SECTION 3.0
ANALYSIS OVERVIEW

3.1 ANALYSIS DESCRIPTION

The measurements performed by the ITS define the GPS receiver interference threshold for a UWB waveform as a function of the UWB signal parameters (e.g., power, PRF, gating, modulation). The interference threshold is measured at the input of the GPS receiver and is used in the analysis for each specific GPS/UWB operational scenario to calculate the maximum allowable emission level at the output of the UWB device antenna. This section of the addendum report describes the analysis method used.

The maximum allowable emission level from the UWB device is based on an EIRP limit. The EIRP is the power supplied to the antenna of the UWB device multiplied by the relative antenna gain of the UWB device in the direction of the GPS receiver. The maximum allowable EIRP is computed using the following equation:

$$EIRP_{max} = I_T - G_r + L_p - L_{mult} - L_{allot} - L_{man} + L_{AF} + L_{BA} + L_{align} - L_{safety} \qquad (1)$$

where:

$EIRP_{max}$ is the maximum allowable EIRP of the UWB device (dBW or dBW/MHz);
I_T is the interference threshold of the UWB signal at the input of the GPS receiver (dBW or dBW/MHz);
G_r is the gain of the GPS antenna in the direction of the UWB device (dBi);
L_p is the radiowave propagation loss (dB);
L_{mult} is the factor to account for multiple UWB devices (dB);
L_{allot} is the factor for interference allotment (dB);
L_{man} is the factor to account for manufacturer variations in GPS receivers (dB);
L_{AF} is the activity factor of the UWB device (dB);
L_{BA} is the building attenuation loss (dB);
L_{align} is the factor for UWB device antenna alignment (dB);
L_{safety} is the aviation safety margin (dB).

The following paragraphs explain each of the technical factors used in the analysis.

3.1.1 UWB Interference Threshold (I_T)

The UWB interference threshold referenced to the input of the GPS receiver is obtained from the single source interference susceptibility measurements performed by ITS as discussed in Section 2.1.1 (Tables 2-2 and 2-3). Adjustments are made to the measured interference susceptibility levels to compute the UWB interference threshold. As discussed in Section 3.3 (Tables 3-13 and 3-14), the adjustments made to the measured interference susceptibility levels are based on the individual UWB signal structure.

3.1.2 GPS Receive Antenna Gain (G_r)

The GPS receive antenna gain model used in this analysis is provided in Table 3-1. The antenna gain used is based on the position of the UWB device with respect to the GPS antenna and is determined from the GPS/UWB operational scenario under consideration.

TABLE 3-1. GPS Antenna Gain Based on UWB Device Position With Respect to GPS Antenna

Off-axis Angle (Measured with Respect to the Horizon)	GPS Antenna Gain (dBi)
-90 degrees to -10 degrees	-4.5
-10 degrees to 10 degrees	0
10 degrees to 90 degrees	3

The off-axis angle measured with respect to the horizon is computed by:

$$\theta = \tan^{-1} [(h_{UWB} - h_{GPS})/D] \qquad (2)$$

where:

θ is the off-axis angle measured with respect to the horizon (degrees);
h_{UWB} is the UWB device antenna height (m);
h_{GPS} is the GPS receiver antenna height (m);
D is the horizontal separation between the GPS receiver and UWB device (m).

3.1.3 Radiowave Propagation Loss (L_p)

The radiowave propagation loss is computed using the minimum distance separation between the GPS receiver and the UWB device as defined by the GPS/UWB operational scenario. The radiowave propagation model used also depends on the GPS/UWB operational scenario. By definition, "free-space" assumes that there is a line-of-sight (LOS) path between the UWB device and the GPS receiver. The radiowave propagation model described by the free-space loss equation is :

$$L_p = 20 \text{ Log } F + 20 \text{ Log } D_{min} - 27.55 \qquad (3)$$

where:

L_p is the free-space propagation loss (dB);
F is the frequency (MHz);
D_{min} is the minimum distance separation between the GPS receiver and UWB device (m).

As a result of antenna heights and terrain conditions, free-space conditions may not exist. There is a phenomenon referred to as the propagation loss breakpoint, which consists of a change in the slope of the propagation loss versus distance curve at a radial distance from the transmitter. It is caused by the reflection of the transmitted signal by the ground. This multipath signal can combine constructively or destructively with the direct path signal and usually occurs only in areas with clear LOS and ground reflection paths.

For the frequency range of interest, the propagation loss changes by 20 dB/decade (i.e., free-space loss) at distances close to the transmitter, and by 40 dB/decade after the propagation loss breakpoint occurs. The propagation loss breakpoint radius from the transmitter, R_b, is calculated using the formula:[44]

$$R_b = 2.3x10^{-6} F (h_t h_r) \qquad (4)$$

where:

R_b is the propagation loss breakpoint radius (mi);
F is the frequency (MHz);
h_t is the UWB device antenna height (ft);
h_r is the GPS receiver antenna height (ft).

When the minimum distance separation between the UWB device and the GPS receiver is less than R_b, the free-space propagation model should be used. When the minimum distance separation between the UWB device and the GPS receiver is greater than R_b, a propagation model that takes into account non-LOS conditions should be used.

3.1.4 Multiple UWB Devices (L_{mult})

The GPS/UWB operational scenario determines whether single or multiple UWB devices should be considered. The factor for multiple UWB devices was obtained from the multiple source (aggregate) measurements performed by ITS. Section 2.1.2 of NTIA Report 01-45, discusses the multiple UWB devices measurement results.[45] Based on the multiple source measurements, the factor to be included in the analysis for multiple UWB devices will depend on whether the interference effect has been characterized as being pulse-like, CW-like, or noise-like. The exception is the en-route navigation operational scenario, where it is assumed that there are a large enough number of UWB devices, such that independent of the individual UWB signal parameters, the aggregate effect causes noise-like interference.

[44] E. N. Singer, *Land Mobile Radio Systems* (Second Edition) at 194.

[45] NTIA Report 01-45 at 2-5.

As discussed in Section 2.2.3 of NTIA Report 01-45, signals that were characterized as being pulse-like for single UWB device interactions were characterized as being noise-like when multiple UWB devices are considered.[46] The occurrence of the transition from pulse-like to noise-like interference was verified in Measurement Case V.[47] The number of UWB devices required for this transition to occur depends on the PRF. For the 1 MHz PRF signals, the measurements show that three UWB signals are required for the transition to occur. In the case of the 100 kHz PRF signals, the number of UWB devices necessary for the transition to occur will be much larger than the number of UWB devices under consideration in the operational scenarios. Based on the measurement results, a factor for multiple UWB devices is not included in this analysis for signal permutations that have been characterized as causing pulse-like interference with a PRF of 100 kHz.

The interference effect for UWB signals that have been characterized as being CW-like is attributed to the single interfering CW line that is coincident with a dominant C/A-code line. This was discussed in Section 2.2.3 of NTIA Report 01-45, and confirmed in Measurement Cases III and IV.[48] Multiple UWB signals that are characterized as causing CW-like interference, do not add to determine the effective interfering signal power. A large number of UWB devices producing spectral lines would be necessary before there is a transition to a noise-like interference effect. This transition from CW-like to noise-like will not occur with the number of UWB devices under consideration in the operational scenarios. Based on the measurement results, a factor for multiple UWB devices is not included in this analysis for UWB signal permutations that have been characterized as causing CW-like interference.

UWB signals permutations with PRFs of 1 MHz, 5 MHz, and 20 MHz that have been characterized as being pulse-like, will transition to noise-like interference as the number of UWB devices is increased. This is discussed in Section 2.2.3 of NTIA Report 01-45 and verified in Measurement Case V.[49] For these UWB signal permutations, a factor of 10 Log (number of UWB devices) is included in the analysis.

As discussed in Section 2.2.3 of NTIA Report 01-45, and verified in Measurement Case I and II, if the individual signals cause an interference effect that is noise-like, the interference effect of the multiple noise-like signals is noise-like.[50] Based on the measurement results, for UWB signal permutations that have been characterized as causing noise-like interference, a factor of 10 Log (number of UWB devices) is included in the analysis.

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[46] *Id.* at 2-15.

[47] *Id* at 2-17.

[48] *Id.*

[49] *Id.*

[50] *Id.*

3.1.5 Interference Allotment (L_{allot})

In addition to the potential interference from UWB devices, several other potential sources of interference to GPS receivers have been identified. These potential sources of interference include but are not limited to: 1) adjacent band interference from mobile satellite service (MSS) handsets; 2) harmonics from television transmitters; 3) adjacent band interference from super geostationary earth-orbiting (super GEO) satellite transmitters[51]; 4) spurious emissions from 700 MHz public safety base, mobile, and portable transmitters; and 5) spurious emissions including harmonics from 700 MHz commercial base, mobile, and portable transmitters. Multiple sources of interference, which might individually be tolerated by a GPS receiver, may combine to create an aggregate interference level (e.g., noise and emissions) that could prevent the reliable reception of the GPS signal. In the GPS/UWB operational scenarios, a percentage of the total allotment for all interfering sources is attributed specifically to UWB devices.

In this analysis the percentage of the total interference allotment that is attributed to UWB devices is dependent on the minimum distance separation between the GPS receiver and the UWB device. The minimum distance separation is established by each operational scenario. For operational scenarios where the minimum distance separation is small (e.g., on the order of several meters), the UWB device is expected to be the dominant source of interference, and 100% of the total interference budget is allotted to the UWB device. For operational scenarios where a larger distance separation exists, there is a greater likelihood that other interfering sources will contribute to the total interference level at the GPS receiver. In these operational scenarios, 50% of the total interference budget is allotted to UWB devices. That is, one half of the total allowable interference is allotted to UWB and the other half is allotted to all other interfering sources combined. For the aviation operational scenarios, larger geographic areas are visible to a GPS receiver onboard an aircraft at altitude. This larger field of view will increase the number of interfering sources that can contribute to the total interference level at the receiver. In the aviation operational scenarios, 10% of the total interference budget is allotted to UWB devices. The factor for UWB device interference allotment is computed from 10 Log (UWB interference allotment ratio). For example, if the UWB device interference allotment is 50% (a ratio of 0.5), a 3 dB factor is included in the analysis.

