EMF Exposure Assessment for Kuiper Fixed Customer Terminals

I. INTRODUCTION

This analysis calculates the non-ionizing radiation levels for three Amazon[1] customer terminal ("CT") types. The calculations performed in this analysis comply with the methods described in FCC Office of Engineering and Technology Bulletin, Number 65 (Edition 97-01) ("Bulletin 65"). This analysis demonstrates that the Amazon CTs will not result in exposure levels exceeding the applicable maximum permissible exposure ("MPE") limits.

II. DESCRIPTION OF AMAZON CUSTOMER TERMINALS

Amazon's CTs will deliver broadband connectivity to customers by establishing a link to Amazon's non-geostationary satellite orbit ("NGSO") system (the "Kuiper System") using certain Fixed-Satellite Service ("FSS") Ka-band frequencies. This application includes three types of terminals—ranging from an ultra-compact model designed for affordability to a larger model designed to provide high performance for business users. The three CT models are referred to as "Type I," "Type II," and "Type III" herein. Each of these three models of CT is a flat-panel, phased array antenna. They operate only while stationary, and establish communication links with the satellites and connect to the Internet via automated processes that align beams/pointing, obtain frequencies/channels and exchange security keys to establish a secure network connection. Additionally, each CT type has a maximum transmit duty cycle. Table 1 provides technical specifications for each CT type.

[1] Kuiper Systems LLC ("Kuiper") is a wholly owned subsidiary of Amazon.com Services LLC (referred to collectively as "Amazon" herein).

Table 1: EIRP and Physical Radiating Area of CTs

	Type I Ultra-Compact	Type II Standard	Type III High-Throughput
Antenna Gain dBi (Tx)	31	34	38
Boresight EIRP (dBW)	35	40.5	45.8
Physical Radiating Area (cm^2)	180	269	660
Maximum Transmit Duty Cycle (%)	30%	40%	50%

Each of the CTs and the Kuiper System as a whole have intrinsic operational characteristics that limit the potential for human exposure. *First*, Amazon will control and limit the transmit duty cycle of each CT, which reduces the average transmit power and potential radiofrequency ("RF") exposure from the CT. The analysis presented herein is based on the maximum transmit duty cycles listed in Table 1. These are a ceiling; the typical duty cycle over a 30-minute window will be less than 10%.

Second, a CT will not transmit until it successfully receives and decodes a message on the downlink that grants it permission to transmit. As discussed more fully below and validated by testing described in Appendix C, the presence of a human body will cause sufficient path attenuation to prevent the CT from successfully decoding the message that grants it permission to transmit, and any direct exposure to the person will be ceased within a millisecond of beam blockage.[2]

Third, beams from the CTs are very narrow and will continuously track the Kuiper System NGSO satellites, operating at elevation angles between 35° and 90°. These narrow beams cause very little exposure outside the main-beam.

[2] As described more fully in Appendix C, Amazon has measured body loss under controlled radio frequency anechoic conditions in a configuration that accurately mimics the satellite-to-CT downlink path at 18.5 GHz to determine under what body blockage conditions this occurs.

Fourth, effective operation of the CTs requires an unobstructed line-of-sight between the CTs and the Kuiper System satellites. To avoid obstructions that interrupt transmissions, Amazon will instruct users to mount the CTs above head height, where a clear line-of-sight free of any obstruction to the satellites can be achieved.

These factors ensure that humans will not experience continuous direct exposure from the CTs.

III. EXPLANATION OF THE ANALYSIS

At the Amazon CT operating frequency, the exposure assessment is based upon calculation of incident power density, S_{exp}, at the exposure location, and the amount of time that the body is illuminated.[3] OET's guidance expresses this time-averaging equation as follows:

$$\Sigma \; S_{exp} T_{exp} = S_{limit} T_{avg}$$

where: S_{exp} = power density level of expsosure (mW/cm^2)

S_{limit} = appropriate power density MPE limit (mW/cm^2)

T_{exp} = allowable time of exposure for S_{exp}

T_{avg} = approprate MPE averaging time.

Consistent with Bulletin 65, Amazon calculated power densities at the antenna surface, in the near-field, and in the far-field. Amazon then calculated the time-averaged exposure in the near-field and far-field by considering beam steering behavior of the antennas and the expected power density levels in the direction of a nearby person.

Bulletin 65 and Section 1.1310 of the Commission's rules specify two exposure limits: one for occupational workers in controlled areas and one for uncontrolled areas accessible to the

[3] According to Bulletin 65 equation 2: "The sum of the products of the exposure levels and the allowed times for exposure must equal the product of the appropriate MPE limit and the appropriate time-averaging interval."

general population. Because CTs may be operated where the general public could have access, this analysis considers the MPE limit for General Population/Uncontrolled exposures for all three CT types, which for the Ka-band frequencies used by these CTs is a power density equal to 1 milliwatt per centimeter squared averaged over a thirty-minute period.

