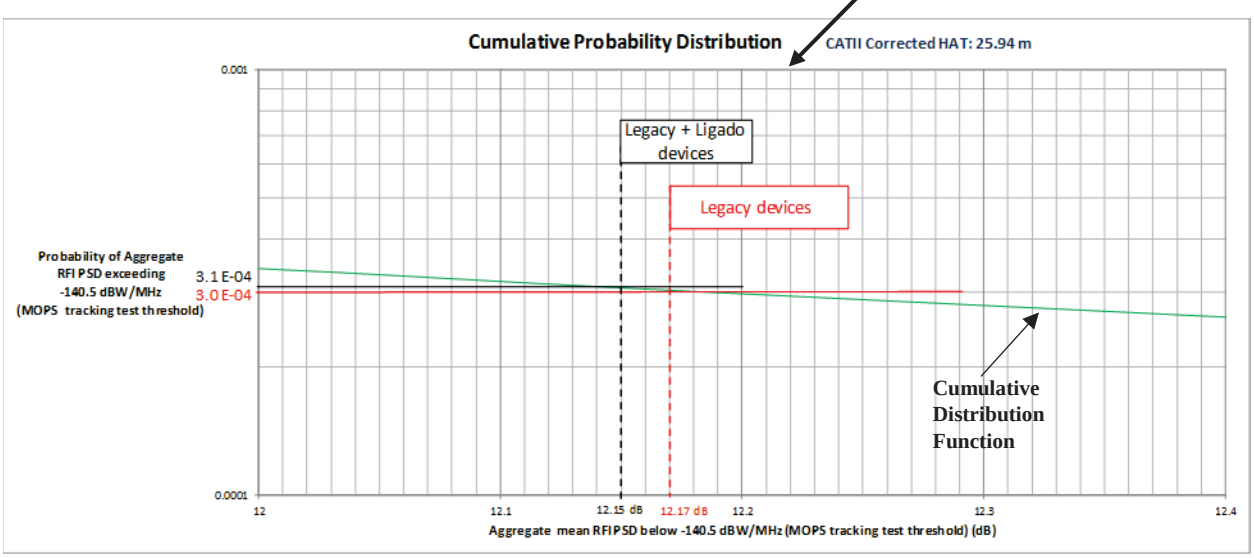


Table 2 Calculations of Exceedance Probability with Ligado UEs' OOBE

	In-Flight Aircraft/Ground Based Handset Case - Baseline			Comments
1	**Parameter**	**Value**	**Unit**	
2	Aircraft Altitude	CAT II DH		Worst case received RFI at 25.94 m height (Ref 1, Table 3)
3	Legacy UE OOBE Tx EIRP	-81.1	dBW/MHz	Surface density ρ_e = 10^-4 per sqm, (100/Sq Km), Height of handset ,H_E = 1.8 m, (Ref 1, Para 2.1)
4	Mean Aggregate received RFI Power density	-152.67	dBW/MHz	Ref 1, Table 3
5	Receiver MOPS test threshold	-140.50	dBW/MHz	Reference 1, Paragraph 4.3.2
6	Ratio of MOPS test threshold to mean aggregate received RFI	12.17	dB	Line 5 - Line 4
7	Ratio of MOPS test threshold to mean aggregate received RFI	16.5	Linear term	Linear term for line 6
8	Probability of Aggregate received RFI exceeding test threshold	3.0E-04	#	Reference 1, Table 5 (generalized model)

Table 3 Calculations of Exceedance Probability with Legacy + Ligado UEs' OOBE

	In-Flight Aircraft/Ground Based Handset Case - RFI Analysis			Comments
1	RFI from legacy devices located outside aircraft on ground	-152.67	dBW/MHz	Reference - 1, Table - 3 for CATII DH (new model Aggr mean)
2	Baseline/Environmental RFI PSD	-152.67	dBW/MHz	Line # 1
3	Aggregate Mean Path loss	71.57	dB	Calculated [-81.1 dBW/MHz-line # 1]
4	RFI from Ligado devices on ground (1 UE/10^4 Sqm)	-176.57	dBW/MHz	Calculated [-105 dBW/MHz - Line # 3]
5	Aggregate RFI	-152.65	dBW/MHz	linear sum of Line # 3 and line # 4)
6	Receiver MOPS test threshold	-140.50	dBW/MHz	Reference 1, Paragraph 4.3.2
7	Ratio of MOPS test threshold to mean aggregate received RFI	12.15	dB	Line # 6 - line # 5
8	Ratio of MOPS test threshold to mean aggregate received RFI	16.4	Linear term	Linear term for line # 7
9	Probability of Aggregate received RFI exceeding test threshold	3.1E-04	#	See chart below (chart is plot of Ref 1, table 4)
10	**Exceedance probability due to additional in-band RFI**	**3.33%**	**#**	**Objective: < 6 %**

2.1.2 Conclusion:

As the FAA requirement is that the increase in exceedance probability caused by OOBE from the new band be less than 6%, Ligado's uplinks comply with this requirement.

2.2 Aircraft on Ground / Onboard Handset Cases

This use case is designed to demonstrate the potential effects of multiple Ligado handsets operating onboard an aircraft which is taxiing.

The relevant excerpt from the FAA Letter, marked by RTCA's SC-159 WG-6[10], is provided below:[11]

> Unlike the inflight scenario above, when the aircraft is on the ground and taxiing toward the gate, the onboard broadband handsets will be assumed to communicate through a standard ground base station outside the aircraft. Because of the partial shielding of the aircraft fuselage, the handsets will be assumed to operate at full transmit power for their necessary emission. The aircraft antenna height is assumed to be 4 m above ground and at a representative location at the start of the taxiway. As in the Sec. 3.1 scenarios, the aircraft GPS receiver is assumed to be in the signal tracking mode. Propagation of both necessary and unwanted handset emissions to the aircraft GPS antenna will be characterized by the same model as in RTCA/DO-235 Appendix E.6.2. For unwanted emission analyses, the GPS receiver is assumed to operate in the presence of a baseline level of unwanted RFI from other randomly-distributed sources outside the aircraft. See Table 4 and [5] for baseline RFI calculation details. Handsets will be distributed in a random assortment of discrete locations throughout the passenger cabin for a few representative values of total handset count. Path loss values at possible locations are to be taken from DO-235 Appendix E, Table E-10.

Table 4 Key Geometric Parameters for the Ground Aircraft - Baseline Unwanted RFI

Parameter	Taxiway Case
Receive Antenna. Ht. (m)	4.0
Std. Dev. Inner Radius, r_s (m)	15.529
Mid-range Inner Rad. R_1 (m)	= r_s
Mid-range Outer Rad. R_2 (m)	1000
Excl. Zone Half-angle (deg)	25
Excl. Zone Inner Rad. (m)	60*
Excl. Zone Outer Rad. (m)	2800
Radio Horizon Radius (km)	13.7813

* Total RFI source exclusion within this radius

Assumptions

<u>UE Power</u>

Ligado, in its December 31, 2015 filing has proposed to reduce the EIRP on uplink channels from 0 dBW to -7 dBW (23 dBm). This is also the maximum power of a device according to the 3GPP standard for LTE. This is an extremely conservative assumption for the *operational power*, which will be further reduced from the above maximum value due to uplink power control. For example, the CSMAC [2] simulations have shown that, in suburban environments, the UE power is less than 10 dBm with a probability greater than 95% for an individual device. However, as a conservative assumption, Ligado has

[10] In its response to the FAA Letter, RTCA SC159 WG 6 provided suggested edits and changes to the FAA's methodology as a markup to the original FAA Letter (the "RTCA Markup")

[11] RTCA Markup, Section 3.2.2.

not factored this 13 dB average reduction in the analysis and the analysis has been done with maximum UE power of 23dBm.

UE antenna coupling loss

A device antenna coupling loss of 0 dB, relative to an isotropic radiator, was used. This value is extremely conservative. For example, in its 2011 assessment, the Cellular subgroup of Technical Working Group tasked by the FCC to study the GPS interference issue assumed a higher antenna coupling loss of 5 dB for a transmit antenna on a cellphone for the use cases that it studied.

Number of simultaneously transmitting devices

All 64 window seats of a Boeing 737-200[12] are assumed to be occupied with simultaneously transmitting users. It should be recognized that this is an implausible scenario that is more conservative than required by the FAA Letter, which requires, "handsets will be distributed in a random assortment of discrete locations throughout the passenger cabin for a few representative values of total handset count". This is an extremely conservative scenario in which 1/3 of all aircraft seats are occupied by a user with a Ligado UE operating at full power with the minimal possible path loss to the aircraft GPS antenna. It is presented here as a way to demonstrate the positive margin inherent in the use case in general, and avoid debate about the number and seat choices of the handsets.

The "baseline level of unwanted RFI from other randomly-distributed sources outside the aircraft",[13] comprised an equal number of legacy and Ligado UEs. As mentioned above, the PSD of baseline RFI was determined by a simplified model of 2-ray propagation to all UEs up to the radio horizon. This model results in less propagation loss than that recommended by the FAA and RTCA. It therefore created a higher baseline RFI than would have resulted from the FAA model had it been calculated at ground level. The model used by Ligado reduced the margin between the composite (from all UEs) mean RFI PSD and the Environmental Limit of -146.5 dBW/MHz. As the compatibility metric specified by the FAA is the positive margin between the Environmental Limit and the composite mean PSD, the approach used by Ligado is more conservative than that recommended by the FAA and RTCA.

OOBE PSD from UE

The Ligado limit of -105 dBW/MHz for OOBE PSD is used instead of the -95 dBW/MHz limit specified in the FAA Letter, which is no longer current based on Ligado's December 31, 2015 FCC filing.

[12] This is the aircraft type specified in the FAA Letter.
[13] RTCA Markup, Section 3.2.2.

OOBE threshold at the GPS receiver

The OOBE threshold used is -206.5 dBW/Hz, as per RTCA DO-229D.

Overload threshold at the GPS receiver

The overload threshold used is -16.7 dBm, as per RTCA DO-229D for a CW signal at 1632.5 MHz.

2.2.1 Result and Discussion

Table 5 Calculations for Aircraft on Ground / Onboard Handset Cases

	Aircraft on ground / Onboard Handset case (64 Users) Use case 3.2.2			
	Item	Value	Unit	Comment
1	Combined received RFI Power density @ 4 m A/C height from legacy and Ligado devices	-149.5	dBW/MHz	Environmental RFI (total) at @ 4 m Aircraft height (sum of legacy and Ligado devices on ground)
2	Total received OOBE	-157.4	dBW/MHz	64 users in all cabin window seat - Calcuated
3	Aggregate RFI	-148.8	dBW/MHz	Linear sum Line # 1 and line # 2
4	dB aviation margin	-146.5	dBW/MHz	Reference 3, Figure C-1
5	**OOBE Margin**	**2.3**	**dB**	**Calculated**
6	Aggregate path Loss (dB)	52.4	dB	(-105 dBW/MHz) - Line # 2
7	Total received fundamental power	-29.4	dBm	(23 dBm) - Line # 6
8	Overload threshold with 6 dB aviation margin	-16.7	dBm	Reference 3, Figure C-1
9	**Overload margin**	**12.7**	**dB**	**Line # 8 - Line # 7**
10	Overload threshold with 6 dB aviation margin (GLONASS)	-22.7	dBm	At 1632.5 MHz ICAO MOPS
11	**Overload Margin for GLONASS Rx**	**6.7**	**dB**	**Line # 10 - line # 7**

As mentioned above, the composite PSD of baseline RFI from legacy and Ligado devices was calculated using a conservative, line-of-sight two-ray model from each source within the radio horizon of receiver (~14 Km radius). With the total count of ~120,000 sources, the PSD value is -149.5 dBW/MHz. The calculations in Table 5 show that the aggregate RFI is below the tracking threshold of receiver with an OOBE margin of 2.3 dB and overload margin of 12.7 dB for GPS receivers and 6.7 dB for GLONASS receivers[14].