3.1.6 GPS Receiver Variation (L_{man})

A 2001 GPS Receiver Survey lists 64 different manufacturers of GPS receivers.[52] The survey lists approximately 500 different models of GPS receivers representing the C/A code, semi-codeless, and narrowly-spaced correlator receiver architectures. The results in NTIA Report 01-45 and this addendum consider four different GPS receivers. Based on the measured data that

[51] Super GEOs are geostationary earth orbiting satellites that are designed to employ a high transmit power to communicate with mobile handsets.

[52] *GPS World Receiver Survey*, GPS World Magazine (Jan. 2001) at 32.

is part of the public record in this proceeding and that are presented in this addendum, a trend has emerged regarding the interference effects of UWB signals on the different GPS receiver architectures. However, the number of different models of GPS receivers and manufacturers considered in the current measurement efforts may not completely represent the performance of all of the GPS receivers currently being manufactured. Ignoring the hardware differences in the GPS receivers, differences also exist in firmware[53] and software (e.g., tracking and acquisition algorithms) employed in the receivers which were not considered in the three measurements efforts.

There will be differences between receivers produced by different manufacturers as well as differences in the models produced by the same manufacturer. Therefore, the inclusion of a factor in the analysis to account for these possible differences is reasonable. Moreover, one of the main conclusions in the JHU/APL report states[54]:

> *Variations in the measures of performance due to different GPS receivers are greater than those due to the operating modes of the UWB tested devices. The impact of UWB devices on all GPS receivers cannot be assessed using a single GPS receiver.*

As shown in Table 2-8, the range of data indicates that the more susceptible interference thresholds (e.g., lower values) are within 3 dB of the median. Therefore, the value of 3 dB used in this analysis for GPS receiver variation is appropriate.

3.1.7 UWB Device Activity Factor (L_{AF})

The activity factor represents the percentage of time that the UWB device is actually transmitting. For example, a UWB device that is transmitting continuously will have an activity factor of 100%, no matter what PRF, modulation, or gating percentage is employed. The activity factor is only applicable when a large number of UWB devices are considered in the GPS/UWB operational scenario. Some UWB devices are expected to have inherently low activity factors such as those that are manually activated with a trigger or "deadman" switch. Others will likely have high activity factors such as a UWB local area network. Since it is not possible to estimate practical values of activity factors for each potential UWB application, an activity factor of 100% (a ratio of 1) is used in all of the operational scenarios considered in this analysis. Thus, the activity factor used is set equal to 0 dB (i.e., 10 Log (1)).

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[53] Firmware is software installed in a device that is typically stored in a read only memory (ROM) or programmable read only memory (PROM).

[54] JHU/APL Report at ES-2.

3.1.8 Building Attenuation (L_{BA})

For GPS/UWB operational scenarios that consider the use of UWB devices operating indoors, a building attenuation factor is included in the analysis. ITS has conducted building attenuation loss measurements at 912, 1920, and 5990 MHz.[55] The measurements were performed for different buildings representing typical residential and high rise office construction. Based on the results of these measurements, whenever the UWB device is considered to be operating indoors an average building attenuation of 9 dB is used in the analysis.

3.1.9 UWB Device Antenna Alignment (L_{align})

The mainbeam of the UWB device antennas considered in the analysis are assumed to be pointing at the GPS antenna. This means that there is no reduction in the UWB device antenna gain to address the alignment of the UWB device antenna. In general this is a valid analysis assumption because of the unknown antenna characteristics and locations of the UWB devices. This analysis assumption is further supported if the UWB devices employ omnidirectional antennas. Omnidirectional antennas provide essentially uniform coverage in the horizontal direction and the vertical direction for low elevation angles. This means that for the land-based (terrestrial, maritime, railway, surveying) operational scenarios the antenna gain of the UWB device in the direction of the GPS antenna is essentially constant. Moreover, these operational scenarios only consider a small number of UWB devices. A similar situation exists for a low altitude aircraft such as that considered in the non-precision approach operational scenario. However, at higher elevation angles, the coverage of an omnidirectional antenna is not uniform in the vertical direction. Since the aircraft altitude considered in the en-route navigation operational scenario is 1000 feet it will be at a high elevation angle relative to the UWB device located on the ground. Also at this altitude larger geographic areas and higher densities of UWB devices will be visible to the GPS receiver onboard the aircraft. Therefore, in the en-route operational scenario it is appropriate to include a factor to take into account the alignment of the UWB device antennas. Based on the pattern of a typical vertical dipole omnidirectional antenna, a factor of 2 dB is included in the analysis of the en-route navigation operational scenario for UWB device antenna alignment.

3.1.10 Aviation Safety Margin (L_{safety})

When the GPS/UWB operational scenario involves aviation applications using GPS (i.e., en-route navigation and non-precision approach landing) inclusion of a safety margin is appropriate. The aviation safety margin is used to account for uncertainties on the aviation side of the link budget that are real but not quantifiable, which include but are not limited to:

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[55] NTIA Report 95-325, *Building Penetration Measurements From Low-height Base Stations at 912, 1920, and 5990 MHz*, National Telecommunications and Information Administration, Institute for Telecommunication Sciences (Sept. 1995), at 43.

multipath of the GPS signal; receiver implementation losses; antenna gain variations; and approach path deviation. Since the GPS signal level cannot be increased, the aviation safety margin is implemented by lowering the allowable interference. A safety margin of 6 dB is included in the analysis for GPS receivers used in aviation applications.[56] The aviation safety margin included in this analysis is consistent with the value specified in ITU-R Recommendation M.1477.[57]

3.1.11 GPS Receiver Architecture

Interference susceptibility measurements reported in this addendum, were performed on a GPS receiver employing narrowly-spaced correlator architecture and a TSO-C129a compliant GPS receiver employing the C/A code architecture. The GPS receiver architecture examined in the analysis are different depending upon the operational scenario under consideration. In all operational scenarios, with the exception of the aviation operational scenarios, measured data for the narrowly-spaced correlator architecture was used. In the non-precision approach and en-route navigation aviation operational scenarios, measured data for the TSO-C129a compliant GPS C/A code receiver architecture was used.

3.2 DEVELOPMENT OF THE GPS/UWB OPERATIONAL SCENARIOS

As discussed in the previous section, the measurements of the maximum tolerable interference threshold at the input to the GPS receiver is used in this analysis to compute the maximum allowable EIRP of the UWB device. The operational scenario is necessary to relate the interference level at the input of the GPS receiver to the output of the UWB device. The GPS/UWB operational scenarios establish: the minimum distance separation between the GPS receiver and the UWB device; the appropriate antenna coupling; the applicable radio wave propagation model; whether single or multiple UWB devices should be considered; and any other scenario specific factors (e.g., building attenuation and aviation safety margin).

On August 31, 2000, NTIA published a notice in the Federal Register announcing a series of public meetings to be held to gather information to be used by NTIA in developing the operational scenarios for assessing the potential interference to GPS receivers from UWB devices.[58] Meetings were held on September 7 and 27, and December 7 giving the Federal agencies and the public opportunities to present documents related to the development of GPS/UWB operational scenarios. Documents were submitted by: Multispectral Solutions Inc., the National Oceanic and Atmospheric Administration/National Ocean Science/National

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[56] The 6 dB aviation safety margin results in only a 2.5 dB margin in C/N+I, which is a critical GPS receiver performance parameter.

[57] ITU-R M.1477 at Annex 5.

[58] NTIA Notice at 1.

Geodetic Survey, NTIA, Time Domain Corporation, the USCG, and the U.S. GPS Industry Council. The specific proposals for operational scenarios included GPS receivers used in the following applications:[59]

- Public Safety (E-911 embedded in a cellular phone);
- Public Safety (emergency response vehicles);
- Geographic Information Systems;
- Precision Machine Control;
- Maritime (constricted waterway navigation, harbor navigation, docking and lock operations;)
- Railway (positive train control (PTC));
- Surveying;
- Aviation (en-route navigation and non-precision approach landings).

In addition to these specific GPS/UWB operational scenarios, NTIA proposed a general operational scenario for GPS receivers used for terrestrial applications that considered multiple UWB device interactions.

As a result of the three public meetings, five categories of GPS applications are considered in the development of the GPS/UWB operational scenarios: terrestrial, maritime, railway, surveying, and aviation. The operational scenario proposals also considered several UWB device applications. The UWB device applications include: embedded functions in a mobile phone, wireless local area networks, short-range communication systems, and intrusion-detection devices.

3.2.1 Terrestrial Applications

The specific operational scenario proposals for the terrestrial use of GPS receivers include: public safety, geographic information systems, and precision machine control.[60] The operational scenario proposals for terrestrial GPS receivers are all based on a minimum distance separation between the GPS receiver and UWB device of 2 meters. Although this minimum distance separation may in some cases be applicable for assessing interference from a single UWB device, it is not applicable when assessing interference to GPS receivers from multiple UWB devices (10 meter minimum distance separation). Both single UWB device and multiple UWB device operational scenarios for terrestrial applications are considered in this analysis.

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[59] All of the documents from the public meetings are available upon request from the NTIA Office of Spectrum Management or from the NTIA website.

[60] U.S. GPS Industry Council Submission to NTIA GPS/UWB Operational Scenario Meeting (Sept. 7, 2000).