IV. RESULTS OF ANALYSIS

The maximum power density levels at the antenna surface, in the near-field, and in the far-field are presented in Appendix A. As noted above, these power density levels represent the maximum instantaneous power density from the antenna and are not representative of the lower time-averaged exposure that a person would experience, as they do not account for the duration of exposure and other operational attributes of the antennas, such as their directional gain, dynamic beam steering, and auto-off functionality.

To ensure proper functioning of the CTs, Amazon will instruct users to mount the CTs above head height and free of potential blockage by surrounding objects or people. Under these conditions, the general population could only be exposed to off-axis RF energy in the far-field, and main-beam illumination will not be possible. Off-axis power density levels in the far-field and near-field are presented in Appendix A and summarized in Table 2. As demonstrated by these calculations, the off-axis far-field and off-axis near-field power density of each CT type are well below the general population MPE limit.

Table 2: Off-axis Power Density Levels

	Unit	TYPE I	TYPE II	TYPE III
Near-Field Distance (R_{nf})	meters	0.60	0.83	3.24
Near-Field Off-Axis Power Density ($S_{nf\text{-}offaxis}$)	mW/cm^2	0.21	0.34	0.31
Far-Field Distance (R_{ff})	meters	1.45	1.99	7.77
Far-Field Off-Axis Power Density ($S_{ff\text{-}offaxis}$)	mW/cm^2	0.004	0.004	0.0002
FCC MPE	mW/cm^2	1.0	1.0	1.0
Meets MPE Limit		Yes	Yes	Yes

Amazon also calculated the time-averaged exposure to a person in close proximity to and at the same elevation of a CT, such that the CT transmit beam may directly illuminate the person. Such direct illumination would be momentary before the CT transmit beam either turns off due to link blockage or is steered in another direction. These time-averaged exposure levels include main-beam and off-axis exposure time intervals, and consider the above-described properties of the Amazon CTs that will intrinsically limit human exposure. The combined effect of (1) each CT's auto-off functionality when the main-beam is blocked by a nearby person, and (2) dynamic beam-steering that prevents continuous illumination by the main-beam, ensures that a person cannot be illuminated continuously by the CT main-beam.

Given that the CT beams will be in motion tracking Kuiper System satellites, the number of times a CT beam is steered in the direction of a nearby person, and thus the average exposure to a nearby person, will depend on a CT's position on earth relative to the satellites in the Kuiper System, and the position of a nearby person relative to the CT. The minimum elevation angle for CTs in all geographies will be 35°, and they will all have an azimuth range of 0-360°, but the average elevation angle and average azimuth angle for a CT will depend on the latitude of the CT. To determine the worst-case beam steering scenario, Amazon simulated the beam steering for antennas at variety of latitudes and person positions relative to the antenna. Amazon performed these simulations over hundreds of 30-minute time windows to identify the worst-case exposure scenario (i.e., the scenario with the highest number of potential direct exposure events over a 30-minute period). For this worst-case scenario, Amazon modeled the power density in the direction of the person in one-second increments, then averaged this exposure level over the 30-minute time window. By using a combination of worst-case assumptions, this analysis is extensively conservative.

This analysis is detailed in Appendix B and the results are summarized in Tables 3, 4, and 5. For the Type I and Type II CT antennas, the maximum computed time-averaged RF exposure meets the MPE limit for a person at the near-field boundary and far-field boundary distances. For the Type III CT, a person at the near-field boundary distance and same elevation as the CT would never be directly illuminated by on-axis RF energy, as the CT's 35° minimum elevation angle ensures that the boresight of the transmitting beam would be above the person's head.[4] Therefore, for the Type III CT, a closer distance within the near-field was analyzed to demonstrate compliance with the time-average MPE limit.

Table 3: 30-minute Average RF Exposure from Type I CT at Same Elevation as Person

Exposure Region	Unit	Near-Field	Far-Field
Distance from Antenna	Meters	0.60	1.45
Time-Averaged Exposure	mW/cm^2	0.59	0.31
FCC MPE	mW/cm^2	1.0	1.0
Meets MPE Limit		Yes	Yes

[4] For a CT transmitting at the minimum elevation angle of 35 degrees, a 1.8m tall person would not be directly illuminated by on-axis RF energy at distances greater than 2.6m, as the Z-axis of the beam would be above the person's head.

Table 4: 30-minute Average RF Exposure from Type II CT at Same Elevation as Person

Exposure Region	Unit	Near-Field	Far-Field
Distance from Antenna	Meters	0.83	1.99
Time-Averaged Exposure	mW/cm^2	0.87	0.03
FCC MPE	mW/cm^2	1.0	1.0
Meets MPE Limit		Yes	Yes

Table 5: 30-minute Average RF Exposure from Type III CT at Same Elevation as Person

Exposure Region	Unit	Near-Field	Far-Field
Distance from Antenna	Meters	1.25	7.77
Time-Averaged Exposure	mW/cm^2	0.70	0.0004
FCC MPE	mW/cm^2	1.0	1.0
Meets MPE Limit		Yes	Yes

V. ADDITIONAL SAFETY MEASURES

Amazon will instruct users to mount the CTs above head height, where a clear line-of-sight free of any obstruction to the satellites can be achieved. Additionally, Amazon documentation that is presented to the user will communicate that the CTs shall be installed and operated to ensure the minimum separation distances for the general population in Tables 3, 4 and 5, above. Amazon CTs will comply with the requirements in Section 1.1307 of the Commission's Rules.