[14] The OOBE limits for GLONASS are identical to those for GPS, so the OOBE margin for GLONASS is not separately stated in this document.

2.2.2 Conclusions

The Ligado uplinks meet the requirements of this use case.

It is noteworthy that the total RFI level is dominated by legacy devices outside the aircraft. Without any Ligado devices in cabin, the in-band tracking margin would have been 3 dB. The 64 Ligado devices inside the aircraft only consumed 0.7 dB of the available margin.

2.3 Aircraft at Gate / Single Handset Source on or near Boarding Stairs or Jetway

This scenario is designed to assess the potential impact of a single user that is boarding a regional jet using a stairway, and is positioned at the top of the stairway, outside of the aircraft.

Excerpt from the RTCA Markup[15]:

> This scenario has a single broadband wireless handset operating potentially at up to full necessary emission power at the center frequencies listed in Section 2.3.1. The propagation is assumed to be free-space ($1/r^2$). Handset location relative to the GPS aircraft antenna is assumed to be such that the receive antenna gain is -5 dBi. Given the propagation conditions and single source, the result is assumed to be deterministic. In this case for a single handset with 0 dBW (30 dBm) EIRP operating at 1616 MHz, the minimum handset antenna separation distance for compatibility[16] is 3.5 m. This separation might be assured by aircraft fuselage size and geometry. Some further verification should be undertaken in the short duration study. Unwanted handset RFI analysis should also include the baseline RFI effect as in Sec. 3.2.2 and also include the effect of unwanted RFI from a concentration of general sources inside the airport terminal.

The scenario assumptions and link calculations are given below.

<u>Maximum UE Power</u>

As a conservative assumption, the maximum operational UE power was assumed to be 23 dBm at a transmit frequency of 1632.5 MHz. In actual use cases, the transmit EIRP will typically be much lower due to uplink power control and a UE transmit antenna coupling loss (antenna gain less than 0 dBi in the direction of transmission).

<u>GPS antenna gain towards UE</u>

As recommended by the FAA, GPS antenna gain of -5 dBi is assumed towards UE.

<u>Number of simultaneously transmitting devices</u>

This scenario involves a single user at the top of the aircraft stairs. It does not appear possible to have more than a single user at this particular location.

---

[15] RTCA Markup, Section 3.3.

16 With respect to 1616 MHz susceptibility (Fig. 1) with 6 dB safety margin (-22.5 dBm)

Separation distance from UE to GPS receiver

As recommended by FAA, the separation distance was assumed to be 3.5 m.

OOBE PSD from UE

The Ligado limit of -105 dBW/MHz for OOBE PSD is used instead of the -95 dBW/MHz limit specified in the FAA Letter, which is no longer current based on Ligado's December 31, 2015 FCC filing.

OOBE threshold at the GPS receiver

The OOBE threshold used is -206.5 dBW/Hz (-146.5 dBW/MHz), as per RTCA DO-229D.

Overload threshold at the GPS receiver

The overload threshold used is -16.7 dBm, as per RTCA DO-229D for a CW signal at 1632.5 MHz.

Link Calculations

Table 6 shows the link calculations for the single user case.

The analysis is performed without any changes to the recommended parameters for the scenario in the FAA Letter. The baseline noise is assumed to be sourced from legacy devices and Ligado devices on ground as described in Section 2.3 of this document.

Table 6 Calculations for Aircraft at Gate / Single Handset Source on or near Boarding Stairs or Jet-way

1	**Single Ligado User near Boarding Stairs or Jet way - Baseline RFI calculations**			
2	**Parameter**	**Value**	**Unit**	**Comment**
3	Mean Aggregate received RFI Power density @ 4 m A/C antenna height from legacy devices on the ground	-149.5	dBW/MHz	Calculated in "Baseline RFI @ 4 m" tab assuming worst case, two ray path loss assumptions. Device OOBE = -81.1 dBW/MHz (Ref -1)
4	Mean Aggregate received RFI Power density @ 4 m A/C antenna height from Ligado devices	-173.4	dBW/MHz	Calculated in "Baseline RFI @ 4 m" tab assuming worst case, two ray path loss assumptions. Device OOBE = -105 dBW/MHz
5	Combined received RFI Power density @ 4 m A/C antenna height from legacy and Ligado devices	-149.5	dBW/MHz	Environmental RFI (total) at @ 4 m Aircraft height (linear sum of line # 3 and line # 4)
6	Mean Aggregate received RFI Power density	-154.0	dBW/MHz	30 legacy devices randomly distributed in terminal (10 trials)
7	Mean Aggregate received RFI Power density	-177.6	dBW/MHz	30 Ligado devices randomly distributed in terminal (10 trials)
8	Baseline/Environmental RFI PSD	-148.2	dBW/MHz	Linear sum of line # 5, # 6 and # 7
9	**Single Ligado User near Boarding Stairs or Jet way - RFI analysis**			
10	Max UE Tx EIRP	23	dBm	
11	UE Maximum OOBE PSD (select)	-105	dBW/MHz	
12	Uplink power control factor (user location: outdoor)	0	dB	
13	Rx Antenna Coupling loss	5	dB	-5 dBi gain of GPS antenna (Reference 2, para 3.3
14	Tx/Rx Distance	3.5	Meters	Minimum plausible distance for use case (Reference 2, para 3.3)
15	Path loss to GPS antenna	47.3	dB	Free Space @ 1575 MHz
16	OOBE received by GPS antenna	-157.3	dBW/MHz	line # 11- # 12 - line # 13 - line # 15
17	Baseline/Environmental RFI PSD	-148.2	dBW/MHz	Line # 8
18	Aggregate RFI	-147.7	dBW/MHz	Linear Sum of Line # 16 and # 17
19	Receiver MOPS test threshold with 6 dB aviation margin	-146.50	dBW/MHz	Reference 3, Figure C-1
20	**OOBE Margin**	**1.2**	**dB**	**Line # 19- line # 18**
21	Fundamental signal power	-29.3	dBm	line # 10 - # 12 - # 13 - # 15
22	Overload threshold with 6 dB aviation margin for GPS	-16.7	dBm	At 1632.5 MHz, Reference 3, Figure C-1
23	**Overload margin for GPS Rx**	**12.6**	**dB**	**Line # 22 - line # 21**
24	Overload threshold with 6 dB aviation margin GL	-22.7	dBm	At 1632.5 MHz ICAO MOPS
25	**Overload Margin for GLONASS Rx**	**6.6**	**dB**	**Line # 23 - line # 21**

2.3.1 Result and Discussion

In addition to baseline noise PSD from legacy and Ligado sources within the radio horizon outside the aircraft, additional RFI sources within the terminal building are also considered contributing the base line noise. Ligado has assumed 30 legacy and 30 Ligado users randomly distributed inside the terminal building where the aircraft is parked, and has used recommendations from the FAA Letter to calculate path loss to the receiver. Even with contribution from background in-band noise, the analysis shows positive 1.2 dB margin for in-band, overload margin of 12.6 dB for GPS receiver and 6.6 dB for GLONASS receiver.

2.3.2 Conclusions

Ligado uplinks comply with this use case for both OOBE and Overload.

2.4 Aircraft at Gate/30 Users Inside Airport

This use case is designed to simulate the effects of multiple users dispersed around the gate area of an airport with an aircraft parked at the gate.

Excerpt from the RTCA Markup[17]:

> The following are proposed features for this new scenario with 30 wireless broadband handsets operating in an airport terminal gate area that generate RFI to a GPS receiver on an aircraft parked outside the terminal in front of the gate area. Unwanted handset RFI analysis should also include the baseline RFI effect as in Sec. 3.3. The choice of the ratio of baseline sources inside the terminal to wireless broadband sources should be justified.
>
> 1. The aircraft GPS antenna height is assumed to be 4 meters above ground and 34 meters from front edge of terminal area.
> 2. The handset antenna heights are all 3 m above the aircraft antenna level (2 m above terminal floor)
> 3. Terminal area is assumed to be symmetrically spaced in front of the aircraft with a 20 meters average depth and 50 meters width
> 4. 30 handsets are assumed to be uniformly distributed throughout the 1000 sq. m. area.
> 5. Handsets are assumed to be operating in the 1610-1656.5 MHz band with -95 dBW/MHz unwanted EIRP in the GPS L1 band.
> 6. Due to the relatively few handsets and the large minimum separation distance, the aggregate unwanted RFI in-band to the GPS receiver is expected to be the dominant effect (c.f. §3.3).
> 7. The median path loss model to be used would be free-space at these distances but with additional building loss incorporated as per the July, 2014 NTIA document. That is, 20% of handsets incur an additional 20 dB loss, 60% an additional 15 dB loss, and 20% an additional 10 dB loss. (excess loss assigned relative to decreasing distance from front terminal wall)
> 8. A Monte Carlo method is suggested for analysis.

Assumptions

Maximum UE Power

As a conservative assumption, the maximum operational UE power was assumed to be 23 dBm. In actual use cases, the transmit EIRP will typically be much lower due to uplink power control and a UE transmit antenna coupling loss (antenna gain less than 0 dBi in the direction of transmission).

[17] RTCA Markup, Section 3.4.

GPS antenna gain towards UE

Using the pattern of an aviation GPS antenna provided in RTCA DO-235B, Fig. G-13, an antenna gain of -2.75 dBi is used for elevation angles +5 degrees for the nearest user device to Aircraft Antenna. This is a conservative, worst case assumption.

Number of simultaneously transmitting devices

It is assumed that all thirty Ligado users are transmitting simultaneously at constant power (as detailed above) at varying distances from an aircraft parked at the gate and that their powers add at the GPS receiver as specified in the FAA Letter and RTCA Markup. Specifically, six users are operating in the front glass of the terminal building at a distance of 0 - 6 meters facing the aircraft, 18 users are in middle section of the terminal at a distance of and 6 – 14 meters, and 6 users are in backside of the terminal at a distance of 14 – 20 meters. These are extremely conservative assumptions, both in terms of the number of active users within the separation distances and in terms of the likelihood of power addition at the GPS receiver. The latter likelihood is low because the TDMA component of the LTE protocol will, with very high probability, assign non-overlapping transmit-time epochs to the users. Indeed, the CSMAC working groups assumed six simultaneous users per cell sector for its modeling assumptions.