3.2.1.1 Single UWB Device

In the terrestrial operational scenario where a single UWB device interaction is considered, a minimum distance separation between the GPS receiver and the UWB device of 2 meters is used. At a minimum distance separation of 2 meters, it is appropriate to only consider the outdoor operation of UWB devices (i.e., no additional losses for building attenuation).

In the single UWB device terrestrial operational scenario, an antenna height of 3 meters is used for the GPS receiver and the UWB device. Based on the antenna model provided in Table 3-1, the antenna gain for the GPS receiver used in this operational scenario is 0 dBi.

For the GPS receiver and UWB device antenna heights of 3 meters, the expected propagation loss breakpoint radius is 568 meters. Since the minimum distance separation is much less than the expected propagation loss breakpoint radius, the free-space propagation model is applicable.

A summary of the technical factors associated with the single UWB device terrestrial operational scenario is provided in Table 3-2.

TABLE 3-2. Technical Factors for the Single UWB Device Terrestrial Operational Scenario

Technical Factors	Value
GPS Receiver Antenna Gain	0 dBi
GPS Antenna Height	3 meters
UWB Device Antenna Height	3 meters
Minimum Distance Separation	2 meters
Propagation Model	Free-space
Interference Allotment to UWB Devices	0 dB (100%)
Variations in GPS Receivers	3 dB
Multiple UWB Devices	1 UWB device
Activity Factor for Each UWB Device	0 dB (100%)
Building Attenuation	0 dB
GPS Receiver Architecture	Narrowly-Spaced Correlator

3.2.1.2 Multiple UWB Devices

After reviewing the operational scenario proposals it is clear that the use of GPS for terrestrial applications is extremely diverse. This makes it difficult to identify a single representative operational scenario to be used in assessing the potential interference to terrestrial GPS receivers from multiple UWB devices. At the December 7, 2000 GPS/UWB operational scenario meeting NTIA presented an operational scenario proposal that considered interference to a terrestrial GPS receiver from multiple UWB devices.[61] In the analysis of multiple UWB devices both indoor and outdoor operation of UWB devices is considered.

In the multiple UWB device terrestrial operational scenario, a minimum distance separation of 10 meters was established between the GPS receiver and each UWB device that is used outdoors. This was the distance separation that was presented at the GPS/UWB operational scenario meeting and is reasonable to use when multiple UWB devices are being considered. For indoor operation, the UWB device is positioned above the GPS receiver (e.g., second floor of a building). The minimum distance separation is computed from the slant range with the GPS receiver located 5 meters from the building and the UWB device 10 meters above the GPS receiver. The following equation is used to compute the minimum distance separation:

$$D_{min} = ((h_{GPS} - h_{UWB})^2 + D^2)^{0.5} \qquad (5)$$

where:

h_{GPS} is the height of the GPS receiver antenna (m);
h_{UWB} is the height of the UWB device antenna (m);
D is the horizontal separation between the GPS receiver and UWB device antennas (m).

Based on the model given in Table 3-1 the antenna gain for the GPS receiver is 0 dBi and 3 dBi for outdoor and indoor operation of UWB devices respectively.

For a distance separation of 10 meters it is reasonable to consider an interaction with multiple UWB devices. Four UWB devices each located 10 meters from the GPS receiver are considered in this operational scenario.

Based on the established operational scenario an antenna height of 3 meters for the GPS receiver is used. An antenna height of 3 meters (outdoor operation) and 10 meters (indoor operation) is used for the UWB devices. Using these antenna heights the expected propagation loss breakpoint radii are 568 meters for UWB devices with a 3 meter antenna height and 1.9 kilometers for UWB devices with a 10 meter antenna height. Since the distance separation used in the multiple UWB general terrestrial operational scenario is less than the expected propagation loss breakpoint radii, the free-space propagation model is applicable.

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[61] National Telecommunications and Information Administration, *Proposal for a General Operational Scenario for Assessing Potential Interference to Terrestrial Global Positioning System Receivers from Ultrawideband Transmission Systems* (Dec. 7, 2000).

A summary of the technical factors associated with the multiple UWB device terrestrial operational scenario is provided in Table 3-3.

TABLE 3-3. Technical Factors for the Multiple UWB Device Terrestrial Operational Scenario

Technical Factors	Value	
	Outdoor UWB Device Operation	Indoor UWB Device Operation
GPS Receiver Antenna Gain	0 dBi	3 dBi
GPS Antenna Height	3 meters	3 meters
UWB Device Antenna Height	3 meters	10 meters
Minimum Distance Separation	10 meters	8.6 meters
Propagation Model	Free-space	Free-space
Interference Allotment to UWB Devices	(3 dB) 50%	3 (dB) 50%
Variations in GPS Receivers	3 dB	3 dB
Multiple UWB Devices	4 UWB devices	4 UWB devices
Activity Factor for Each UWB Device	0 dB (100%)	0 dB (100%)
Building Attenuation	0 dB	9 dB
GPS Receiver Architecture	Narrowly-Spaced Correlator	

3.2.2 Maritime Applications

The operational scenario proposals for the maritime use of GPS receivers include: navigation in constricted waterways, harbor navigation, docking operations, navigation around bridges, and lock operations.[62] The USCG has indicated that the limiting operational scenario for maritime applications is when the GPS receiver is used for navigation in constricted waterways. In this analysis, indoor and outdoor UWB device operation is considered.

In the two operational scenario proposals for navigation in constricted waterways, the GPS receiver antenna is assumed to be mounted on the mast of the vessel. Therefore, the minimum distance separation has both a horizontal and vertical component. The minimum distance separation between the GPS receiver and the UWB device is computed from the slant range using Equation 5.

[62] United States Coast Guard Navigation Center Submission to NTIA GPS/UWB Operational Scenario Meeting (Sept. 27, 2000).

The first restricted waterway operational scenario implementation uses an antenna height of 45 feet (13.5 meters) and a horizontal separation from the UWB devices of 125 feet (37.5 meters). The second implementation uses an antenna height of 25 feet (7.5 meters) and a horizontal separation from the UWB devices of 170 feet (51 meters). An antenna height of 3 meters (outdoor operation) and 10 meters (indoor operation) is used for the UWB devices. The computed minimum distance separations for the two implementations in the maritime navigation, constricted waterways operational scenario are given in Table 3-4.

TABLE 3-4. Minimum Distance Separations for the Maritime Navigation in Constricted Waterways Operational Scenario

GPS Receiver Antenna Height (Meters)	UWB Device Antenna Height (Meters)	Minimum Distance Separation (Meters)
13.5	3	38.9
7.5	3	51.2
13.5	10	37.7
7.5	10	51.1

For these minimum distance separations it is reasonable to consider multiple UWB devices. Four UWB devices each located at the minimum distance separations are considered in the maritime navigation in constricted waterways operational scenario.

Based on the model given in Table 3-1, when the off-axis angle is greater than -10 degrees the GPS antenna gain in the direction of the UWB device is 0 dBi. When the off-axis angle is less than -10 degrees the USCG has specified that the GPS antenna gain in the direction of the UWB device is -3 dBi.

Based on the GPS receiver antenna heights and the UWB device antenna heights the expected propagation loss breakpoint radii are computed and given in Table 3-5. Since the computed minimum distance separations are much less than the expected propagation loss breakpoint radii the free-space propagation model is applicable.

TABLE 3-5. Expected Propagation Loss Breakpoint Radii for the Maritime Navigation in Constricted Waterways Operational Scenario

GPS Receiver Antenna Height (Meters)	UWB Device Antenna Height (Meters)	Propagation Loss Breakpoint Radii (Kilometers)
13.5	3	2.5
7.5	3	1.4
13.5	10	8.5
7.5	10	4.7

A summary of the technical factors associated with the maritime navigation in constricted waterways operational scenario is provided in Table 3-6.

TABLE 3-6. Technical Factors for the Navigation in Constricted Waterways Operational Scenario

Technical Factors	Value	
	Outdoor UWB Device Operation	Indoor UWB Device Operation
GPS Receiver Antenna Gain	-3 and 0 dBi	0 dBi
GPS Antenna Height	13.5 and 7.5 meters	13.5 and 7.5 meters
UWB Device Antenna Height	3 meters	10 meters
Minimum Distance Separation	38.9 and 51.2 meters	37.7 and 51.1 meters
Propagation Model	Free-space	Free-space
Interference Allotment to UWB Devices	3 dB (50%)	3 dB (50%)
Variations in GPS Receivers	3 dB	3 dB
Multiple UWB Devices	4 UWB devices	4 UWB devices
Activity Factor for Each UWB Device	0 dB (100%)	0 dB (100%)
Building Attenuation	0 dB	9 dB
GPS Receiver Architecture	Narrowly-Spaced Correlator	

3.2.3 Railway Applications

The operational scenario proposal for the railway use of GPS receivers is for PTC.[63] PTC is a data system that utilizes a computer on board the locomotive to minimize collisions between trains. The locomotive computer obtains movement authorization from a host computer and calculates when it needs to stop the train based on the speed and weight of the train. If the limits of authority are going to be violated, the computer will stop the train automatically. The specifics of this operational scenario proposal were provided by the NTIA.[64] In this analysis, indoor and outdoor operation of UWB devices is considered.

In the operational scenario proposal for PTC the GPS receiver antenna is mounted on top of the train. Therefore, the minimum distance separation has both a horizontal and vertical

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[63] U.S. Department of Transportation and U.S. Department of Defense 1999 Federal Radionavigation Plan (Dec. 1999) at 2-25.

[64] *Summary of GPS/UWB Operational Scenarios* Prepared by the NTIA (Nov. 20, 2000) (hereinafter "NTIA Summary").

component. The minimum distance separation between the GPS receiver and the UWB device is computed from the slant range using Equation 5.