VI. CONCLUSION

This analysis demonstrates that the Amazon CTs each satisfy Commission requirements to not exceed the MPE limit of 1 mW/cm^2 averaged over a thirty-minute period. Specifically, Amazon CTs will typically be mounted above human height, preventing main-beam human exposure. In the event that a human body is illuminated by the CT's main-beam, the intrinsic shut-off feature ceases transmission in the presence of a body blockage, and beam steering prevents continuous exposure.

Appendix A: Detailed Power Density Calculations

Table A.1: Power Density from Type I CT Antenna

Input Parameters	
Frequency	29.0 GHz
Wavelength, $\lambda = \frac{c}{f}$	0.0103 m
Diameter of Antenna (Maximum Dimension)	15.8 cm
Area of Antenna	180.0 cm^2
Antenna Efficiency, η	78.5%
Average Power into Antenna (Includes transmit duty cycle of 30%)	0.75 W
Antenna Gain	31.0 dBi
Calculated Values	
Near-Field Distance, $R_{nf} = \frac{D^2}{4\lambda}$	0.60 m
Far-Field Distance, $R_{ff} = \frac{0.6D^2}{\lambda}$	1.45 m
Maximum Power Density Calculations	
Power Density at Antenna Surface, $S_{surface} = \frac{4P}{A}$	16.7 mW/cm^2
Near-Field Power Density (Maximum, On-Axis), $S_{nf} = \frac{4P}{\eta A}$	21.2 mW/cm^2
Far-Field Power Density (Maximum, On-Axis), $S_{ff} = \frac{PG}{4\pi R^2}$	3.6 mW/cm^2
Off-Axis Power Density Calculations	
Near-field Off-Axis Power Density Reduction [5]	20 dB
Near-Field Power Density (Off-Axis), $S_{nf-offaxis} = \frac{4P}{100\eta A}$	0.21 mW/cm^2
Far-Field Off-Axis Gain[6], $G(\varphi) = 52 - 10\log\left(\frac{D}{\lambda}\right) - 25\log(\varphi)$	1.56 dBi
Far-Field Power Density (Off-Axis), $S_{ff-offaxis} = \frac{PG(\varphi)}{4\pi R^2}$	0.004 mW/cm^2

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[5] *See* OET Bulletin 65 at 30 ("For off-axis calculations in the near-field and in the transition region it can be assumed that, if the point of interest is at least one antenna diameter removed from the center of the main beam, the power density at that point would be at least a factor of 100 (20 dB) less than the value calculated for the equivalent distance in the main beam (see Reference [15])" (alteration in original).).

[6] *See id.* ("For practical estimation of RF fields in the off-axis vicinity of aperture antennas, use of the antenna radiation pattern envelope can be useful."). OET Bulletin 65 considers use of the Commission's Rules for antenna sidelobe gain patterns that apply to geostationary satellite earth station antennas. This analysis uses the earth station antenna pattern contained in Annex 3b of the ITU Radio Regulations for fixed-satellite service earth station antennas with a $\frac{D}{\lambda} < 100$. The off-axis angle is conservatively assumed to be minimum elevation angle of the CT.

Table A.2: Power Density from Type II CT Antenna

Input Parameters	
Frequency	29.0 GHz
Wavelength, $\lambda = \frac{c}{f}$	0.0103 m
Diameter of Antenna (Maximum Dimension)	18.5 cm
Area of Antenna	268.8 cm^2
Antenna Efficiency, η	78.5%
Average Power into Antenna (Includes transmit duty cycle of 30%)	1.8 W
Antenna Gain	34.0 dBi
Calculated Values	
Near-Field Distance, $R_{nf} = \frac{D^2}{4\lambda}$	0.83 m
Far-Field Distance, $R_{ff} = \frac{0.6D^2}{\lambda}$	1.99 m
Maximum Power Density Calculations	
Power Density at Antenna Surface, $S_{surface} = \frac{4P}{A}$	26.8 mW/cm^2
Near-Field Power Density (Maximum, On-Axis), $S_{nf} = \frac{4P}{\eta A}$	34.1 mW/cm^2
Far-Field Power Density (Maximum, On-Axis), $S_{ff} = \frac{PG}{4\pi R^2}$	9.12 mW/cm^2
Off-Axis Power Density Calculations	
Near-field Off-Axis Power Density Reduction [7]	20 dB
Near-Field Power Density (Off-Axis), $S_{nf-offaxis} = \frac{4P}{100\eta A}$	0.34 mW/cm^2
Far-Field Off-Axis Gain[8], $G(\varphi) = 52 - 10\log\left(\frac{D}{\lambda}\right) - 25\log(\varphi)$	0.87 dBi
Far-Field Power Density (Off-Axis), $S_{ff-offaxis} = \frac{PG(\varphi)}{4\pi R^2}$	0.004 mW/cm^2

[7] *See supra* n.5.