The high number of users in this instance demonstrates the substantial margin that exists overall for this type of use case.

Separation distance from UE to GPS receiver

As recommended by FAA, the separation distances vary from 34-60 meters from the aircraft GPS receive antenna.

OOBE PSD from UE

The Ligado limit of -105 dBW/MHz for OOBE PSD is used instead of the -95 dBW/MHz limit specified in the FAA Letter, which is no longer current based on Ligado's December 31, 2015 FCC filing.

OOBE threshold at the GPS receiver

The OOBE threshold used is -206.5 dBW/Hz (-146.5 dBW/MHz), as per RTCA DO-229D.

Overload threshold at the GPS receiver

The overload threshold used is -16.7 dBm, as per RTCA DO-229D for a CW signal at 1632.5 MHz.

2.4.1 Results and Discussion

The analysis in Table 7 was conducted using Monte Carlo method by simulating the 30 Ligado users in the airport terminal as discussed above. Hundreds of trials were performed (ten trails per each calculation epoch) to determine the median RFI. The environmental RFI PSD for background noise was considered to originate from an equal number of legacy and Ligado devices distributed within the radio horizon. The in-band aggregate RFI was compared with the receive threshold of -146.5 dBW/MHz. The analysis shows positive margin of 1.7 dB for OOBE and 31.2 dB for overload RFI. Overload margin of 25.2 dB is available for GLONASS receiver.

Table 7 Calculations for Aircraft at Gate/30 Users Inside Airport

	Aircraft at Gate, 30 users inside terminal - Baseline RFI calculations			
	Parameter	Value	Unit	Note
1	Combined received RFI Power density @ 4 m A/C height from legacy and Ligado devices	-149.5	dBW/MHz	Environmental RFI (total) at @ 4 m Aircraft height (sum of legacy and Ligado devices on ground)
2	Mean Aggregate received RFI Power density	-154.0	dBW/MHz	30 legacy devices randomly distributed in terminal (10 trials)
3	Baseline/Environmental RFI PSD	-148.2	dBW/MHz	Linear sum of line # 1 + line # 2
4	**30 Ligado Users inside terminal - RFI analysis**			
5	Mean Aggregate received RFI Power density	-175.9	dBW/MHz	30 Ligado devices randomly distributed in terminal (10 trials)
6	Aggregate OOBE received by GPS antenna	-148.2	dBW/MHz	Linear sum of line # 3 and # 5
7	Receiver MOPS test threshold with 6 dB aviation margin	-146.50	dBW/MHz	Reference 3, Figure C-1
8	OOBE Margin	**1.7**	dB	Line # 7 - line # 6
9	Aggregate path Loss (dB)	70.9	dB	Calculated, (-105 dBW/MHz) - line # 5
10	Total received fundamental power	-47.9	dBm	(23 dBm) - line 9
11	Overload threshold with 6 dB aviation margin	-16.7	dBm	DO-229D At 1632.5 MHz, Reference 3, Figure C-1
12	Overload margin (GPS) Rx	**31.2**	dB	Line # 11-line # 10
13	Overload threshold with 6 dB aviation margin GLONASS	-22.7	dBm	At 1632.5 MHz ICAO MOPS
14	Overload Margin for GLONASS Rx	**25.2**	dB	Line # 13 - line # 10

2.4.2 Conclusions

Compatibility is demonstrated for both OOBE and Overload, with the use of highly conservative assumptions.

2.5 TAWS / HTAWS and Pos/Nav Scenarios with Ground-based Mobile Broadband Handsets

This scenario was constructed to assess the potential impact of Ligado UEs located on the ground on aircraft that are using GPS with terrain awareness systems (TAWS for fixed wing aircraft and HTAWS for helicopters) as well as other positioning and navigation systems that rely on receivers certified to the RTCA DO-229D and related MOPS.

Excerpt from RTCA Markup[18]:

> The RTCA results [3] for mobile broadband handset aggregate unwanted emissions were largest for the Cat II DH scenario where the aircraft antenna was 25.94 m above the ground. For this scenario, exclusion zones were assumed where mobile handsets could NOT be (e.g., within the airport runway object-free area, obstacle clearance zone, etc. - see Table B-3 in [3]). This exclusion zone was a rather substantial annular wedge (~50 degrees). The handset interference results would be worse for the (TAWS/HTAWS) scenarios developed during the base station studies performed by the FAA with LightSquared during late 2011/early 2012 [4]. In those scenarios, the airborne user would be roughly the same height above ground but without exclusion zones for mobiles beneath the aircraft.
>
> In this study, the mobile broadband handsets are assumed to be randomly distributed at one of 3 different surface concentrations (30, 75, 180 per sq. km). Their assumed unwanted emission is -95 dBW/MHz in the GPS L1 receiver passband. At these surface concentration values, the fundamental emission effects will be insignificant by comparison. The two different aircraft antenna height cases to be analyzed are: 25.94 and 53.34 m. Comparison can then be made with the final approach cases from Sec. 3.1.1 which contain source exclusion zones.

Assumptions

Maximum UE Power

As a conservative assumption, the maximum operational UE power was assumed to be 23 dBm.

Uplink power control

No Uplink power control is assumed.

Antenna coupling loss

UE transmit antenna coupling loss is assumed to be 0 dB.

[18] RTCA Markup, Section 3.5.1

GPS antenna gain towards UE

Using the pattern of an aviation GPS antenna provided in RTCA DO-235B, Fig. G-13, varying GPS receive antenna gain are considered, based on the angle of arrival of the RFI signal from randomly located user device.

Number of simultaneously transmitting devices

Device concertation of 30, 75 and 180 per Sq. Km. in the radio horizon.

Height of GPS receiver

As suggested by FAA, the 25.94 meters and 53.34 meters are considered

OOBE PSD from UE

The Ligado limit of -105 dBW/MHz for OOBE PSD is used instead of the -95 dBW/MHz limit specified in the FAA Letter, which is no longer current based on Ligado's December 31, 2015 FCC filing.

OOBE threshold at the GPS receiver

The OOBE threshold used is -146.5 dBW/Hz, as per RTCA DO-229D.

Overload threshold at the GPS receiver

The overload threshold used is -16.7 dBm, as per RTCA DO-229D for a CW signal at 1632.5 MHz.

Exclusion Zone

For uplink use cases, the term "Exclusion Zone" refers to potential restrictions on the placement of Ligado base stations, which would then eliminate UEs from those areas as well. In the case of the current analysis, no exclusion zones have been assumed.

Propagation Model

Two-Ray Line of Sight

2.5.1 Results and Discussion

The RFI analysis in Table 8 shows that significant margin exists (more than 23 dB) for OOBE and more than 25 dB exists for the overload conditions for all aircraft heights, and device concentrations considered. Considering the fact that tracking threshold (Environmental Limit) for in-band (OOBE) was at -146.5 dBW/MHz, even for the calculating the increase in exceedance probability, the mean RFI would be approximately 29 dB (23 + 6) below the -140.5 dBW/MHz reference threshold. This also would result in an extremely small increase (less than 1 %) in exceedance probability.

Table 8

Calculations for TAWS / HTAWS and Pos/Nav Scenarios with Ground-based Mobile Broadband Handsets

Ground Based Handsets for TAWS/HTAWS				
UE Concentration (per Sq Km)	Aircraft height = 25.94 m		Aircraft height = 53.34 m	
	OOBE Margin (dB) (Threshold -146.5 dBW/MHz)	O/L Margin (dB) at 1632.5 MHz	OOBE Margin (dB) (Threshold -146.5 dBW/MHz)	O/L Margin (dB) at 1632.5 MHz
30	**31.4**	**33.2**	**31.8**	**33.6**
75	**27.4**	**29.2**	**27.8**	**29.6**
180	**23.6**	**25.4**	**24.0**	**25.8**

2.5. 2 Conclusions

The calculations use the Ligado limit of -105 dBW/MHz for OOBE PSD instead of the -95 dBW/MHz limit specified in the FAA Letter, which is no longer current.

Reference

[1] Frazier, R., Erlandson, R. J. and Peterson, K. M. “Final Report: A Generalized Statistical Model for Aggregate Radio Frequency Interference to Airborne GPS Receivers from Ground Based Emitters”, DOT/FAA/TC-14/30, RTCA Paper No. 267-14/SC159-1023, September 30, 2014.

[2] Peterson, K. M. and Erlandson, R. J., “Analytic Statistical Model for Aggregate Radio Frequency Interference to Airborne GPS Receivers from Ground-Based Emitters”, NAVIGATION: Journal of the Institute of Navigation, Vol. 59, No. 1, Spring 2012.

Attachment B

Changes in C/N0 are Not a Reliable Indicator of KPI Impact

Before the
Federal Communications Commission
Washington, D.C. 20554

	)	
	)	IB Docket No. 11-109
In the Matter of	)	IBFS File Nos.
GPS Interference Indicators	)	SES-MOD-20151231-00981,
	)	SAT-MOD-20151231-00090, and
	)	SAT-MOD-20151231-00091

DECLARATION OF MARK A. STURZA

1. My name is Mark A. Sturza. I am the President of 3C Systems Company; in this capacity I consult with startups and established corporations on GPS-related issues. I have over forty years of experience in the design, development, analysis, and application of GPS systems.

2. Prior to founding 3C Systems, I worked at several major electronics companies developing GPS technology. At Teledyne Systems Company (1975 – 1979), I supported development of the Tactical GPS Guidance receiver, the GPS Phase IIA program, development of a GPS satellite simulator, and development of the Missile Accuracy Evaluator GPS receiver. At Magnavox (1979 – 1981), I designed the set moding for their GPS Phase II User Equipment receivers. As Director, GPS Development at Litton Aero Products (1981 – 1987), I led the development of the first GPS receivers specifically designed for the commercial aviation market. At Litton Guidance and Control Systems (1987 – 1989), I provided my expertise to all of the company's integrated GPS/inertial navigation system developments.

3. Since founding 3C Systems in 1989 (twenty-seven years ago), I have been involved in a wide range of GPS product developments, including development of SiRF Technology's SiRFstar GPS chipsets, development of NAVSYS's TIDGET GPS receiver,

development of one of the first software GPS receivers, and redesign of Allen Osborne Associates' Rogue GPS receiver RF section.

4. I have been awarded thirty patents in GPS and related fields, nine of which specifically cover GPS technology. These patents include innovations for acquiring extremely weak GPS signals (such as revived inside of buildings) and operating GPS chipsets in micro power mode (to improve battery life). I have presented over thirty technical papers, twenty-one of which focus on GPS technology. Two of these papers were published in *Navigation*, the journal of the Institute of Navigation. I have lectured at GPS short courses on thirteen occasions.

5. I am a Senior Member of the Institute of Electrical and Electronic Engineers, a Senior Member of the American Institute of Aeronautics and Astronautics, and a member of the Institute of Navigation, the Pacific Telecommunications Council, and the Society of Satellite Professionals International. I hold a General Radiophone Operator License from the FCC.