The GPS receiver antenna in the railway PTC operational scenario has an antenna height of 10 meters and a horizontal separation from the UWB devices of 7 meters. An antenna height of 3 meters (outdoor operation) and 10 meters (indoor operation) is used for the UWB devices. The computed minimum distance separations are 9.8 meters for outdoor UWB device operation and 7 meters for indoor UWB device operation.

Using the model given in Table 3-1, the antenna gain for the GPS receiver antenna is 0 dBi for indoor UWB device operation and -4.5 dBi for outdoor UWB device operation.

For these minimum distance separations, it is reasonable to consider multiple UWB devices. Based on the operational scenarios presented at the NTIA GPS/UWB operational scenario meetings, three UWB devices each located at the minimum distance separation are considered in the railway PTC operational scenario.

Based on the GPS receiver antenna heights and the UWB device antenna heights the expected propagation loss breakpoint radii are 1.9 kilometers for outdoor UWB device operation and 6.3 kilometers for indoor UWB device operation. Since the computed minimum distance separations are much less than the expected propagation loss breakpoint radii the free-space propagation model is applicable.

A summary of the technical factors associated with the railway PTC operational scenario is provided in Table 3-7.

TABLE 3-7. Technical Factors for the Railway PTC Operational Scenario

Technical Factors	Value	
	Outdoor UWB Device Operation	**Indoor UWB Device Operation**
GPS Receiver Antenna Gain	-4.5 dBi	0 dBi
GPS Antenna Height	10 meters	10 meters
UWB Device Antenna Height	3 meters	10 meters
Minimum Distance Separation	9.8 meters	7 meters
Propagation Model	Free-space	Free-space
Interference Allotment to UWB Devices	3 dB (50%)	3 dB (50%)
Variations in GPS Receivers	3 dB	3 dB
Multiple UWB Devices	3 UWB devices	3 UWB devices
Activity Factor for Each UWB Device	0 dB (100%)	0 dB (100%)
Building Attenuation	0 dB	9 dB
GPS Receiver Architecture	Narrowly-Spaced Correlator	

3.2.4 Surveying Applications

Two operational scenario proposals were provided for the surveying use of GPS receivers.[65] The surveying operational scenarios considered interference from both single and multiple UWB device interactions.

In the surveying operational scenarios the GPS receiver is located below the antenna of the UWB device. When a single UWB device is considered a minimum distance separation of 30 meters was proposed. For multiple UWB devices it was proposed that the first UWB device be located 30 meters from the GPS receiver. Two additional UWB devices are located at distances of 300 and 750 meters respectively from the GPS receiver.

If an antenna height of 3 meters is used for the GPS receiver and 10 meters is used for the UWB device, the expected pathloss breakpoint radius is 1.2 kilometers. For the surveying operational scenarios the minimum distance separation is less than the expected pathloss breakpoint radius, therefore the free-space propagation model is applicable.

A summary of the technical factors associated with the surveying operational scenarios is provided in Table 3-8.

TABLE 3-8. Technical Factors for the Surveying Operational Scenarios

Technical Factors	Value	
	Single UWB Device	Multiple UWB Devices
GPS Receiver Antenna Gain	3 dBi	3 dBi, 0 dBi
GPS Antenna Height	3 meters	3 meters
UWB Device Antenna Height	10 meters	10 meters
Minimum Distance Separation	30 meters	30, 300, 750 meters
Propagation Model	Free-space	Free-space
Interference Allotment to UWB Devices	3 dB (50%)	3 dB (50%)
Variations in GPS Receivers	3 dB	3 dB
Multiple UWB Devices	1 UWB device	3 UWB devices
Activity Factor for Each UWB Device	0 dB (100%)	0 dB (100%)
Building Attenuation	0 dB	0 dB
GPS Receiver Architecture	Narrowly-Spaced Correlator	

[65] National Oceanic and Atmospheric Administration/National Ocean Service/National Geodetic Survey Submission to NTIA GPS/UWB Operational Scenario Meeting (Sept. 27, 2000).

3.2.5 Aviation Applications [66]

The operational scenario proposals for the aviation use of GPS receivers include: en-route navigation and non-precision approach landings.[67] En-route navigation is a phase of navigation covering operations between a point of departure and termination of the flight. Non-precision approach landing is a standard instrument approach procedure using a ground-based system in which no electronic glide slope is provided.[68]

3.2.5.1 En-Route Navigation

For the en-route navigation operational scenario, the aircraft with the GPS receiver is at an altitude of 1,000 feet.[69] The maximum LOS distance (d_{LOS}) for an aircraft at an altitude of 303 meters (1,000 feet) is given by:

$$d_{LOS} = 3.57\,(k)^{0.5}\left((h_{UWB})^{0.5} + (h_{GPS})^{0.5}\right) \qquad (6)$$

where:

k is the effective Earth radius factor;
h_{UWB} is the antenna height of the UWB device (m);
h_{GPS} is the height of the GPS receiver antenna located on the aircraft (m).

Using an antenna height of 3 meters for the UWB device and a typical value of k in a temperate climate of 1.33, the computed LOS distance for the aircraft is 78.5 kilometers. Since such a large geographic area is visible to an aircraft at this altitude, the impact of multiple UWB devices is considered for the aviation en-route navigation operational scenario.

To compute the aggregate emission level into the GPS receiver from multiple UWB devices a computer model developed by NTIA is used. This computer model computes the power-sum aggregate emission level from a surface density of UWB devices with the same emission frequency and emission level. The computer model assumes that all of the UWB devices are radiating in the direction of the airborne GPS receiver. The UWB devices are distributed uniformly in concentric rings on a spherical dome of the Earth's surface as shown in Figure 3-1 such that the distance from any UWB device to its closest neighbor remains

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66 Another aviation application that was discussed at the NTIA operational scenario meetings, was the use of GPS receivers in airport surface movement operations. Sufficient information is not available at this time to include an assessment of this operational scenario in this report. This operational scenario is being actively addressed within RTCA and the results will be made available when the study is complete.

67 NTIA Summary at 10.

68 Glide slope is a descent profile determined for vertical guidance during a final approach.

69 Document No. RTCA/DO-235, *Assessment of Radio Frequency Interference Relevant to the GNSS* (Jan. 27, 1997) at A-2 (hereinafter "DO-235 ").

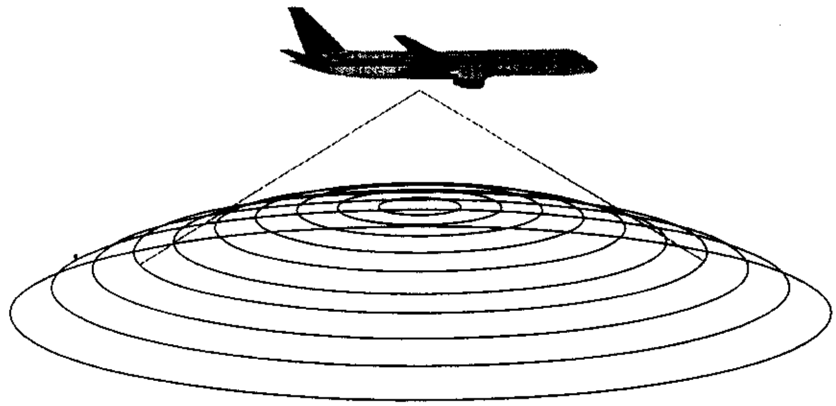

Figure 3-1. Airborne Geometry for the NTIA Aggregate Emitter Model

approximately constant throughout the distribution. The model employs the free-space model for the propagation loss computations. A detailed description of the computer model is provided in a separate NTIA report.[70]

Determining the density of a large number of UWB devices is a key factor affecting the aggregate interference to a GPS receiver used for en-route navigation. Factors that should be considered when estimating the density of a large number of UWB devices include: population; assumed rate for technology penetration; and activity factor. In the absence of such information, this analysis computes the maximum allowable EIRP as a function of active UWB device density.

Indoor and outdoor operation of UWB devices are considered in the aviation en-route navigation operational scenario. Since it is not possible to estimate what percentage of the UWB devices are operating indoor versus those operating outdoor, two cases are considered. In the first case all of the UWB devices are assumed to be operating outdoors and in the second case all of the UWB devices are assumed to be operating indoors.

In the en-route navigation operational scenarios, the GPS receiver antenna is located on top of the aircraft. In a previous analysis of terrestrial interference to GPS receivers, an antenna gain below the aircraft of -10 dBi was used.[71] Since there are no specifications on antenna gain below the aircraft and sufficient installed antenna pattern data is lacking on civil aircraft the value of antenna gain of -10 dBi is used in the aviation en-route navigation operational scenario.

A factor of 2 dB is included in the analysis to take into account the alignment of the UWB device antennas with respect to the airborne GPS receiver in the en-route navigation operational scenario.

Since en-route navigation is a safety-of-life function it is appropriate to include a 6 dB safety margin in this operational scenario.

[70] NTIA Report 01-43 at 5-5.

[71] DO-235 at F-13.

A summary of the technical factors associated with the aviation en-route navigation operational scenario is provided in Table 3-9.