[8] *See supra* n.6.

Table A.3: Power Density from Type III CT Antenna

Input Parameters	
Frequency	29.0 GHz
Wavelength, $\lambda = \frac{c}{f}$	0.0103 m
Diameter of Antenna (Maximum Dimension)	36.6 cm
Area of Antenna	660.0 cm^2
Antenna Efficiency, η	58.9%
Average Power into Antenna (Includes transmit duty cycle of 30%)	3 W
Antenna Gain	38.0 dBi
Calculated Values	
Near-Field Distance, $R_{nf} = \frac{D^2}{4\lambda}$	3.24 m
Far-Field Distance, $R_{ff} = \frac{0.6D^2}{\lambda}$	7.77 m
Maximum Power Density Calculations	
Power Density at Antenna Surface, $S_{surface} = \frac{4P}{A}$	18.2 mW/cm^2
Near-Field Power Density (Maximum, On-Axis), $S_{nf} = \frac{4P}{\eta A}$	30.9 mW/cm^2
Far-Field Power Density (Maximum, On-Axis), $S_{ff} = \frac{PG}{4\pi R^2}$	2.49 mW/cm^2
Off-Axis Power Density Calculations	
Near-field Off-Axis Power Density Reduction [9]	20 dB
Near-Field Power Density (Off-Axis), $S_{nf-offaxis} = \frac{4P}{100\eta A}$	0.31 mW/cm^2
Far-Field Off-Axis Gain[10], $G(\varphi) = 52 - 10\log\left(\frac{D}{\lambda}\right) - 25\log(\varphi)$	-2.1 dBi
Far-Field Power Density (Off-Axis), $S_{ff-offaxis} = \frac{PG(\varphi)}{4\pi R^2}$	0.0002 mW/cm^2

[9] *See supra* n.5.

[10] *See supra* n.6.

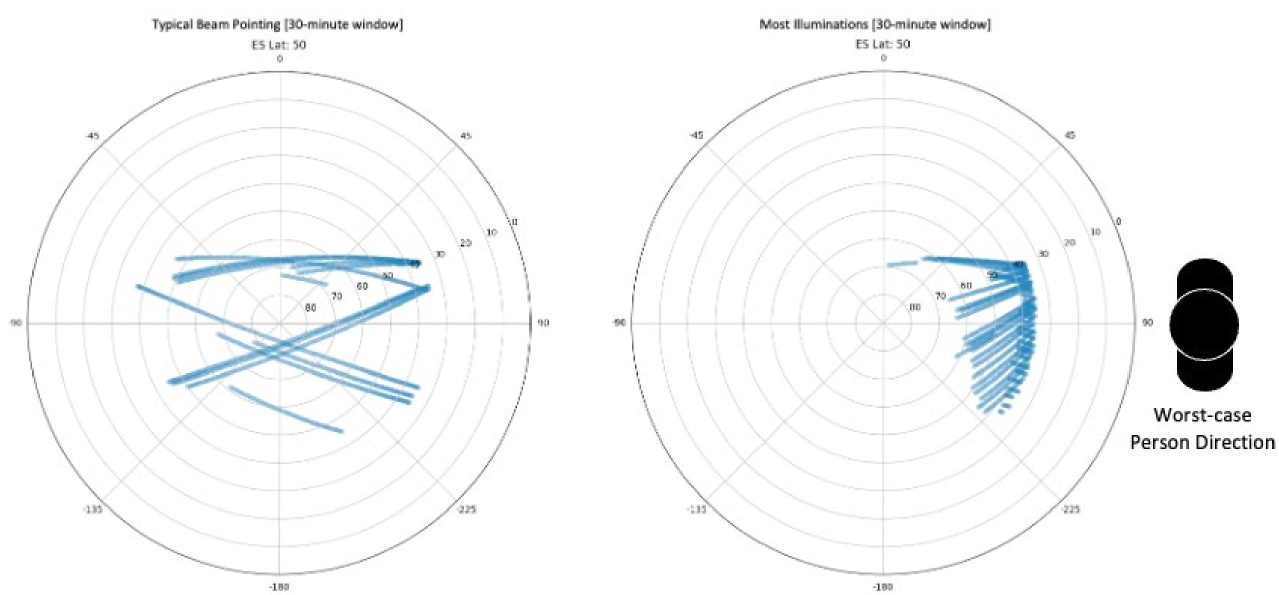
Appendix B: Time-Averaged Exposure Analysis

This appendix provides a detailed explanation of Amazon's time-averaged RF exposure analysis.