6. I earned a BS degree from Caltech, an MSEE degree from USC, and an MBA degree from Pepperdine University.

7. I have been retained by Ligado Networks' counsel to research the applicability of changes in C/N_0 to GPS device performance. To do so, I reviewed the latest GPS standards documents, latest technical papers, and latest vendor datasheets.

8. Based on this research and my forty years of experience in this field, I have authored the following white paper illustrating that changes in C/N_0 are an unreliable indicator of impact to GPS key performance indicators. The paper is true and accurate to the best of my knowledge.

Signed: _____/s/_____

Mark A. Sturza

Date: June 6, 2016

Changes in C/N_0 are Not a Reliable Indicator of KPI Impact

Introduction and Summary

Changes in the C/N_0 values output by a GPS device are an unreliable indicator of impact to GPS Key Performance Indicators (KPI's). A GPS KPI is the appropriate metric for evaluating performance, a metric that correlates in a consistent way with the position, velocity, and time (PVT) outputs of the device. KPIs fall into two categories – accuracy and response time. Metrics not based on PVT outputs, such as the number of GPS satellites being tracked or C/N_0 measurements, are only indirectly related to the PVT metrics. In isolation, they do not predict PVT performance.

Changes to the C/N_0 values output by a GPS device occur during normal operation. These changes result from several sources including:

- Variations in the GPS devices antenna pattern as a function of look angles to the GPS satellites
- Changes in path loss as the GPS signals passes through foliage
- GPS signal amplitude fades due to ionospheric scintillation
- Fading due to multipath reflections of the GPS satellite signals and building blockage of the GPS satellite signals (urban canyons).

GPS devices are designed to operate over large ranges of C/N_0. Some devices can operate from 50 dB-Hz down to 5 dB-Hz. Depending on user dynamics and embedded oscillator stability, GPS devices can auto tune to ensure that tracking errors -- errors in the device's measurement of its distance from GPS satellites -- are relatively unchanged over large ranges of C/N_0. Ranges from 20 dB to 44 dB can be achieved.

Tracking errors are only one component of the PVT accuracy. The other components are the inaccuracies due to the GPS satellites and the GPS ground control system, multipath, and tropospheric delay computation. These error components are independent of C/N_0, and in typical operating scenarios, they dominate the tracking error component.

To summarize, changes in the C/N_0 values output by a GPS device are an unreliable indicator of impact to GPS KPI's. Changes to the C/N_0 values output by a GPS device occur during normal operation. GPS devices are designed to operate over large ranges of C/N_0. They can auto tune to ensure that tracking errors are relatively unchanged over large ranges of C/N_0. Tracking errors are typically dominated by the other components of PVT accuracy, which are independent of C/N_0.

What is C/N_0?

C/N_0 is a measure of GPS signal power relative to thermal noise density. In a GPS receiver, C/N_0 is the ratio of received GPS satellite signal power to equivalent noise power spectral density at the input of the receiver. It is expressed in units of dB-Hz[1]. Often C/N_0 is used to represent what is more accurately $C/(N_0+I_0)$, the ratio of received GPS satellite signal power to the sum of equivalent noise power spectral density and equivalent interference power spectral density, all referenced to the input of the receiver.

[1] C has units of power and N_0 has units of power per Hz. If the same measure of power is used for both C and N_0, it will cancel when the ratio is taken, and C / N_0 will have units of Hz. This is converted to dB-Hz by $10 \times \log_{10}(C / N_0)$.

What is C?

C is the received GPS satellite signal power at the GPS receiver input. For commercial GPS devices, it is the received L1 C/A-code power. It is often expressed in units of dBm[2]. The specified minimum GPS satellite signal L1 C/A power at the Earth's surface for unobstructed satellite views above a 5° elevation angle is -128.5 dBm as measured at the output of a 3 dBi antenna[3]. Maximum received L1 C/A power is not expected to exceed -123 dBm.

What is N_0?

N_0 is the equivalent thermal noise power spectral density at the receiver input. It is typically expressed in units of dBm/Hz. Thermal noise is generated by the thermal agitation of the electrons inside an electrical conductor. It is present in every electrical circuit. At room temperature, N_0 is given by -174 dBm/Hz + NF, where NF is the noise figure of the GPS receiver in dB. NF represents the noise added by the receiver front-end components. Typically, it is dominated by the noise figure of the low-noise amplifier (LNA) and the losses of the components, cables and filters, between the LNA and the antenna. A recent survey of GPS antennas[4], most of which contain integrated low noise amplifiers, showed a range of noise figures from 0.6 to 4 dB, with a median of 2 dB. Assuming a 2 dB noise figure results in an N_0 of -172 dBm/Hz.

What is I_0?

I_0 is the equivalent in-band interference power spectral density at the receiver input. It is typically expressed in units of dBm/Hz. By design, the GPS system is self-interfering. All of the GPS satellites transmit on the same L1 frequency (1575.42 MHz). To function, GPS devices need to receive signals from at least 4 satellites. Typically, they receive signals from 8 to 12 satellites simultaneously. GPS uses direct sequence spread spectrum (DSSS) modulation to allow a GPS device to isolate a single satellite's signal for tracking. However, this isolation is imperfect. Each additional GPS satellite's signal adds some equivalent in-band interference power density at the receiver input. Other Global Navigation Satellite Systems (GNSS's), such as Galileo, and the Space Based Augmentation Systems (SBAS), such as WAAS, also contribute equivalent in-band interference power density at the GPS receiver input. At unobstructed locations, the combined effects might result in an I_0 of -174.2 dBm/Hz[5].

The harmonics of many standard broadcast signals fall in the GPS L1 signal band. Harmonics are unintended signals at integer multiples of the intended signal frequency. They arise due to imperfections in the transmitters and can also be generated by discontinuities in conductors near a transmitter. For example, the following harmonics overlap the GPS L1 signal:

- 2nd harmonic of Upper 700 MHz A Block (787 – 788 MHz)
- 2nd harmonic of Upper 700 MHz D Block (788 – 793 MHz)
- 3rd harmonic of UHF TV channel 23 (524 – 530 MHz)
- 8th harmonic of VHF TV channel 10 (192 – 198 MHz)

---

[2] Power in units of milliwatts is converted to dBm by 10 x $\log_{10}$ (power in milliwatts). IF the power is expressed in watts, it is converted to dBm by 10 x $\log_{10}$(power in watts) + 30 dB.

[3] Global Positioning Systems Directorate Systems Engineering & Integration, Interface Specification IS-GPS-200, Navstar GPS Space Segment/Navigation User Interfaces, IS-GPS-200H, 24 September 2013, page 17.

[4] GPS World Antenna Survey 2016.

[5] RTCA/DO-235B, Assessment of Radio Frequency Interference Relevant to the GNSS L1 Frequency Band, RTCA SC-159, March 13, 2008, page 127.

- 9th harmonic of VHF TV channel 7 (174 – 180 MHz)
- 15th harmonic of FM radio station 105.1 MHz
- 16th harmonic of FM radio station 98.5 MHz
- 17th harmonic of FM radio station 92.7 MHz

Another occasional source of in-band interference power is GPS jammers. While these devices are illegal in the United States, the FCC has been forced to take numerous enforcement actions against them[6], suggesting that they continue to be an interference source.

What are Typical C/N_0 Values

For a 2 dB noise figure receiver, N_0 = -172 dBm/Hz, and the range of unobstructed GPS L1 C/A received power levels, the C/N_0 ranges from 43.5 dB-Hz to 49 dB-Hz. This is computed as:

-128.5 dBm – (-174 dBm/Hz + 2 dB) = 43.5 dB-Hz

-123 dBm – (-174 dBm/Hz + 2 dB) = 49 dB-Hz

Using the I_0 of -174.2 dBm/Hz discussed above, the $C/(N_0+I_0)$ range is 41.5 dB-Hz to 47 dB-Hz.

What is the C/N_0 Value Output by GPS Receivers?

Some GPS receivers output an estimate of the received C/N_0. Although labeled C/N_0, these estimates are actually of $C/(N_0+I_0)$. The algorithms used to compute them, and the accuracy of the resulting estimates, vary by manufacturer. For all algorithms, the estimation error tends to grow as C/N_0 decreases.

The GPS devices actually measure the C/N_0 at the code error detector input, not at the receiver input. The difference between these two values is referred to as the "implementation loss" of the GPS receiver. Implementation loss results from non-ideal processing. It includes loss due to quantization, sampling, filter non-linearity, bandlimiting, frequency tracking error, and code tracking error. For a typical GPS device, implementation loss might be 0.5 to 2.5 dB[7].

What Causes Changes in the Output C/N_0 Value?

Anything that changes the received GPS satellite power, the equivalent input thermal noise power spectral density, the effective, in-band, input interference power spectral density, or the receiver implementation loss will change the C/N_0 output. Under normal operating conditions, the equivalent input thermal noise density and the receiver implementation loss do not experience significant changes. The most dynamic parameter is the received GPS satellite power.

Some of the factors that impact received GPS satellite power are discussed below.

GPS Device Antenna Gain

While the specified minimum GPS satellite signal L1 C/A power at the Earth's surface for unobstructed satellite views above a 5° elevation angle is -128.5 dBm, there are several factors that can cause significant reduction in received power. The -128.5 dBm is specified at the output

[6] http://www.gps.gov/spectrum/jamming/

[7] Christopher J. Hegarty, "Analytical Model for GNSS Receiver Implementation Losses"

of a 3 dBi reference antenna. Figure 1 and Figure 2 show typical antenna patterns for handheld GPS devices.