TABLE 3-9. Technical Factors for the Aviation En-Route Navigation Operational Scenario

Technical Factors	Value	
	Outdoor UWB Device Operation	**Indoor UWB Device Operation**
GPS Receiver Antenna Gain	-10 dBi	-10 dBi
GPS Antenna Height	303 meters	303 meters
UWB Device Antenna Height	3 meters	3 meters
Minimum Distance Separation	303 meters	303 meters
Propagation Model	Free-space	Free-space
Interference Allotment to UWB Devices	10 dB (10%)	10 dB (10%)
Variations in GPS Receivers	3 dB	3 dB
Aviation Safety Margin	6 dB	6 dB
UWB Device Antenna Alignment	2 dB	2 dB
Multiple UWB Devices	Variable	Variable
Activity Factor for Each UWB Device	0 dB (100%)	0 dB (100%)
Building Attenuation	0 dB	9 dB
GPS Receiver Architecture	C/A-code (TSO-C129a Compliant)	

3.2.5.2 Non-Precision Approach Landing

The FAA distinguishes a precision approach landing from a non-precision approach landing by requiring that a precision approach have a combined lateral and vertical (glide slope) guidance. The term non-precision approach refers to landings at facilities without a glide slope capability. The FAA maintains the same level of flight safety for non-precision approaches as it does for precision approaches. They achieve this equity by requiring a much larger displacement area at the missed approach point and a higher minimum descent height (MDH) for the non-precision approach landings than they do for the precision approach landings. The MDH is the lowest altitude to which descent shall be authorized for procedures not using a glide slope (vertical guidance).[72]

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[72] RTCA Special Committee 159, *Second Interim Report to the Department of Transportation: Ultra-Wideband Technology Radio Frequency Interference Effects to Global Positioning System Receivers and Interference Encounter Scenario Development* (March 14, 2001) at 46.

Associated with each non-precision approach landing segment there is a MDH. The MDH is computed by:

$$\text{MDH} = 250 \text{ feet} + (\text{Obstacle Height}) \qquad (7)$$

If there are no obstructions, then the MDH is 250 feet. Assuming that a UWB device can be located on top of an obstacle, or at ground level within an obstacle-free zone, and assuming that the GPS antenna is located 7 feet above the aircraft control point[73], the following equation is used to compute the minimum distance separation between the GPS receiver used for non-precision approach landings and a UWB device:

$$D_{min} = 257 - \text{TSE} \qquad (8)$$

where TSE is the Total System Error.

The TSE is comprised of both the aircraft and its navigation system tracking errors. It is the difference between true position and desired position. The TSE is computed from the root-sum-square of the Flight Technical Error (FTE) and the Navigation System Error (NSE):

$$\text{TSE} = ((\text{FTE})^2 + (\text{NSE})^2)^{0.5} \qquad (9)$$

The FTE is the error contribution of the pilot using the presented information to control aircraft position. The NSE is the error attributable to the navigation system in use. It includes the navigation sensor error, receiver error, and path definition error.

The 95% probability (2σ) value for the FTE is 100 feet.[74] The NSE for the vertical guidance for the 3σ value is 103 feet corresponding to the minimum accuracy requirements for vertical guidance equipment.[75] Based on the 3σ value, the 2σ value for NSE is then 68.6 feet. Using Equation 9 the TSE is then 121.2 feet. Using Equation 8, the minimum distance separation between the GPS receiver used for the non-precision approach landings and a UWB device is 135.8 feet.

In the previous analyses that have been performed examining interference from terrestrial emitters to a GPS receiver used for precision approach landings it was assumed that a single emitter was below the aircraft and located at the Category I decision point.[76] The effect of multiple interfering emitters was not considered in this analysis. A methodology was presented

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[73] The aircraft control point is the point on the aircraft at which vertical and lateral deviations of the aircraft are measured.

[74] Document No. RTCA/DO-208, *Minimum Operational Performance Standards for Airborne Supplemental Navigation Equipment Using GPS* (July 1991) at E-4.

[75] *Id.* at 34.

[76] DO-235 at Appendix F Annex 2.

in RTCA Working Group 6 to address multiple interfering sources.[77] As an aircraft passes over the UWB devices, the antenna located on top of the aircraft projects a plane on the surface of the Earth as shown in Figure 3-2. As shown in Figure 3-2, point P represents the GPS receiver antenna. The surface E represents the plane containing the interfering sources. The parameter h is the minimum distance from point P to plane E. The parameter d is the distance from points on plane E whose propagation loss differs from the minimum loss at distance h by a fixed propagation loss ratio (LR). The parameter r is the radius of the plane (circle) containing the points of the fixed propagation loss ratio. The radius of this circle is given by:

$$r = h\,(LR-1)^{0.5} \qquad (10)$$

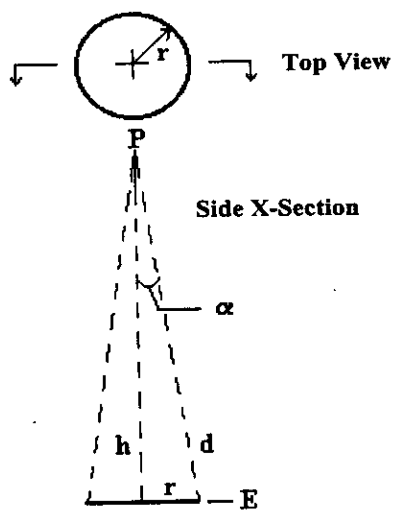

Figure 3-2. Airborne Antenna Projection Geometry

A derivation of Equation 10 is provided in Appendix A of NTIA Report 01-45. Another factor to be considered is the variation in antenna gain. This can be examined from the angle α in Figure 3-2 using the following equation:

$$\alpha = \cos^{-1}\,(1/(LR)^{0.5}) \qquad (11)$$

A derivation for Equation 11 is also provided in Appendix A of the NTIA Report 01-45.

In determining a representative value for LR, the variation in antenna gain should be taken into consideration. Although the antenna gain specified in Table 3-1 shows a constant antenna gain in the region of -90 to -10 degrees, the actual antenna pattern contains many peaks and nulls

[77] R. J. Erlandson, Rockwell Collins, *UWB Cumulative RFI Effects Aspects for Aviation Precision Approach Scenarios,* SC-159 WG 6 Presentation (Oct. 25, 2000).

(maximum and minimum values of antenna gain).[78] Therefore, the value of LR should be selected to minimize the variation in antenna gain, thereby permitting the use of a single representative antenna gain in the analysis. Using Equation 10 with the minimum distance separation of 136 feet and a propagation loss ratio of 0.1 dB, a circle with a radius of 20.7 feet (41.4 feet in diameter) is computed. For the fixed propagation loss ratio of 0.1 dB, the computed antenna cone angle (α) is 8.68 degrees. This angle is assumed to be small enough to neglect antenna gain variations and will permit the use of a single value of antenna gain in the analysis.

A circle with a diameter of 41.4 feet is large enough to contain several UWB devices. In the aviation non-precision approach landing operational scenario four UWB devices are considered.

In the non-precision approach landing operational scenario, the GPS receiver antenna is located on top of the aircraft. As discussed in the en-route navigation operational scenario, a previous analysis of terrestrial interference to GPS receivers used an antenna gain below the aircraft of -10 dBi. Since there are no specifications on antenna gain below the aircraft and sufficient installed antenna pattern data is lacking on civil aircraft an antenna gain of -10 dBi will be used in this operational scenario.

In this operational scenario, the minimum distance separation between the GPS receiver and the UWB devices is 136 feet. Typically, when the aircraft is at this altitude there are no buildings or structures that are located along the area approaching the runway. Therefore, this analysis only considers UWB devices that are operating outdoors.

Since non-precision approach landings are considered a safety-of-life function it is appropriate to include a 6 dB safety margin in this operational scenario.

A summary of the technical factors associated with the aviation non-precision approach landing operational scenario is provided in Table 3-10.

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[78] DO-235 at Appendix E Annex 2.

TABLE 3-10. Technical Factors for the Aviation Non-Precision Approach Landing Operational Scenario

Technical Factors	Value
GPS Receiver Antenna Gain	-10 dBi
GPS Antenna Height	41.4 meters
UWB Device Antenna Height	3 meters
Minimum Distance Separation	41.4 meters
Propagation Model	Free-space
Interference Allotment to UWB Devices	10 dB (10%)
Variations in GPS Receivers	3 dB
Aviation Safety Margin	6 dB
Multiple UWB Devices	4 UWB devices
Activity Factor for Each UWB Device	0 dB (100%)
Building Attenuation	0 dB
GPS Receiver Architecture	C/A-code (TSO C-129a Compliant)

3.3 ANALYSIS RESULTS

The results of the analysis are presented in this section. Prior to using the measured interference susceptibility levels (I_{meas}) in the analysis, adjustments must be made based on the signal structure of the interfering signal to compute the UWB interference threshold (I_T).

For signals that have been characterized as causing CW-like interference, the value of I_T used in the analysis is based on the power in a single spectral line. As such, the computed values of maximum allowable EIRP represent the power in a single CW-line, independent of the modulation employed.

For interfering signals that have been characterized as causing pulse-like interference, the value of I_{meas} used to compute I_T, was the average measured value. Those cases where neither a break-lock (BL) or reacquisition (RQT) threshold could be measured were referred to as Did Not Break Lock (DNBL). The value of I_{meas} used in the analysis was the maximum available UWB power. It should be noted that the maximum available UWB power was limited by the peak power of the UWB generator. In the case of UWB signals employing 20% gating, where neither a BL or RQT condition was obtained, the maximum available UWB power was reduced by a factor of 10 Log (gating percentage) to obtain an average value for I_T. This can result in an incongruous situation, where the computed value of maximum allowable EIRP is lower for the gated UWB signal versus the non-gated signal.

The GPS receivers considered in the analysis employ one of two receiver architectures: C/A-code (TSO-C129a compliant) and narrowly-spaced correlator. A GPS receiver that employs C/A-code architecture processes the transmitted C/A-code signal, which has a null-to-null bandwidth of 2.046 MHz.[79] A GPS receiver that employs the narrowly-spaced correlator architecture, also processes the C/A-code signal. However, in order to attain a higher degree of accuracy by reducing the effects of mulipath, GPS receivers employing the narrowly-spaced correlator architecture process a wider portion of the transmitted C/A-code signal. GPS receivers employing narrowly-spaced correlator architecture process approximately 16 to 18 MHz of the C/A-code signal. Since the interference effects are different depending on the spectral characteristics of the UWB signals, adjustments must be made to the values of I_{meas} before they can be used in the analysis.