To determine the worst-case beam steering scenario, Amazon simulated the beam steering for antennas as they will track the Kuiper System constellation orbits at a variety of latitudes and person positions relative to the antenna. Amazon performed these simulations over hundreds of 30-minute time windows to identify the worst-case exposure scenario, in which a person would most frequently experience direct illumination. Figure B.1 shows a CT's beam pointing throughout a 30-minute window on azimuth/elevation polar plots. The left figure shows a typical 30-minute window, whereas the right figure shows the pointing over a worst-case 30-minute window.

Figure B.1. CT Beam Pointing Examples

Polar plots represent antenna beam pointing in Azimuth and Elevation.



For the worst-case geometric scenario and time window represented above, Amazon modeled the precise beam steering behavior of the antenna and potential exposure to a nearby person in one-second increments. For each time step, Amazon calculated the power density along the main-beam axis and the power density in the direction of the person, applying off-axis power density reductions and spatial averaging as appropriate.[11] For periods when the beam is sufficiently blocked to cause the antenna to automatically cease transmissions (see Appendix C), the power density is set to 0 mW/cm^2. Amazon then averaged the exposure levels over the 30-minute time window. Below, the results are shown for the three CT antenna types at distances in the near-field for each. The figures below show (1) the incident power density at the person as a function of the beam pointing direction, using the same worst-case beam pointing scenario represented in Figure B.1 above, and (2) histograms of the power density in the direction of the person, along with the time-averaged exposure as a vertical line. These figures demonstrate that even in the conservative case, a nearby person would be exposed to low power density levels through most of the averaging time-window.

[11] For the near-field off-axis power density model, Amazon relied on previous work documented in *An Efficient and Accurate Method for Calculating and Representing Power Density in the Near-Zone of Microwave Antennas*. *See* Richard L. Lewis and Allen C. Newell, National Bureau of Standards, U.S. Department of Commerce, NBSIR 85-3036, *An Efficient and Accurate Method for Calculating and Representing Power Density in the Near-Zone of Microwave Antennas* (1985).

Figure B.2. Time-Averaged RF Exposure for Type I Antenna at 0.6m Distance (Left: RF Exposure by Beam Pointing Direction; Right: Histogram of RF Exposure over 30-minute Window)

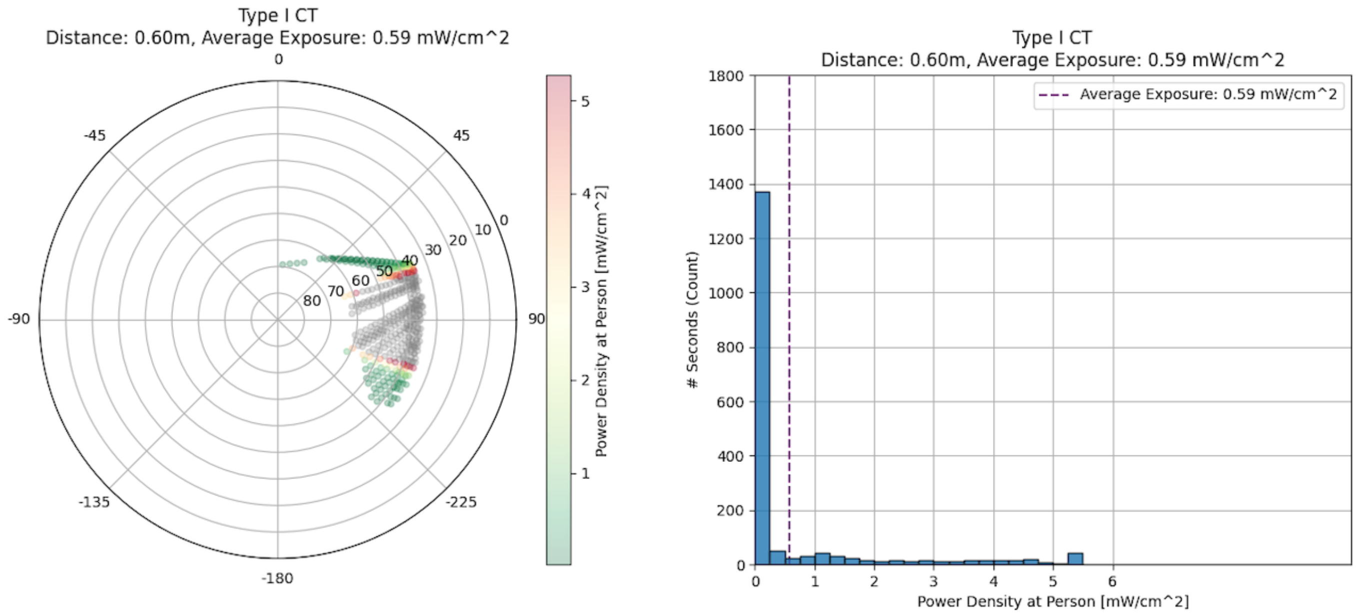


Figure B.3. Time-Averaged RF Exposure for Type 2 Antenna at 0.83m Distance (Left: RF Exposure by Beam Pointing Direction; Right: Histogram of RF Exposure over 30-minute window)