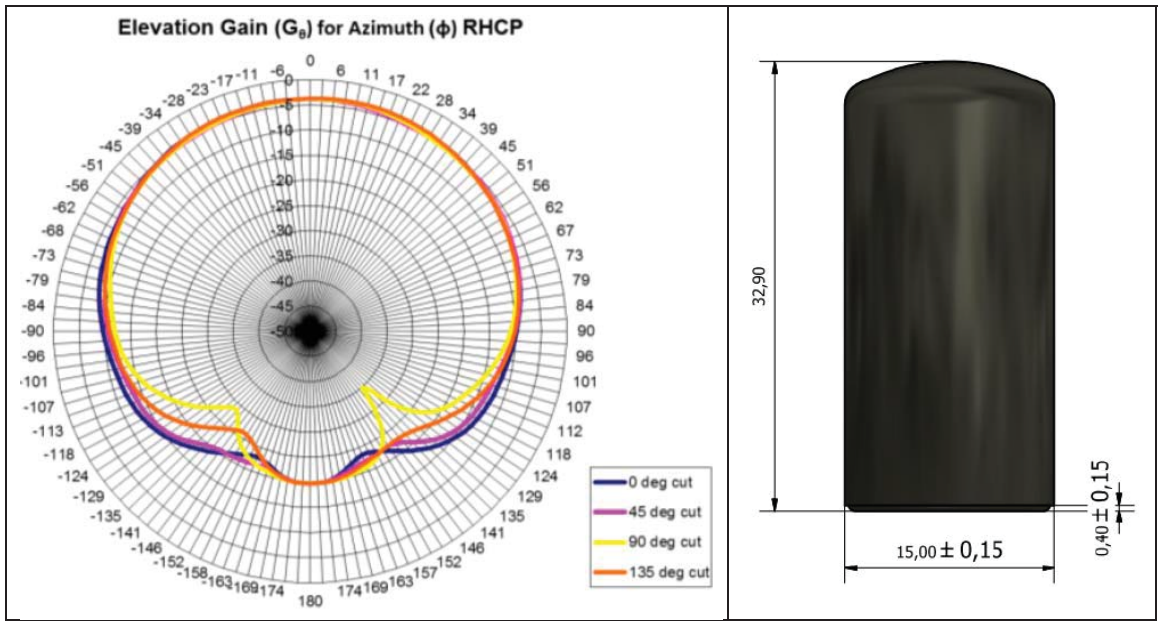


Figure 1 – MARUWA MWSL1203D GPS L1 antenna[8]

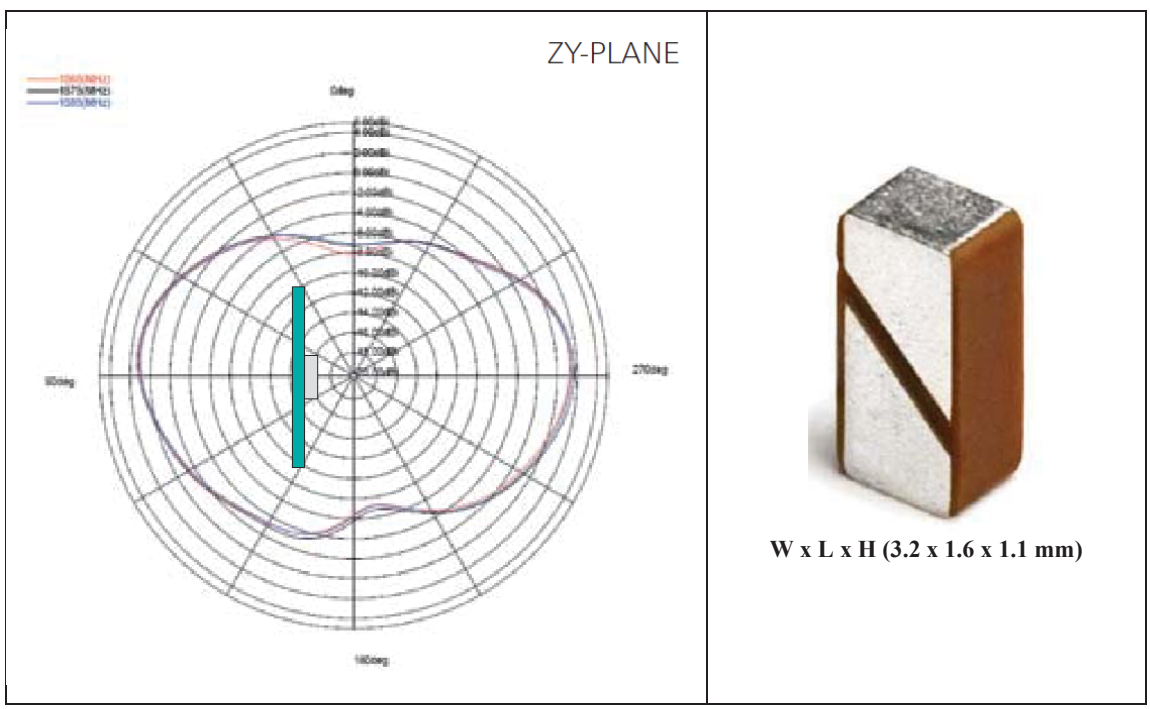


Figure 2 – Typical Chip Antenna Pattern[9]

[8] Maruwa MWSL 1203D Datasheet
[9] http://productfinder.pulseeng.com/productSearch/w3011

Depending on the particular antenna, the orientation of the device, proximity to people and objects, and nearby conductive surfaces, the gain can be up to 10 dB, or more, below the reference antenna 3 dBi. So, even without obstruction, the minimum received signal level could be as low as -138.5 dBm, corresponding to a 31.5 dB-Hz C/N_0.

Foliage Attenuation

Obstructions are objects that block, or partially obscure, the path between the GPS device and the GPS satellite. Table 1 shows the average attenuation (in dB) that occurs when the GPS signal passes through various tree types[10].

Table 1 – Average Foliage Attenuation by Tree Type

Tree Type	Average Attenuation (dB)
Willow	10.45
Pine	18.0
Linden	9.1
European Alder	7.0
Acacia	6.75
Poplar	3.5
Elm	9.0
Hazelnut	2.75
Maple	16.25
White Spruce	20.1
Laurel Cherry	12.0
Plane	16.9
Fir	12.75
Fruit	9.6
Mean	11.0

Average signal loss due to blockage by a tree ranges from 3.5 dB to 20.1 dB, with a mean of 11 dB. Tree blockage reduces the minimum received signal power with the 3 dBi reference antenna to the range from -148.6 dBm to -132 dBm, with a mean of -139.5 dBm. These received GPS satellite signal levels correspond to a C/N_0 range from 21.4 dB-Hz to 38 dB-Hz, with a mean of 30.5 dB-Hz.

Ionospheric Scintillation

Electron density irregularities in the ionosphere cause amplitude scintillation, a rapid variation in the amplitude of a RF signal. Ionospheric scintillation is associated with high levels of solar and geomagnetic activities. It results in power fluctuations of the received GPS signal. Scintillation effects are seasonal, and more significant in equatorial regions where they can cause 20 dB fades in the GPS signal. Near the polar caps, fades can reach 10 dB. Variability of delays through the ionosphere, and its impact on accuracy, is discussed in a later section.

[10] Julius Goldhirsh and Wolfhard J. Vogel, Handbook of Propagation Effects for Vehicular and Personal Mobile Satellite Systems – Overview of Experimental and Modeling Results, NASA Reference Publication 1274, Second Edition, January 3, 2001, Table 2-2.

Multipath Fading

Multipath fading occurs when GPS satellite signals reflect off of a building or the ground and find a second path to the GPS device. Depending on the relative amplitude and phases, fading can occur. More significant is the case where there is no direct path, only the reflected signal reaches the receiver. As only a portion of the signal is reflected, it is received with significant loss, especially in cases of double reflections.

Are There Other Things That Can Cause Changes in the Output C/N_0 Value?

Yes, there are. One of these in a phenomenon called "blocking," or "desensitization". Blocking occurs when a strong out-of-band signal is present at the GPS receiver input. It effectively increases the noise figure of the GPS device, resulting in higher effective input thermal noise, and hence lower C/N_0.

Another phenomenon is called "intermodulation." Intermodulation occurs when two signals mix due to a non-linearity inside of the GPS receiver. This mixing results in signals at the sum and difference of the input frequency harmonics. Intermodulation could result in two out-of-band signals mixing inside of the GPS receiver and generating in-band interference, effectively creating equivalent input interference power density, I_0. [11]

Over What Range of C/N_0's Can a GPS Device Operate

The GPS receivers embedded in all GPS devices perform two basic functions: acquiring GPS satellite signals, and tracking those GPS satellite signals after they have been acquired. Acquiring a GPS satellite signal is the process of searching for it in time and frequency dimensions, detecting the signal, pulling it in to reduce tracking errors, and finally demodulating the GPS satellite clock and ephemeris data it contains. Tracking a GPS satellite signal is the process of maintaining lock on the signal and generating GPS measurements. The tracking process can operate at lower signal levels than those required for acquisition.

Telit's JUPITER SE873 GNSS module (shown in Figure 3) is intended for use in fleet management systems, GPS-assisted road tolling systems, cellular base stations, in-car navigation systems, automotive telematics systems, and GPS-based personal sports training monitors. It is based on Qualcomm's SiRFstarV. The SE873 specified acquisition threshold is -146 dBm and its navigation threshold is -165 dBm[12]. Assuming a 2 dB noise figure, these translate to an acquisition threshold of 26 dB-Hz and a tracking threshold of 7 dB-Hz.

[11] The contribution of internal intermodulation is *indirect* and depends on the architecture of the GPS receiver. Improved frequency selectivity and linearity in the receiver's front end reduces the potential for intermodulation.

[12] http://www.telit.com/fileadmin/user_upload/products/Downloads/GNSS/se868aas/Telit_Jupiter_SE873_Datasheet.pdf

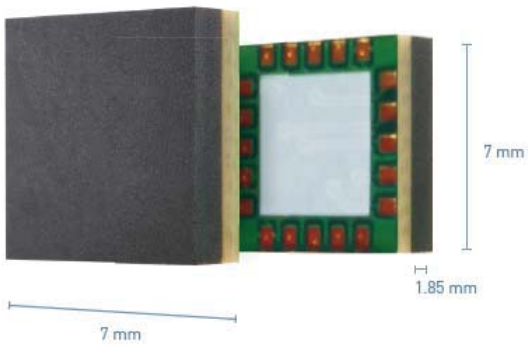


Figure 3 – Telit Jupiter SE873 GNSS Module

u-blox's CAM-M8 module (Figure 4) contains an embedded antenna. It targets industrial and consumer applications. Specified performance is -148 dBm for acquisition and -167 dBm for navigation[13]. Again, assuming a 2 dB noise figure, the acquisition threshold is 24 dB-Hz and the tracking threshold is 5 dB-Hz.

Figure 4 – u-blox CAM-M8 Module

Furuno's GN-8615 module (Figure 5) is targeted to automotive/industrial and consumer applications. The GN-8615's specified acquisition performance is -147 dBm and its specified navigation performance is -161 dBm. Assuming a 2 dB noise figure, these translate to a 25 dB-Hz acquisition threshold and a 11 dB-Hz navigation threshold.

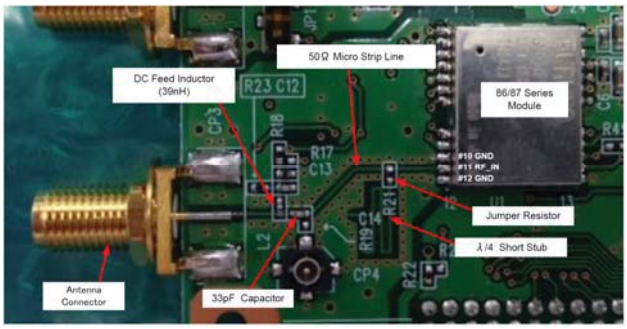


Figure 5 – Furuno GN-8615 Modulate on Circuit Board

For the three devices discussed, the acquisition threshold ranges from 24 to 26 dB-Hz, and the navigation threshold from 5 to 11 dB-Hz. The maximum received GPS satellite signal level of -120 dBm combined with

[13] https://www.u-blox.com/sites/default/files/CAM-M8_ProductSummary_%28UBX-13003595%29.pdf

a 2 dB noise figure results in a 52 dB-Hz C/N_0. Thus GPS devices can acquire GPS satellites signals over roughly a 25 dB C/N_0 range, and navigate over a roughly 45 dB C/N_0 range.