The C/A signal has an approximate $sinc^2$ power spectral envelope with a null-to-null bandwidth of 2.046 MHz. Each GPS satellite employs one of a family of short pseudo-random codes known as Gold codes to generate the C/A-code signal. Due to the short period (1 millisecond) length Gold code there are distinct spectral lines spaced 1 kHz apart. The spectral lines deviate from the $sinc^2$ envelope enough to create dominant spectral lines that are more vulnerable to CW-like interference. In the measurements when a UWB signal structure contains spectral lines, one of the lines is placed close (nominally 500 Hz) to a dominant GPS spectral line.[80] As discussed in Section 2.2 of NTIA Report 01-45, when a UWB signal structure contains spectral lines an adjustment is made to the measured interference susceptibility level to determine the power in the spectral line prior to using this level in the analysis.[81] An adjustment is also made to the measured interference susceptibility levels when the UWB signal is gated. When the UWB signal appears noise-like an adjustment must also be made to the measured interference susceptibility level to correct for the difference in the measurement bandwidth (20 MHz) and the bandwidth used in the analysis (1 MHz). Section 2.2.2.1 of NTIA Report 01-45 provides a more detailed discussion of the adjustments made to the measured susceptibility levels based on the UWB signal structure.[82] Tables 3-11 and 3-12 provide the equations as a function of the interfering signal structure that are necessary to compute the UWB interference thresholds used in the analysis for GPS receivers employing the narrowly-spaced correlator and C/A code (TSO-C129a) architectures respectively.

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[79] The L-band Standard Positioning Service (SPS) ranging signal is a 2.046 MHz null-to-null bandwidth signal centered on L1. The transmitted ranging signal that comprises the GPS-SPS is not limited to the null-to-null signal and extends through the band 1563.42 to 1587.42 MHz.

[80] Due to the spectral content of each C/A code signal, the location of the dominant spectral line is different and could be close to a UWB spectral line that is present in the passband of the GPS receiver.

[81] NTIA Report 01-45 at 2-8.

[82] *Id.* at 2-12.

TABLE 3-11. Equations Used to Compute the Single-Entry UWB Interference Thresholds for the Narrowly-Spaced Correlator GPS Receiver Architecture

Interfering Signal Structure	UWB Interference Threshold Equation
Broadband Noise	$I_T = I_{meas}$ (dBm/20MHz) -30 (dBW/dBm) - 10 Log (20 MHz/1 MHz)
PRF: 100 kHz Modulation: None Gating: 100%	$I_T = I_{meas}$ (dBm/20MHz) - 30 (dBW/dBm) - 10 Log (20 MHz/1 MHz)
PRF: 1, 5, and 20 MHz Modulation: None Gating: 100%	$I_T = I_{meas}$ (dBm/20MHz) -30 (dBW/dBm) - 10 Log (# of lines in a 20 MHz bandwidth) 1 line (20 MHz), 5 lines (5 MHz), and 21 lines (1 MHz)
PRF: 100 kHz and 1MHz Modulation: None Gating: 20%	$I_T = I_{meas}$ (dBm/20MHz) - 30 (dBW/dBm) - 10 Log (20 MHz/1 MHz) + 10 Log (Gating %)
PRF: 5 and 20 MHz Modulation: None Gating: 20%	$I_T = I_{meas}$ (dBm/20MHz) -30 (dBW/dBm) - 10 Log (# of lines in a 20 MHz bandwidth) + 10 Log (Gating %) - 7 dB[1] 1 line (20 MHz) and 5 lines (5 MHz)
PRF: 100 kHz, 1, 5, and 20 MHz Modulation: 2% Rel. and 50% Abs. Dithering Gating: 100%	$I_T = I_{meas}$ (dBm/20MHz) -30 (dBW/dBm) - 10 Log (20 MHz/1 MHz)
PRF: 100 kHz, 1, 5, and 20 MHz Modulation: 2% Rel. and 50% Abs. Dithering Gating: 20%	$I_T = I_{meas}$ (dBm/20MHz) -30 (dBW/dBm) - 10 Log (20 MHz/1 MHz) + 10 Log (Gating%)
PRF: 100 kHz Modulation: OOK Gating: 100%	$I_T = I_{meas}$ (dBm/20MHz) -30 (dBW/dBm) - 10 Log (20 MHz/1 MHz)
PRF: 1, 5, and 20 MHz Modulation: OOK Gating: 100%	$I_T = I_{meas}$ (dBm/20MHz) -3dB[2] - 30 (dBW/dBm) - 10 Log (# of lines in a 20 MHz bandwidth) 1 line (20 MHz) 5 lines (5 MHz), and 21 lines (1 MHz)
PRF: 100 kHz and 1MHz Modulation: OOK Gating: 20%	$I_T = I_{meas}$ (dBm/20MHz) -30 (dBW/dBm) - 10 Log (20 MHz/1 MHz) + 10 Log (Gating %)
PRF: 5 and 20 MHz Modulation: OOK Gating: 20%	$I_T = I_{meas}$ (dBm/20MHz) -3dB[2] - 30 (dBW/dBm) - 10 Log (# of lines in a 20 MHz bandwidth) + 10 Log (Gating %) - 7dB[1] 1 line (20 MHz) and 5 lines (5 MHz)

Notes:
1. Adjustment to compute the power in a single spectral line that is spread in frequency by the gating period resulting in a $sinc^2$ shape around each line.
2. Adjustment for the division of power between discrete spectral lines and continuous spectrum for OOK modulated UWB signal.

TABLE 3-12. Equations Used to Compute the Single-Entry UWB Interference Thresholds for the C/A Code GPS Receiver Architecture (TSO-C129a Compliant)

Interfering Signal Structure	UWB Interference Threshold Equation
Broadband Noise	$I_T = I_{meas}$ (dBm/20MHz) -30 (dBW/dBm) - 10 Log (20 MHz/1 MHz)
PRF: 100 kHz Modulation: None Gating: 100%	$I_T = I_{meas}$ (dBm/20MHz) - 30 (dBW/dBm) - 10 Log (20 MHz/1 MHz)
PRF: 1, 5, and 20 MHz Modulation: None Gating: 100%	$I_T = I_{meas}$ (dBm/20MHz) -30 (dBW/dBm) - 10 Log (# of lines in a 20 MHz bandwidth) 1 line (20 MHz), 5 lines (5 MHz), and 21 lines (1 MHz)
PRF: 100 kHz Modulation: None Gating: 20%	$I_T = I_{meas}$ (dBm/20MHz) - 30 (dBW/dBm) - 10 Log (20 MHz/1 MHz) + 10 Log (Gating %)
PRF: 1, 5, and 20 MHz Modulation: None Gating: 20%	$I_T = I_{meas}$ (dBm/20MHz) -30 (dBW/dBm) - 10 Log (# of lines in a 20 MHz bandwidth) + 10 Log (Gating %) - 7 dB[1] 1 line (20 MHz), 5 lines (5 MHz), and 21 lines (1 MHz)
PRF: 100 kHz, 1, 5, and 20 MHz Modulation: 2% Rel. and 50% Abs. Dithering Gating: 100%	$I_T = I_{meas}$ (dBm/20MHz) -30 (dBW/dBm) - 10 Log (20 MHz/1 MHz)
PRF: 100 kHz, 1, 5, and 20 MHz Modulation: 2% Rel. and 50% Abs. Dithering Gating: 20%	$I_T = I_{meas}$ (dBm/20MHz) -30 (dBW/dBm) - 10 Log (20 MHz/1 MHz) + 10 Log (Gating%)
PRF: 100 kHz Modulation: OOK Gating: 100%	$I_T = I_{meas}$ (dBm/20MHz) -30 (dBW/dBm) - 10 Log (20 MHz/1 MHz)
PRF: 1, 5, and 20 MHz Modulation: OOK Gating: 100%	$I_T = I_{meas}$ (dBm/20MHz) -3dB[2] - 30 (dBW/dBm) - 10 Log (# of lines in a 20 MHz bandwidth) 1 line (20 MHz), 5 lines (5 MHz), and 21 lines (1 MHz)
PRF: 100 kHz Modulation: OOK Gating: 20%	$I_T = I_{meas}$ (dBm/20MHz) -30 (dBW/dBm) - 10 Log (20 MHz/1 MHz) + 10 Log (Gating %)
PRF: 1, 5, and 20 MHz Modulation: OOK Gating: 20%	$I_T = I_{meas}$ (dBm/20MHz) -3dB[2] - 30 (dBW/dBm) - 10 Log (# of lines in a 20 MHz bandwidth) + 10 Log (Gating %) - 7dB[1] 1 line (20 MHz), 5 lines (5 MHz), and 21 lines (1 MHz)

Notes:
1. Adjustment to compute the power in a single spectral line that is spread in frequency by the gating period resulting in a $sinc^2$ shape around each line.
2. Adjustment for the division of power between discrete spectral lines and continuous spectrum for OOK modulated UWB signal.

Tables 3-13 and 3-14 provide the UWB interference thresholds for each of the GPS receiver architectures measured. The UWB interference threshold and the GPS receiver criteria used to determine the levels are shown for the different interfering signal structures considered in this analysis for both single-entry and multiple-entry (aggregate) UWB device interactions.