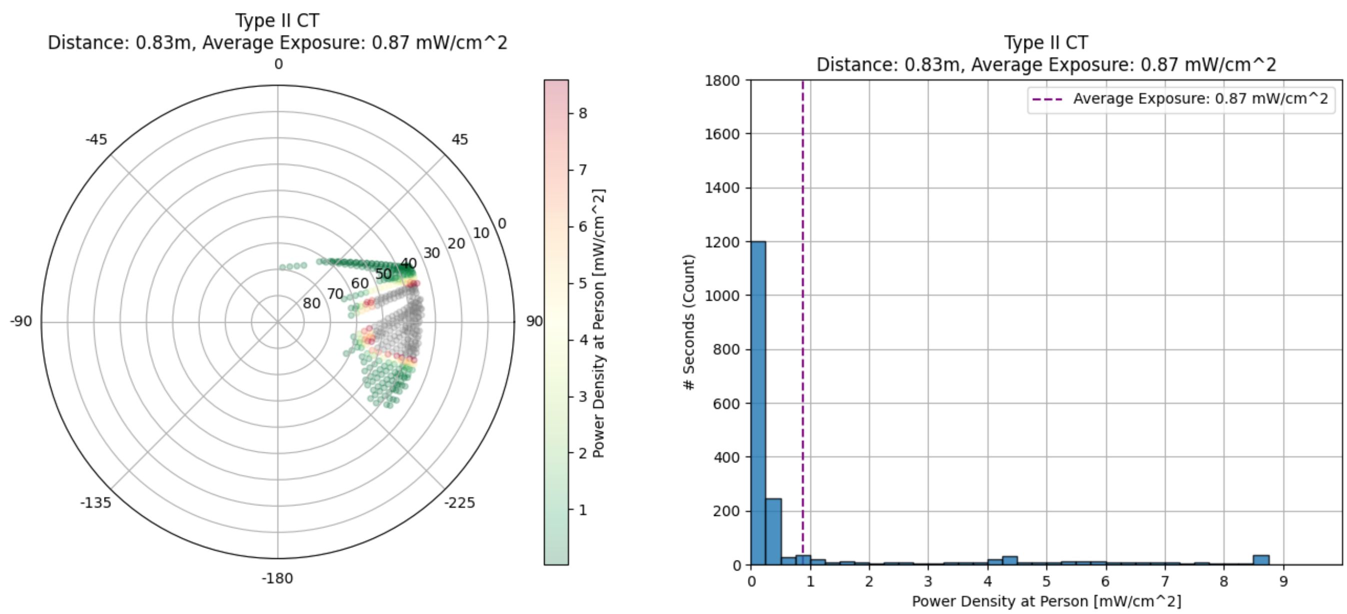
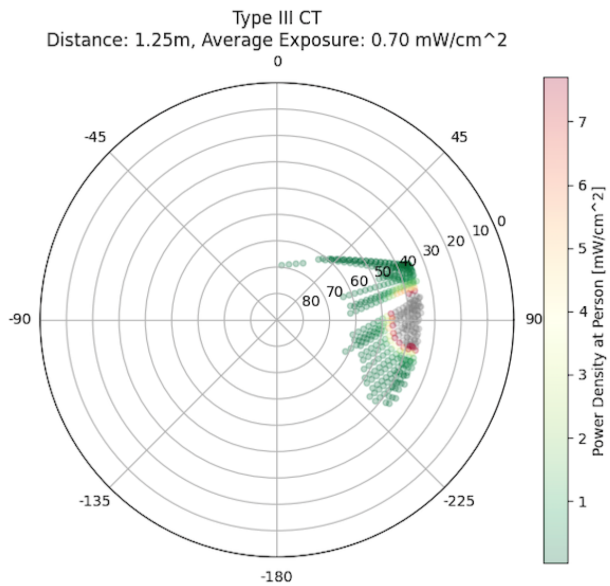
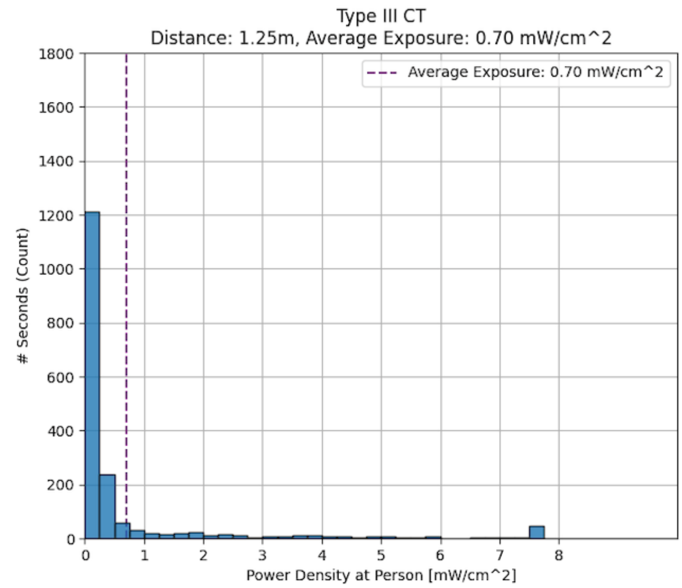