What is a KPI?

A Key Performance Indicator (KPI) is the appropriate metric for evaluating performance. In this context, the metric is "appropriate" since it correlates in a consistent way with outputs of the device. GPS is a PVT (Position/Velocity/Time) system. Thus, KPI's related to position, velocity, and time are appropriate as GPS KPI's. The Standard Positioning Service (SPS), which is the GPS service available to everyone, typically provides 10-meter positon accuracy, 10 cm/second (1/4th mile per hour) velocity accuracy, and 100 nanosecond time accuracy. GPS KPI's are metrics related to these PVT outputs. They fall into two categories – accuracy and response time. Metrics based on non-functional outputs, such as the number of GPS satellites being tracked or C/N_0 measurements, are only indirectly related to the PVT metrics. In isolation, they do not predict PVT performance.

Accuracy KPI's

Position accuracy, velocity accuracy, and time accuracy are the three GPS accuracy KPI's. While three-dimensional (3D) position accuracy, velocity accuracy, and time accuracy are critical to some GPS applications, by far, the vast majority of GPS devices are used for horizontal (2D) positioning. The more common GPS position accuracy KPI's are shown in Table 2. The third column provides conversion factors, assuming that the "1D" position errors have Gaussian distribution. The 68% and 98% horizontal accuracy metrics are favored by the cellular industry, while the 67% and 95% metrics are favored for GPS personnel navigation applications.

Table 2 – Horizontal Positon Error KPI's

KPI	Definition	Relative to 2DRMS
Circular Error Probable (CEP)	Radius of a circle centered at true position containing 50% of position estimates	0.84
2D Root Mean Square (2dRMS)	Square root of mean of squared horizontal errors	1
67% Horizontal Accuracy	Radius of a circle centered at true position containing 67% of position estimates	1.06
68% Horizontal Accuracy	Radius of a circle centered at true position containing 68% of position estimates	1.07
95% Horizontal Accuracy	Radius of a circle centered at true position containing 95% of position estimates	1.74
98% Horizontal Accuracy	Radius of a circle centered at true position containing 98% of position estimates	1.99

Response KPI's

A common GPS response time KPI is Time-to-First-Fix (TTFF). Three flavors of the TTFF KPI are often considered: cold start (factory or out-of-the-box start), warm start, and hot start. While there is no standardized test conditions for TTFF, typical conditions are[14]:

Cold Start: No almanac or ephemeris data, position is unknown, and time is unknown.

[14] http://www.spirent.com/go/What-is-GPS-Receiver-Testing

Warm Start: Almanac data, but no ephemeris data, position known to 100 km, and time know to 2 seconds.

Hot Start: Ephemeris data, position known to 100 km, and time known to 2 seconds.

Another related KPI is reacquisition time. This is the time it takes a receiver that was recently tracking and then lost all GPS signals, to output a valid fix. For example, when a car passes through a tunnel. All GPS signals are lost upon entering the tunnel, and reacquisition time is how long it takes for the GPS device to start outputting valid position after the car exits the tunnel.

Is There a Relationship Between Changes in Output C/N_0 Value and GPS Position Error KPI?

There is an indirect relationship between changes in output C/N_0 and GPS position error. GPS devices are designed to operate over large ranges of C/N_0. Depending on user dynamics and embedded oscillator stability, GPS devices can auto tune to ensure that tracking errors are relatively unchanged over large ranges of C/N_0. Furthermore, tracking errors are only one component of the PVT accuracy. The other components do not depend on C/N_0, and in typical operating scenarios, they dominate the tracking error component.

GPS position accuracy is a function of two factors: 1) the geometry of the GPS satellite constellation as seen from the user location, and 2) the measurement error in determining the pseudorange[15] from the user device to each of the GPS satellites. GPS is a trilateration system where the user device measures pseudorange to four GPS satellites and solves for 3D position and time.

The basic position accuracy equation for GPS is[16]:

$$\sigma_P = PDOP \times \sigma_{UERE}$$

Where σ_P is the position error standard deviation (m)

PDOP is the position dilution of precision

σ_{UERE} is the user equivalent range error standard deviation (m)

PDOP captures the impact of the GPS constellation geometry. It is computed from the elevation and azimuth angles from the GPS device location to each of the GPS satellites. PDOP can be separated into horizontal and vertical components, HDOP and VDOP. They are related by

$$PDOP = \sqrt{HDOP^2 + VDOP^2}$$

Assuming the baseline 24 satellite constellation, a 5° elevation mask angle, and that all satellites in view are included in the PVT solution, then HDOP ranges from 0.68 to 2.49. The average HDOP value is 0.96, and the 95th percentile value is 1.25.[17]

[15] Pseudorange is a measure of the range from the GPS device to the GPS satellite that also contains a time bias term converted to distance by multiplying times the speed of light.

[16] This equation assumes that the pseudorange errors are independent-and-identically-distributed zero-mean Gaussian random variables.

[17] GLOBAL POSITIONING SYSTEM STANDARD POSITIONING SERVICE PERFORMANCE STANDARD, 4th Edition, GPS SPS PS, September 2008

The horizontal and vertical position error standard deviations, σ_H and σ_V, are computed as:

$$\sigma_H = HDOP \times \sigma_{UERE}$$

and

$$\sigma_V = VDOP \times \sigma_{UERE}$$

The user equivalent range error standard deviation, σ_{UERE}, has three components:

1) The pseudorange inaccuracy due to the GPS signal-in-space (SIS). This includes effects from the GPS satellites and the GPS ground control system. The SIS performance is independent of the GPS user device and its local environment. The US government manages the SIS performance to a specification.
2) The pseudorange inaccuracy attributed to the GPS device and its local environment that are independent of C/N_0. These include multipath and tropospheric delay computation.
3) The measurement error made by the GPS device. The code tracking loop error is the major contributor. This error is sensitive to C/N_0.

In words, the user equivalent range error standard deviation is the root-sum-square (RSS) of the pseudorange inaccuracy standard deviations due to the signal-in-space and the local effects plus the C/A-code tracking error standard deviation. In equation form:

$$\sigma_{UERE} = \sqrt{{\sigma_{SIS}}^2 + {\sigma_L}^2 + {\sigma_{C/A}}^2}$$

Where σ_{SIS} is pseudorange inaccuracy standard deviation due to the SIS (m)

σ_L is the pseudorange inaccuracy standard deviation due to local effects (m)

$\sigma_{C/A}$ is the C/A-code tracking error standard deviation (m)

Table 3 shows the SIS error budget for the Standard Positioning Service (the commercial GPS service). The two columns correspond to two different AOD (age of data) conditions. AOD is the time since the Control Segment generated the satellite clock and ephemeris data currently being broadcast by the GPS satellite. Zero AOD represents the best case accuracy specification. In normal operation, the maximum AOD ranges from 8.5 hours to 26 hours, depending on the quality of the GPS satellite clock. The poorer the quality, the more often the data must be uploaded to maintain specified SIS performance. Max AOD represents the normal operations worst case accuracy specification. Also, note that a range is provided for the Control Segment Iono Delay Model Terms. This is the biggest contributor to the SIS error budget.

Table 3 – SPS SIS Error Budgets (m, 1-sigma)[18]

	Error Source	Zero AOD	Max. AOD
Space Segment	Clock Stability	0	4.45
	Group Delay Stability	1.55	1.55
	Diff'l Group Delay Stability	0	0
	Satellite Acceleration Uncertainty	0	1
	Other Space Segment Errors	0.5	0.5
Control Segment	Clock/Ephemeris Estimation	1	1
	Clock/Ephemeris Prediction	0	3.35
	Clock/Ephemeris Curve Fit	0.4	0.4
	Iono Delay Model Terms	4.9 - 9.8	4.9 - 9.8
	Group Delay Time Correction	2.25	2.25
	Other Control Segment Errors	0.5	0.5
	σ_{SIS} (m)	5.8 – 10.3	8.1 – 11.7

An error budget for the local effects is shown in Table 4.

Table 4 – Local Effects Error Budget[19]

Error Source	(m, 1-sigma)
Tropospheric Delay Compensation	1.95
Multipath	0.1
Other User Segment Errors	0.5
σ_L (m)	2.0

The GPS receiver C/A-code tracking error standard deviation is the one component of the position error that is a function of C/N_0. It is shown in the Appendix that it is also a function of the GPS receiver tuning parameters – code correlator spacing, predetection integration time, and code loop bandwidth. GPS receivers are typically capable of optimizing these parameters to reduce tracking errors. However, there is a trade-off, as the parameter sets that reduce tracking errors also require higher C/N_0 and reduce the dynamics capability of the receiver. This is similar to the way your car's engine control unit adjusts engine parameters to increase power output. The trade here is that the parameter sets that increase output power also reduce fuel economy and the time between trips to the repair shop.

Several example parameter sets are shown in Table 5.

[18] GLOBAL POSITIONING SYSTEM STANDARD POSITIONING SERVICE PERFORMANCE STANDARD, 4th Edition, GPS SPS PS, September 2008, page A-12.
[19] Ibid, page B-6.

Table 5 – Example Receiver Parameter Sets

Correlator Spacing (chips)	Integration Time (msec)	Code Loop Bandwidth (Hz)
0.5	1	1
0.5	4	0.3
0.25	4	0.3
0.25	20	0.1
0.1	20	0.1
0.1	20	0.01

Figure 6 plots the C/A-code tracking error standard deviation as a function of C/N_0 for each of the parameter sets in Table 5.

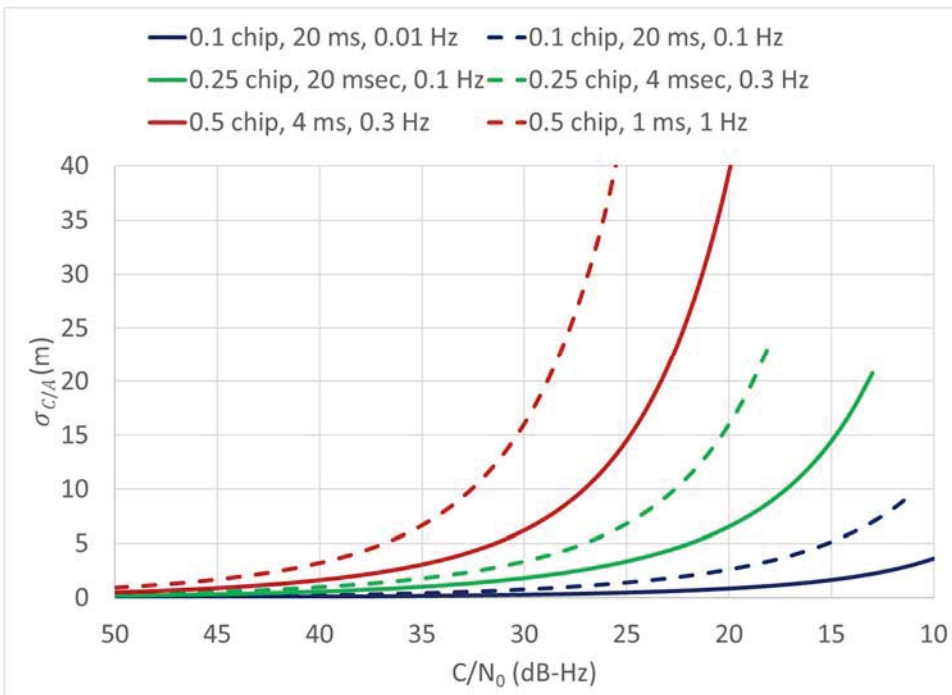


Figure 6 – Impact of C/N_0 Changes on $\sigma_{C/A}$

GPS receivers implement complex moding (mode changes) to cope with different C/N_0 conditions. Figure 7 shows how a GPS device might use moding to bound the code tracking error as C/N_0 decreases. Note that the lower tracking loop bandwidths, those used below 31 dB-Hz in this example, may not be consistent with higher dynamic applications.