TABLE 3-13. UWB Interference Thresholds for Narrowly-Spaced Correlator Receiver Architecture

Interfering Signal Structure	Category of Interfering Signal (Single-Entry)	UWB Interference Threshold (Single-Entry)	Category of Interfering Signal (Aggregate)	UWB Interference Threshold (Aggregate)
Broadband Noise	Noise-Like	-132.2 dBW/MHz	Noise-Like	-132.2 dBW/MHz
0.1 MHz PRF, No Mod, 100% Gate	Pulse-Like	-100.2 dBW/MHz[a]	Pulse-Like	-100.2 dBW/MHz[a]
0.1 MHz PRF, No Mod, 20% Gate	Pulse-Like	-107.1 dBW/MHz[a]	Pulse-Like	-107.1 dBW/MHz[a]
0.1 MHz PRF, OOK, 100% Gate	Pulse-Like	-103.2 dBW/MHz[a]	Pulse-Like	-103.2 dBW/MHz[a]
0.1 MHz PRF, OOK. 20% Gate	Pulse-Like	-110.2 dBW/MHz[a]	Pulse-Like	-110.2 dBW/MHz[a]
0.1 MHz PRF, 50% abs, 100% Gate	Pulse-Like	-100.1 dBW/MHz[a]	Pulse-Like	-100.1 dBW/MHz[a]
0.1 MHz PRF, 50% abs, 20% Gate	Pulse-Like	-107.1 dBW/MHz[a]	Pulse-Like	-107.1 dBW/MHz[a]
0.1 MHz PRF, 2% rel, 100% Gate	Pulse-Like	-100.1 dBW/MHz[a]	Pulse-Like	-100.1 dBW/MHz[a]
0.1 MHz PRF, 2% rel, 20% Gate	Pulse-Like	-107.1 dBW/MHz[a]	Pulse-Like	-107.1 dBW/MHz[a]
1 MHz PRF, No Mod, 100% Gate	CW-Like	-144.1 dBW	CW-Like	-144.1 dBW
1 MHz PRF, No Mod, 20% Gate	Pulse-Like	-94.8 dBW/MHz[a]	Noise-Like	-132.2 dBW/MHz[b]
1 MHz PRF, OOK, 100% Gate	CW-Like	-139.9 dBW	CW-Like	-139.9 dBW
1 MHz PRF, OOK, 20% Gate	Pulse-Like	-97.8 dBW/MHz[a]	Noise-Like	-132.2 dBW/MHz[b]
1 MHz PRF, 50% abs, 100% Gate	Pulse-Like	-105.9 dBW/MHz	Noise-Like	-132.2 dBW/MHz[b]
1 MHz PRF, 50% abs, 20% Gate	Pulse-Like	-94.8 dBW/MHz[a]	Noise-Like	-132.2 dBW/MHz[b]
1 MHz PRF, 2% rel, 100% Gate	Pulse-Like	-87.8 dBW/MHz[a]	Noise-Like	-132.2 dBW/MHz[b]
1 MHz PRF, 2% rel, 20% Gate	Pulse-Like	-94.7 dBW/MHz[a]	Noise-Like	-132.2 dBW/MHz[b]
5 MHz PRF, No Mod, 100% Gate	CW-Like	-145.7 dBW	CW-Like	-145.7 dBW
5 MHz PRF, No Mod, 20% Gate	CW-Like	-146.6 dBW	CW-Like	-146.6 dBW
5 MHz PRF, OOK, 100% Gate	CW-Like	-146.7 dBW	CW-Like	-146.7 dBW
5 MHz PRF, OOK, 20% Gate	CW-Like	-142.6 dBW	CW-Like	-142.6 dBW
5 MHz PRF, 50% abs, 100% Gate	Noise-Like	-127.7 dBW/MHz	Noise-Like	-127.7 dBW/MHz
5 MHz PRF, 50% abs, 20% Gate	Pulse-Like	-88.5 dBW/MHz[a]	Noise-Like	-132.2 dBW/MHz[b]
5 MHz PRF, 2% rel, 100% Gate	Noise-Like	-127.6 dBW/MHz	Noise-Like	-127.6 dBW/MHz
5 MHz PRF, 2% rel, 20% Gate	Pulse-Like	-88.5 dBW/MHz[a]	Noise-Like	-132.2 dBW/MHz[b]
20 MHz PRF, No Mod, 100% Gate	CW-Like	-146.1 dBW	CW-Like	-146.1 dBW
20 MHz PRF, No Mod, 20% Gate	CW-Like	-146.9 dBW	CW-Like	-146.9 dBW
20 MHz PRF, OOK, 100% Gate	CW-Like	-146.5 dBW	CW-Like	-146.5 dBW
20 MHz PRF, OOK, 20% Gate	CW-Like	-145.4 dBW	CW-Like	-145.4 dBW
20 MHz PRF, 50% abs, 100% Gate	Noise-Like	-133.6 dBW/MHz	Noise-Like	-133.6 dBW/MHz
20 MHz PRF, 50% abs, 20% Gate	Pulse-Like	-100.5 dBW/MHz	Noise-Like	-132.2 dBW/MHz[b]
20 MHz PRF, 2% rel, 100% Gate	Noise-Like	-135.5 dBW/MHz	Noise-Like	-135.5 dBW/MHz
20 MHz PRF, 2% rel, 20% Gate	Pulse-Like	-122.2 dBW/MHz	Noise-Like	-132.2 dBW/MHz[b]

Note: a. Interference threshold not reached at maximum available UWB generator power.
b. Based on more than three UWB devices.

TABLE 3-14. UWB Interference Thresholds for C/A-Code (TSO-C129a Compliant) Receiver Architecture

Interfering Signal Structure	Category of Interfering Signal (Single-Entry)	UWB Interference Threshold (Single-Entry)	Category of Interfering Signal (Aggregate)	UWB Interference Threshold (Aggregate)
Broadband Noise	Noise-Like	-136 dBW/MHz	Noise-Like	-136 dBW/MHz
0.1 MHz PRF, No Mod, 100% Gate	Pulse-Like	-117.9 dBW/MHz[a]	Pulse-Like	-117.9 dBW/MHz[a]
0.1 MHz PRF, No Mod, 20% Gate	Pulse-Like	-106.8 dBW/MHz[a]	Pulse-Like	-106.8 dBW/MHz[a]
0.1 MHz PRF, OOK, 100% Gate	Pulse-Like	-103.1 dBW/MHz[a]	Pulse-Like	-103.1 dBW/MHz[a]
0.1 MHz PRF, OOK. 20% Gate	Pulse-Like	-109.9 dBW/MHz[a]	Pulse-Like	-109.9 dBW/MHz[a]
0.1 MHz PRF, 50% abs, 100% Gate	Pulse-Like	-115 dBW/MHz[a]	Pulse-Like	-115 dBW/MHz[a]
0.1 MHz PRF, 50% abs, 20% Gate	Pulse-Like	-106.8 dBW/MHz[a]	Pulse-Like	-106.8 dBW/MHz[a]
0.1 MHz PRF, 2% rel, 100% Gate	Pulse-Like	-97.9 dBW/MHz[a]	Pulse-Like	-97.9 dBW/MHz[a]
0.1 MHz PRF, 2% rel, 20% Gate	Pulse-Like	-106.9 dBW/MHz[a]	Pulse-Like	-106.9 dBW/MHz[a]
1 MHz PRF, No Mod, 100% Gate	CW-Like	-140.8 dBW	CW-Like	-140.8 dBW
1 MHz PRF, No Mod, 20% Gate	CW-Like	-146.7 dBW	CW-Like	-146.7 dBW
1 MHz PRF, OOK, 100% Gate	CW-Like	-140.8 dBW	CW-Like	-140.8 dBW
1 MHz PRF, OOK, 20% Gate	CW-Like	-140.7 dBW	CW-Like	-140.7 dBW
1 MHz PRF, 50% abs, 100% Gate	Noise-Like	-142 dBW/MHz	Noise-Like	-142 dBW/MHz
1 MHz PRF, 50% abs, 20% Gate	Noise-Like	-139.5 dBW/MHz	Noise-Like	-139.5 dBW/MHz
1 MHz PRF, 2% rel, 100% Gate	Noise-Like	-141.5 dBW/MHz	Noise-Like	-141.5 dBW/MHz
1 MHz PRF, 2% rel, 20% Gate	Noise-Like	-133.5 dBW/MHz	Noise-Like	-133.5 dBW/MHz
5 MHz PRF, No Mod, 100% Gate	CW-Like	-138.4 dBW	CW-Like	-138.4 dBW
5 MHz PRF, No Mod, 20% Gate	CW-Like	-143.2 dBW	CW-Like	-143.2 dBW
5 MHz PRF, OOK, 100% Gate	CW-Like	-139.4 dBW	CW-Like	-139.4 dBW
5 MHz PRF, OOK, 20% Gate	CW-Like	-143.3 dBW	CW-Like	-143.3 dBW
5 MHz PRF, 50% abs, 100% Gate	Noise-Like	-142 dBW/MHz	Noise-Like	-142 dBW/MHz
5 MHz PRF, 50% abs, 20% Gate	Noise-Like	-141.9 dBW/MHz	Noise-Like	-141.9 dBW/MHz
5 MHz PRF, 2% rel, 100% Gate	Noise-Like	-143 dBW/MHz	Noise-Like	-143 dBW/MHz
5 MHz PRF, 2% rel, 20% Gate	Noise-Like	-142.4 dBW/MHz	Noise-Like	-142.4 dBW/MHz
20 MHz PRF, No Mod, 100% Gate	CW-Like	-139.8 dBW	CW-Like	-139.8 dBW
20 MHz PRF, No Mod, 20% Gate	CW-Like	-147.8 dBW	CW-Like	-147.8 dBW
20 MHz PRF, OOK, 100% Gate	CW-Like	-138.2 dBW	CW-Like	-138.2 dBW
20 MHz PRF, OOK, 20% Gate	CW-Like	-142.1dBW	CW-Like	-142.1 dBW
20 MHz PRF, 50% abs, 100% Gate	Noise-Like	-141 dBW/MHz	Noise-Like	-141 dBW/MHz
20 MHz PRF, 50% abs, 20% Gate	Noise-Like	-140.4 dBW/MHz	Noise-Like	-140.4 dBW/MHz
20 MHz PRF, 2% rel, 100% Gate	Noise-Like	-141 dBW/MHz	Noise-Like	-141 dBW/MHz
20 MHz PRF, 2% rel, 20% Gate	Noise-Like	-139.9 dBW/MHz	Noise-Like	-139.9 dBW/MHz

Note: a. Interference threshold not reached at maximum available UWB generator power.