Figure B.4. Time-Averaged RF Exposure for Type 3 Antenna at 1.25m Distance (Left: RF Exposure by Beam Pointing Direction; Right: Histogram of RF Exposure over 30-minute Window)





In the above time-averaged exposure analysis, Amazon applied spatial averaging for near-field exposure. In an *X-Y* plane that represents a cross section of the beam normal to direction of propagation, *Z*, the power density, contains peaks (e.g., 4P/*Ae* in OET 65 Eq 12) and nulls that occur with off-axis angle and oscillate with axial distance from the antenna that are caused by Fresnel zone diffraction.[12] The Amazon analysis uses the total transmitter power, *P*, and the effective area, *Ae*, of the beam for its spatial average to calculate the total power density contained within the beam and which may radiate the body over a time window. This is consistent with the Commission's current rules and Amazon's application based upon the beam causing "whole body" exposure. The Commission addressed spatial-peak localized power density averaging, noting that

[12] *See* E.V. Jull, *Aperture Antennas and Diffraction Theory* 46-47 (1981).

4mW/cm^2 (4*X*) may apply in the future.[13] Amazon notes that a factor of "4" would be consistent with the current OET 65 maximum, on-axis power density formula Eq 12 – 4*P*/*Ae*, which peaks with a factor of "4." The Amazon calculation computes an upper bound of the power density over the beam cross sectional area, *P*/*Ae*, by assuming that all the transmitter power is real-valued, and is completely contained within the effective area of the beam—this approach results in the highest possible exposure to a "whole body."

[13] *See Proposed Changes in the Commission's Rules Regarding Human Exposure to Radiofrequency Electromagnetic Fields et al*, Report and Order, Notice of Proposed Rulemaking, Memorandum Opinion and Order, 34 FCC Rcd 11687 ¶ 127 (2019).

Appendix C: Body Loss Measurements

I. BACKGROUND

When the CTs lose a receive signal due to blockage, the transmitter is shut down until the downlink is restored. This shutdown occurs within a millisecond of losing the downlink. This feature prevents continuous human exposure by the CT main-beam at the antenna surface, in the near-field and in the far-field. To prove the efficacy of the auto-off functionality in preventing continuous human exposure, Amazon measured the attenuation caused by human blocking of the CT antenna beam. This Appendix details these measurements.

II. TEST SETUP

In a fully anechoic chamber, two paths were created—a physical path for a person to stand and a radio beam path between a CT (receive antenna) and a horn antenna (transmitting antenna). The physical and radio beam paths were precisely aligned with a laser range finder and by pointing CT and transmitting horn beams for maximum power. The beam was 1.5m above and parallel to the floor and illuminated the torso at chest height. At the transmitting end, a conical horn was used to radiate a constant power LHCP modulated signal at 18.5 GHz to simulate a Kuiper System satellite downlink, and at the receiving end a Type II CT was mounted at 60° to the floor with its beam electronically pointed precisely at the transmitting horn. This was done to ensure that the beam area and propagation path matched conditions that would be present in actual operations.

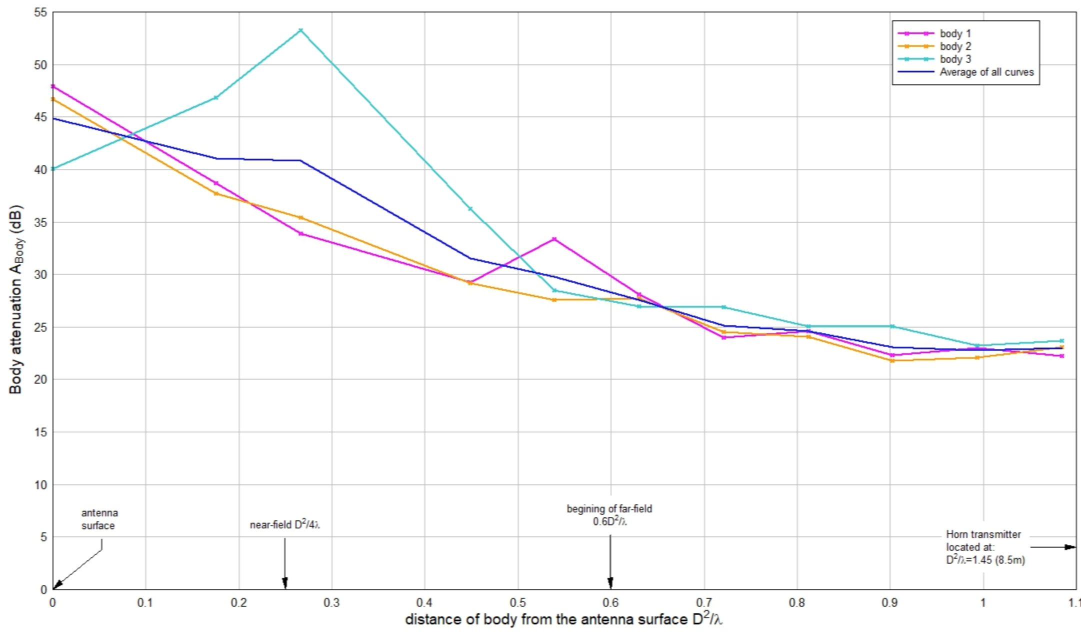
III. ON-AXIS MEASUREMENTS

Without a body present, the signal power from the CT is recorded as P_1. A human body is then introduced into the center of the beam path at on-axis distances, every 0.5m.[14] For each location, ten power measurements were made and logged by the spectrum analyzer and the average