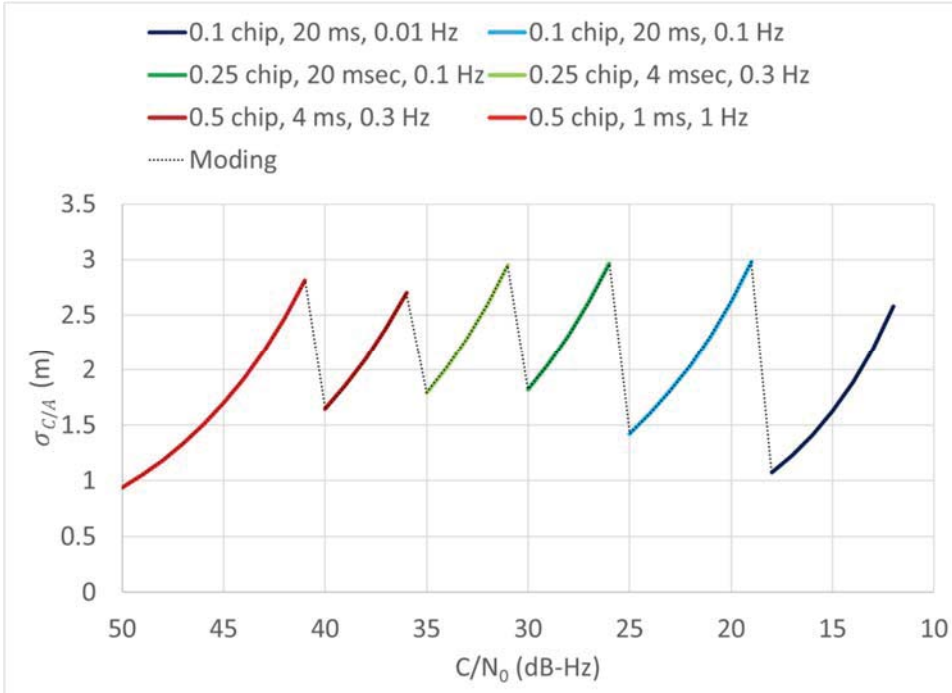


Figure 7 – Impact of C/N₀ Changes on $\sigma_{C/A}$ With Moding

For the first case in Table 5 (1/2-chip correlator spacing, 0.001 sec predetection integration time, and 1 Hz loop bandwidth) the C/A-code tracking error standard deviation at 40 dB-Hz C/N_0 is 3.2 m. Decreasing the C/N_0 by 1 dB to 39 dB-Hz increases the standard deviation to 3.7 m, a 15.6% increase. However, this is not the complete picture.

As discussed previously, the C/A-code tracking error standard deviation is only part of the accuracy picture. It is one of the components that must be combined using root-sum-square (RSS) to compute the user equivalent ranging error (UERE). Table 6 shows the impact of a 1-dB reduction in C/N_0 on UERE standard deviation – less than a 4% impact for all conditions.

Table 6 – Impact of 1 dB C/N₀ Reduction on σ_{UERE} at Zero AOD and Max AOD

	Zero AOD				Max AOD			
Iono Error	**Low**		**High**		**Low**		**High**	
C/N_0 (dB-Hz)	**40**	**39**	**40**	**39**	**40**	**39**	**40**	**39**
σ_{SIS} (m)	5.8	5.8	10.3	10.3	8.1	8.1	11.7	11.7
σ_L (m)	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
$\sigma_{C/A}$ (m)	3.2	3.7	3.2	3.7	3.2	3.7	3.2	3.7
σ_{UERE} (m)	6.92	7.16	10.97	11.13	8.94	9.13	12.29	12.43
σ_{UERE} Increase Due to 1-dB C/N_0 Reduction	0.24 m (3.5%)		0.16 m (1.4%)		0.19 m (2.1%)		0.14 m (1.1%)	

Figure 8 shows the UERE standard deviation as a function of C/N_0 for the third row of parameters from Table 5 for the four cases of SIS errors. Note that the σ_{UERE} is relatively insensitive to changes in C/N_0 over a broad range, and then experiences rapid growth until the tracking loop is unable to maintain lock.

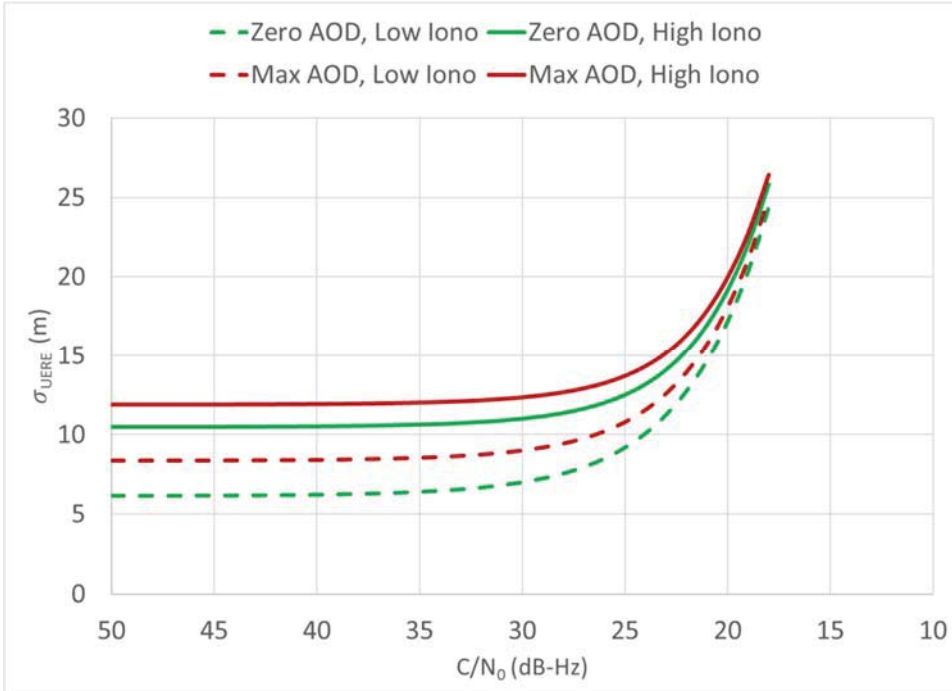


Figure 8 – σ_{UERE} as a Function of C/N₀ for ¼-chip, 4-msec, 0.3 Hz Parameters

Figure 9 shows the sensitivity of σ_{UERE} to a 1 dB reduction in C/N_0 for the same parameter set used in Figure 8. Note that there is less than a 1% change in UERE for a 1 dB reduction above 35 dB-Hz, for all four SIS cases. Less than a 10% change for a 1 dB reduction above 24 dB-Hz.

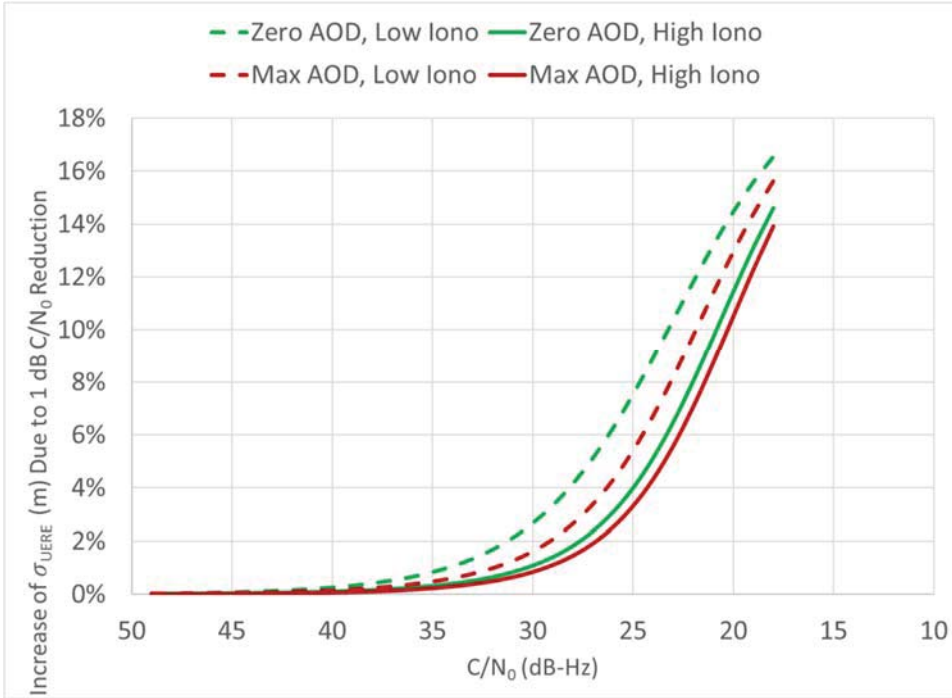


Figure 9 - Sensitivity of σ_{UERE} to 1 dB Reduction in C/N$_0$

Figure 10 shows σ_{UERE} versus C/N$_0$ using the same mode changes as in Figure 7. Clearly, a GPS device with the moding postulated in this paper is insensitive to changes in C/N$_0$, until the receiver is no longer able to change modes. Mode changes could be limited by the dynamics or oscillator quality. It is expected that most consumer GPS applications would at least allow operation with the first three modes, down to 31 dB-Hz.