Sections 3.3.1 through 3.3.5 present the results of the maximum allowable EIRP scenario dependent analysis. Each section gives the analysis results for one of the five categories of GPS receiver applications considered. For each GPS receiver application several operational scenarios were analyzed. The analysis results are presented in the form of graphs where the bar represents the value of maximum allowable EIRP (i.e., a longer bar represents a lower value of maximum allowable EIRP). Both single-entry and multiple-entry UWB device interactions were considered. In a multiple-entry UWB device interaction, the maximum allowable EIRP level of a single-entry UWB device as shown on the graph was determined by partitioning the total interference allotment in accordance with the multiple (aggregate) UWB device factor as discussed in Section 3.1.4.

The maximum allowable EIRP (based on average power) of a single UWB device is displayed on the x-axis. The UWB signal permutations examined are displayed on the y-axis. Each UWB signal permutation is identified by three parameters: PRF, gating percentage, and modulation type. For example, a UWB signal employing a PRF of 1 MHz, 20% gating, and on-off keying modulation is identified as: 1 MHz, 20%, OOK. For UWB signals that employ gating, the threshold (I_T), used to compute the maximum allowable EIRP, is based on the average power measured over the entire gating period.

In addition to identifying the UWB signal parameters, each entry on the y-axis identifies the criteria used in the single-entry interference measurements, which were then used to compute the UWB interference thresholds. As discussed in Section 1.3.1, the two GPS receiver criteria used in this assessment are break-lock and reacquisition identified on the y-axis as BL and RQT respectively. UWB signal permutations for which neither a break-lock or reacquisition condition could be measured are identified on the y-axis as DNBL. For these signal permutations, the maximum available UWB signal power was used in the analysis. When multiple UWB devices were considered, resulting in noise-like interference, the UWB interference threshold was computed based on the broadband noise break-lock threshold. This is identified as NBL on the y-axis.

The results of the spreadsheet analysis program used to generate the graphs are provided in Appendix A.

There is a vertical dashed line shown on each graph that represents the current Part 15 level of -71.3 dBW/MHz. UWB signals that have been characterized as causing noise-like or pulse-like interference can be directly compared to the current Part 15 level. UWB signals that have been characterized as causing CW-like interference can be compared to the current level, if it is assumed that there is only a single spectral line in the measurement bandwidth. When the value of maximum allowable EIRP associated with a UWB signal permutation is located on the left side of the dashed line, additional attenuation below the current Part 15 level is not necessary in order to protect the GPS receiver architecture under consideration. When the value of maximum allowable EIRP associated with a UWB signal permutation is located on the right side of the dashed line, additional attenuation below the current Part 15 level is necessary to protect the GPS receiver architecture under consideration. For example, if the value of maximum allowable EIRP is -93 dBW/MHz, 21.7 dB of additional attenuation below the current Part 15 level is necessary to protect the GPS receiver architecture under consideration.

Three graphs are given for each of the operational scenarios that were analyzed. The first graph presents the analysis results for the UWB signal permutations that were characterized as causing pulse-like interference. The second graph presents the analysis results for the UWB signal permutations that were characterized as causing noise-like interference. The third graph presents the analysis results for the UWB signal permutations that were characterized as causing CW-like interference.

3.3.1 Terrestrial Applications

In the operational scenarios for terrestrial applications, the narrowly-spaced correlator receiver architecture is considered. The analysis results for the narrowly-spaced correlator receiver architecture are given in Figures 3-3 through 3-11. The operational scenarios considered both single and multiple UWB device interactions as well as indoor and outdoor UWB device operation. The values of maximum allowable EIRP shown in Figures 3-3 through 3-11 are for a single UWB device and are based on average power.

The values of maximum allowable EIRP that are required to protect the narrowly-spaced correlator receiver architecture considered in the terrestrial application operational scenarios will vary depending on the UWB signal parameters, single-entry versus multiple-entry UWB device interactions, and whether the UWB devices are used indoors or outdoors. The analysis results for the operational scenarios associated with terrestrial applications can be discussed in terms of the characterization of the UWB signal interference effects. As shown in Figure 3-3 the maximum allowable EIRP levels for the UWB signals that have been characterized as causing pulse-like interference range from -82.8 to -48.4 dBW/MHz for single UWB device interactions. Figures 3-6 and 3-9 show that for multiple-entry UWB device interactions resulting in pulse-like interference, the values of maximum allowable EIRP range from -59.9 to -49.8 dBW/MHz for outdoor UWB device operation and from -55.2 to -45.1 dBW/MHz for indoor UWB device operation. As shown in Figure 3-4 for UWB signals that have been characterized as causing noise-like interference, the values of maximum allowable EIRP range from -96.1 to -88.2 dBW/MHz for single-entry UWB device interactions. As shown in Figures 3-7 and 3-10, for multiple-entry UWB interactions resulting in noise-like interference, the values of maximum allowable EIRP range from -86.5 to -78.6 dBW/MHz for indoor UWB operation and from -91.2 to -83.3 dBW/MHz for outdoor UWB device operation. Figures 3-5, 3-8, and 3-11 give the analysis results for the UWB signals that have been characterized as causing CW-like interference. As shown in Figure 3-5, the values of maximum allowable EIRP range from -107.5 to -100.5 dBW for single-entry UWB device interactions. Figures 3-8 and 3-11 show that for multiple-entry UWB device interactions, the values of maximum allowable EIRP range from -91.9 to -84.9 dBW for indoor UWB device operation and from -96.6 to -89.6 dBW for outdoor UWB operation.

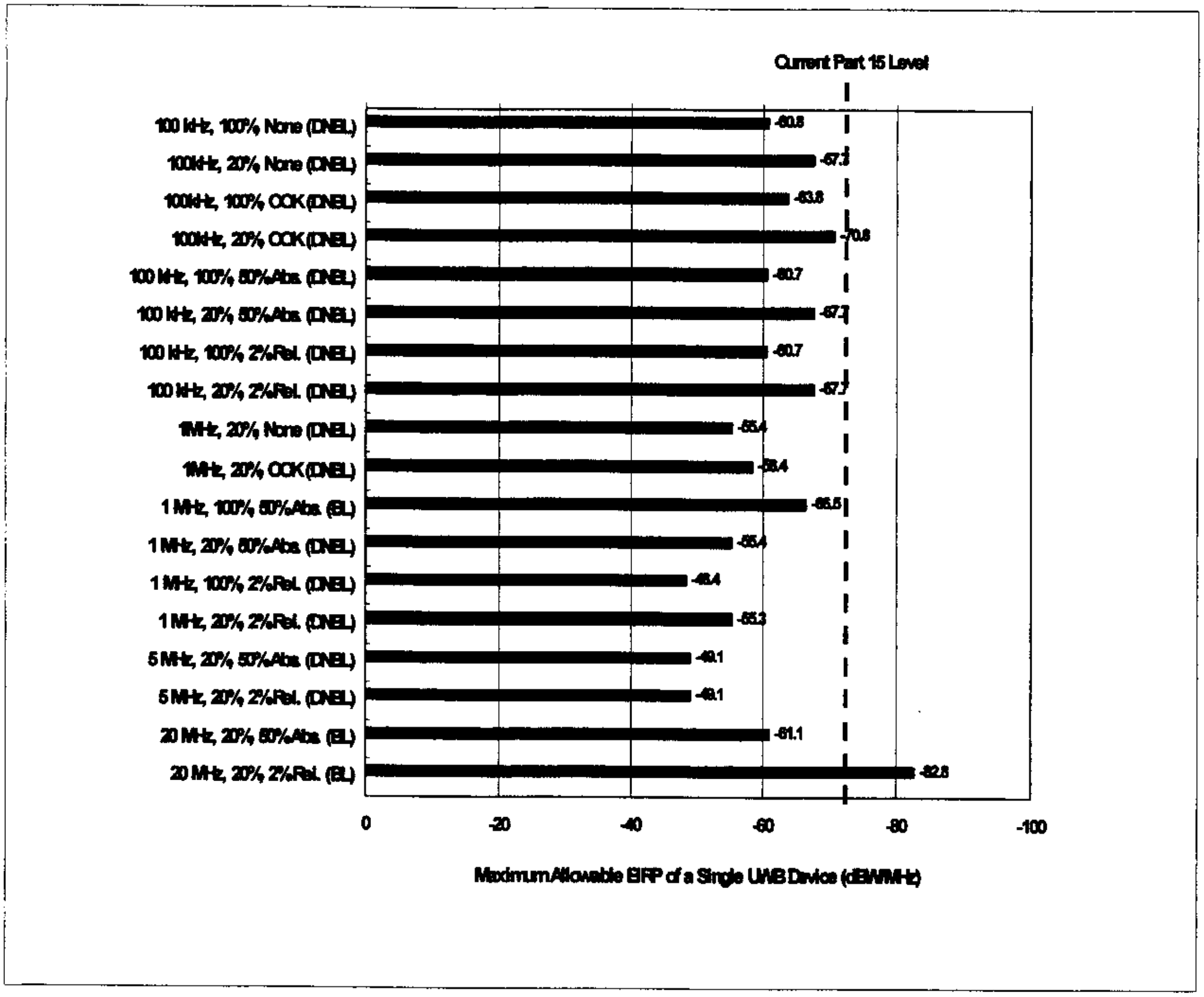

Figure 3-3. Analysis Results for Terrestrial Operational Scenario: Narrowly-Spaced Correlator Receiver and Single UWB Device (Pulse-Like UWB Signals)