[14] All measurements were made with the body in the far-field of the transmitting horn antenna.

calculated as P_2. The body loss at each distance, $A_{body} = P_1 - P_2$, was calculated and plotted in Figure C.1.

Figure C.1. Attenuation Caused by Body Blockage (On-Axis)



At all distances up to 2.4m[15] from the CT the body loss is 30dB or greater, exceeding the attenuation threshold which causes the CT to lose reception of the satellite downlink, and therefore to cease transmitting.[16]

IV. OFF-AXIS MEASUREMENTS

Measurements were taken with a body at various distances outside of the on-axis path. The results of these measurements are shown in Figure C.2 below. The off-axis measurements showed that when body #1 was moved out of the beam path by 60 cm the attenuation dropped, indicating that the beam is less affected by the body outside of a narrow path.

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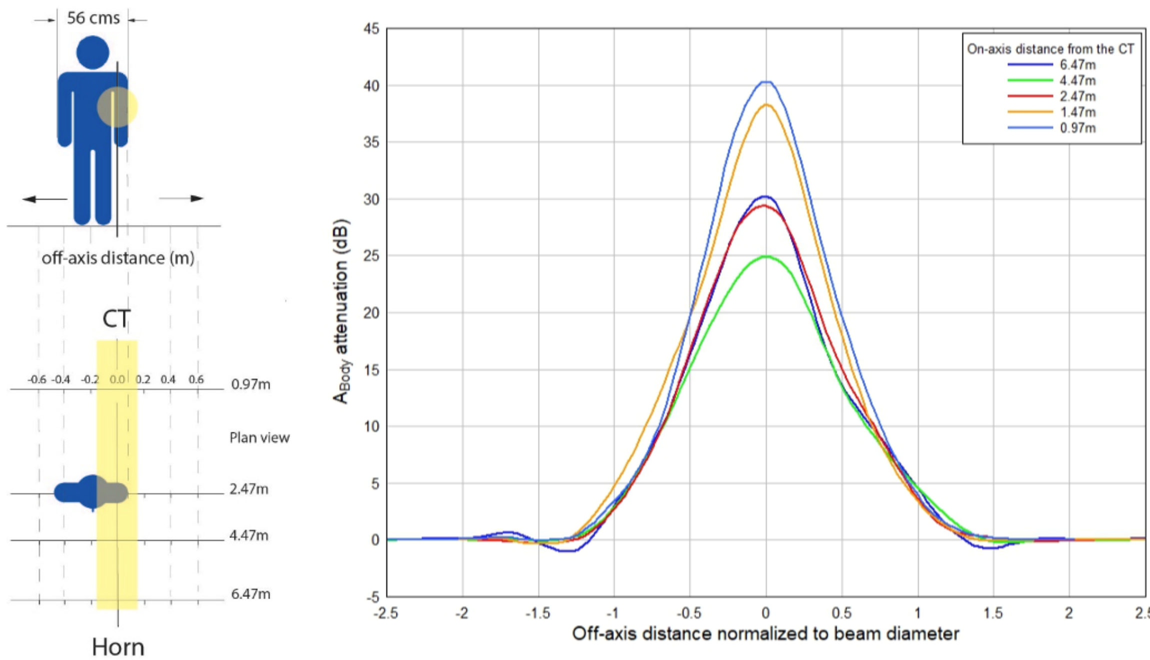
[15] 2.4m or greater is the distance at which the beam passes over a person's head when the antenna base is at the same height as the person.

[16] The maximum power-flux density for Kuiper System customer terminal downlinks is -113 dBW/m^2/MHz. With the highest receive-gain CT and under best-case conditions and the shortest slant-range, the C/N is computed to be 21.0 dB. Typical link performance will vary due to additional scan-loss and placement of the CT within a beam.

Figure C.2. Attenuation Caused by Body Blockage (Off-Axis)



V. MEASUREMENT CONCLUSIONS

These measurements demonstrate that the attenuation caused by a body in the path of a Kuiper System downlink beam will be significant and will greatly exceed the CT receive threshold, causing the CT to reliably stop transmitting. The attenuation levels exceed the CT receive threshold when the body is at the antenna surface, in the near-field, and in the far-field out to distances in which a human body may be directly illuminated by a CT at the same height as a person.