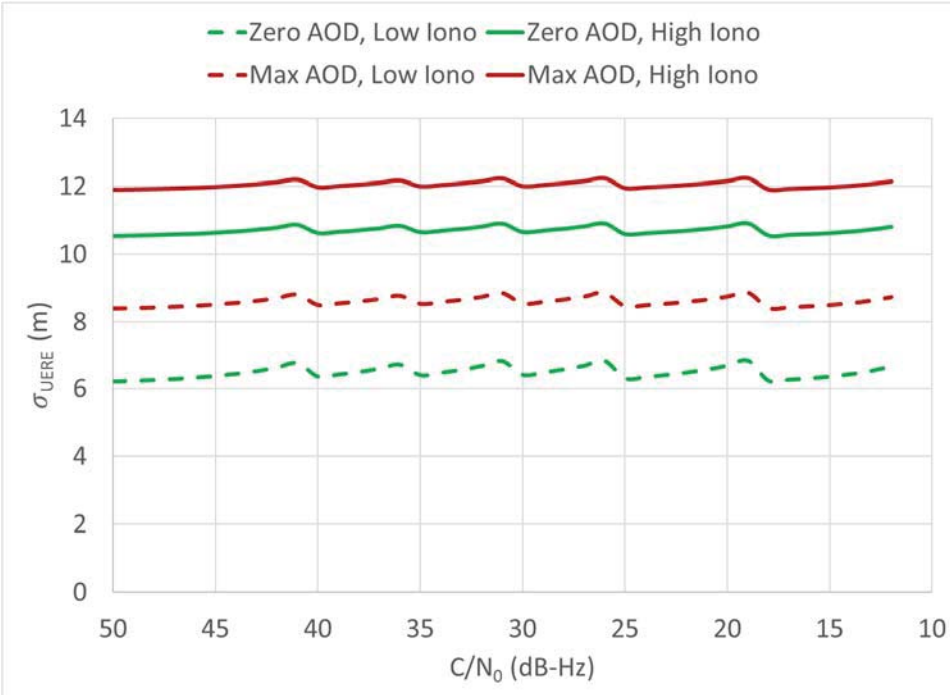


Figure 10 - σ_{UERE} as a Function of C/N₀ With Mode Changes

Figure 11 shows σ_{UERE} versus C/N_0 for an example of the mode changes being limited by user dynamics or oscillator quality. The first three modes shown in Figure 10 are used, demonstrating how the UERE eventually increases as C/N_0 decreases without the additional mode changes.

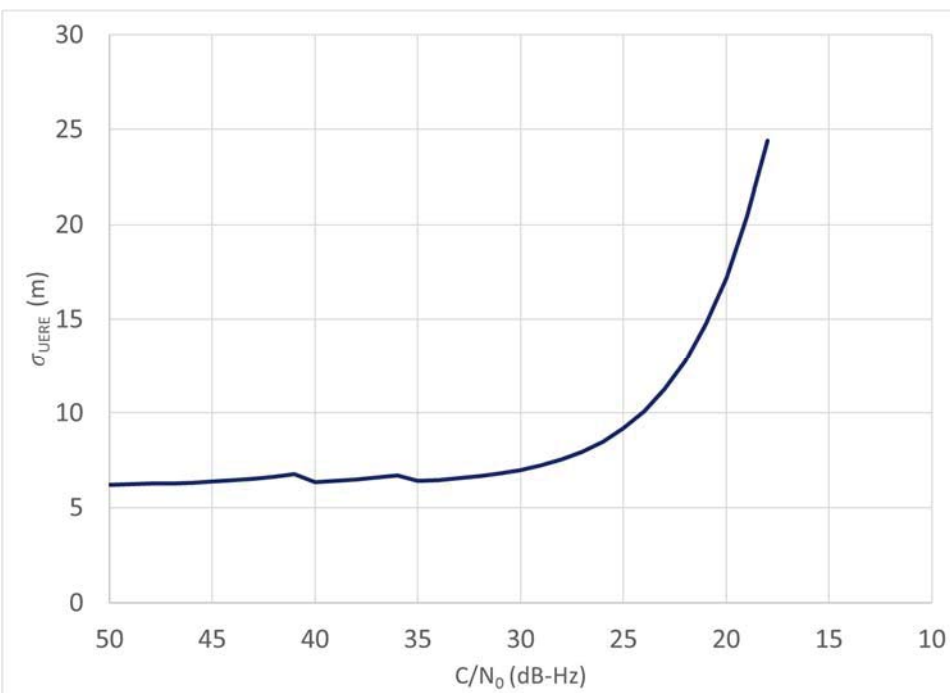


Figure 11 - σ_{UERE} as a Function of C/N₀ With Limited Mode Changes

Note that augmented GPS services such as DGPS, NDGPS, WAAS, LAAS, and CORS reduce the contributions of the SIS errors. This makes these services more sensitive to C/N_0 degradation.

Is There a Relationship Between Changes in Output C/N_0 Value and GPS Time to Fix KPI's?

Just as with position error, there is an indirect relationship between changes in output C/N_0 and GPS time-to-first-fix (TTFF). GPS devices are designed to operate over large ranges of C/N_0. While the dynamic range is not as great as for tracking, it is still substantial, around 25 dB. The lower limit on C/N_0 for acquisition is the required SNR to demodulate the 50 bps GPS satellite data. TTFF is the sum of several components: signal acquisition, tracking loop pull-in, and data demodulation (cold and warm starts). Collecting the satellite ephemeris and clock data requires 18 to 36 seconds, depending on when in the 30 second data frame the signal is acquired. This data collection time is independent of C/N_0, and typically dominates Cold Start and Warm Start TTFF.

Appendix – GPS Receiver C/A-Code Tracking Error

The GPS receiver C/A-code tracking error standard deviation can be estimated by[20]:

$$\sigma_{C/A} = L_C \sqrt{\frac{4d^2 B_L}{C/N_0}\left(2(1-d) + \frac{4d}{T\,C/N_0}\right)}$$

where

L_C is the code chip lenght (293 m for C/A-code)[21]
d is the code correlator spacing (fraction of a chip)
B_L is the code tracking loop bandwidth (Hz)
T is the predetection integration time (sec)
C/N_0 is the carrier-to-noise-density ratio (dB-Hz)

The code correlator spacing, code tracking loop bandwidth, and predetection integration time are tuning parameters of the GPS receiver. GPS receivers are typically capable of optimizing these parameters to reduce tracking errors. However, there is a trade-off, as the parameter sets that reduce tracking errors also require higher C/N_0 and reduce the dynamics capability of the receiver. This is similar to the way your car's engine control unit adjusts engine parameters to increase power output. The trade here is that the parameter sets that increase output power also reduce fuel economy and the time between trips to the repair shop.

From the above equation, it is seen that a GPS receiver can reduce the code tracking loop bandwidth and/or increase the predetection integration time to mitigate the effect of reduced C/N_0. Typically, these adjustments are made as needed to maintain good performance. There are limits as to how small the code tracking loop bandwidth can be set and as to how long the predetection integration time can be extended. The prediction integration time is typically limited by the 50 bps data rate to 20 msec[22]. The code tracking loop bandwidth is limited by the quality of the receiver oscillators and the carrier phase tracking errors. Hence there is a lower C/N_0 limit beyond which the receiver can no longer operate. Typically, a dynamic receiver might be limited to 0.3 Hz, while a static receiver with high quality oscillator could operate at 0.01 Hz. The code correlator spacing can also be adjusted to reduce tracking error. An added benefit is that reduced correlator spacing also reduces the effects of multipath.

[20] Fanchen Meng, et. al., "GNSS Reliability and Positioning Accuracy Enhancements Based on Fast Satellite Selection Algorithm and RAIM in Multiconstellation", IEEE Aerospace and Electronics Systems Magazine, Vol 30, No 15, October 2015.
[21] The duration of one C/A-code chip is 977.5 nanoseconds, multiplying by the speed of light gives 293 meters.
[22] Some GPS devices use a data bit aiding or prediction technique to allow longer predetection integration times, up to 100 msec, or even 200 msec, allowing operation down to 5 dB-Hz C/N_0 and below.

Before the
Federal Communications Commission
Washington, D.C. 20554

	)	
	)	IB Docket No. 11-109
In the Matter of	)	IBFS File Nos.
GPS Interference Indicators	)	SES-MOD-20151231-00981,
	)	SAT-MOD-20151231-00090, and
	)	SAT-MOD-20151231-00091

DECLARATION OF KENNETH ZDUNEK

1. My name is Kenneth Zdunek. I am Vice President and Chief Technology Officer of Roberson and Associates, LLC. I have worked at Roberson and Associates for nine years. I have over thirty-five years of experience designing, analyzing, and measuring the performance of wireless systems in both lab and operating environments.

2. Prior to joining Roberson and Associates, I was Vice President of Networks Research at Motorola for nine years. While at Motorola I was an architect of cellular and public safety wireless networks, and was awarded seventeen patents in the wireless field.

3. In 2009 I was elected a Fellow of the Institute of Electrical and Electronic Engineers, the highest grade of membership with the IEEE. I am a Registered Professional Engineer in the State of Illinois.

4. Concurrent with my position at Roberson and Associates, I am an Adjunct Professor in the Electrical and Computer Engineering Department at the Illinois Institute of Technology, where I do research in the areas of RF spectrum sharing, measuring and optimizing spectrum utilization, and cognitive radio. I have also taught graduate courses in wireless systems design.

5. I earned a Ph.D. in electrical engineering from the Illinois Institute of Technology and a MSEE and a BSEE degrees from Northwestern University.

6. Based on my thirty-five years of experience in this field, and my review of the Roberson and Associates data, I agree with the conclusions of the white paper authored by Mark Sturza, and know it to be true and relevant to the conclusions Roberson and Associates have reached independently via measurements on actual GPS receivers. C/N_0 is a measure of GPS signal power relative to thermal noise power spectral density. C represents the measure of the desired GPS signal power at the GPS receiver input. This value varies naturally regardless of noise or interference. N_0 is the equivalent thermal noise power spectral density at the GPS receiver input. Therefore, even without any variation in N_0, changes in C/N_0 values result from a variety of natural sources, including blockage of satellite signals from foliage or urban canyons.

7. The value of C/N_0 measured by an actual GPS receiver is decreased by interference in-band to GPS signals, and can also be decreased by signals in frequency bands adjacent to GPS signals but within the GPS receiver passband, and strong enough to cause receiver overload. Consequently, C/N_0 as measured by a GPS receiver can be decreased by both in-band interference and strong adjacent band signals.

8. The mathematical analysis in the Sturza white paper shows that, independent of a specific GPS receiver design, a 1 dB change in C/N_0 does not necessarily imply that a GPS position calculation results in a noticeable error from the true position. Due to this aspect of GPS position calculation, there may not be an impact on position error until the change in the C/N_0 is significantly greater than 1 dB. This is illustrated by the “hockey stick effect” shown in the graphs in the Sturza white paper.

9. Consistent with Sturza white paper, practical GPS devices are therefore able to be designed to operate without noticeable position error impact over ranges of C/N_0 values that vary significantly greater than 1 dB.

10. Based on my thirty-five years of experience in mobile communications and networking and my review of the Roberson and Associates measurement data, changes in the C/N_0 values output by a GPS device are not a reliable indicator of impact on GPS key performance indicators, because key indicators are related to the position, velocity, and time functional outputs of the device, whereas changes in the C/N_0 outputs of a device are not a user functional output. Furthermore, the C/N_0 output of a device is only an estimate of the actual C/N_0 level at the input to the GPS receivers. Changes in C/N_0 in isolation do not predict position, velocity, and time functional performance.

11. It is my opinion that the mathematical evidence offered in the Sturza white paper is true and describes the limited impact that changes in C/N_0 have on GPS device performance. This is consistent with, and supports the conclusions that Roberson and Associates reached independently in their evaluation of various GPS devices.

Signed: ____/s/_____

Kenneth Zdunek

Date: June 6, 2016