Non-Ionizing RF Radiation Hazard Assessment for the Connexion by Boeing^{SM} Ku-Band Transmit Antennas

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1. Introduction

This analysis assesses the compliance of the Connexion by Boeing^{SM} aircraft earth station ("AES") transmit antennas with the limits for human exposure to radiofrequency ("RF") fields adopted by the Federal Communication Commission ("FCC"). The Boeing AES transmit antennas under consideration, shown in Figures 1 and 2, are an oval shaped 873-element electronically scanned phased array and a mechanically steered reflector antenna.

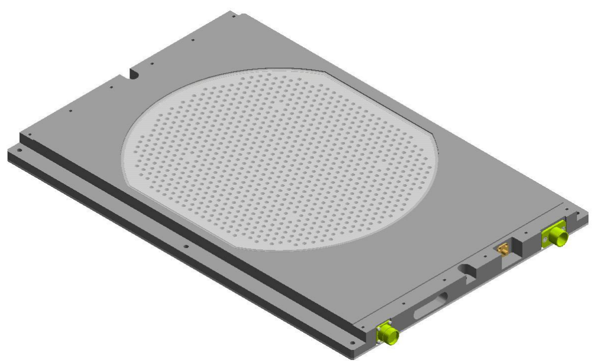

Figure 1. Phased Array Antenna

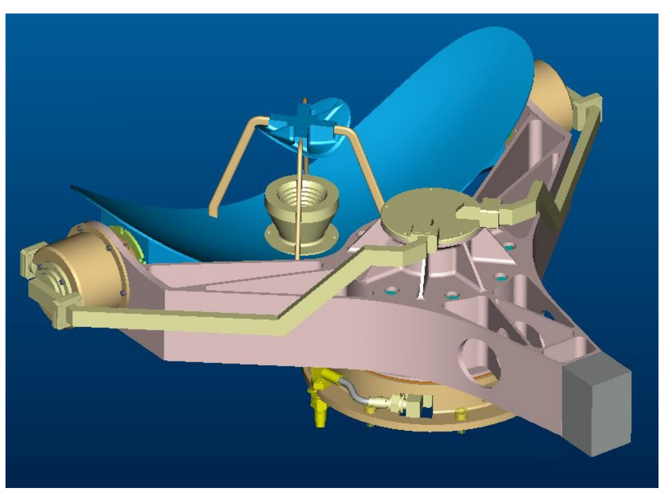

Figure 2. Reflector Antenna

The primary difference for purposes of this analysis between the two antennas is that there is no loss of gain with increasing scan angle in the reflector antenna as there is in the phased array antenna. The total transmit power of the reflector antenna is approximately the same as that of the phased array antenna at scan angles near 55° from zenith, and there is very little change in the horizontal extent of the hazardous zone (except that it will remain constant with scan angle). Both antennas are installed along the crown of the aircraft and, to communicate with satellites, the antennas point upwards and electronically or mechanically scan towards the serving satellite.

For a typical aircraft, the system will be switched on at the same time that the aircraft cabin power busses are powered on, but the transmitter is muted until a receive link is initiated. Because the AES may operate while the aircraft is on the ground, this analysis of the RF non-ionizing radiation levels studies the following exposure regions:

- RF radiation below the antenna towards nearby crew and passengers;
- RF radiation above the plane of the antenna where the maintenance crew may be working; and
- RF radiation impinging upon nearby airport facilities.

In order to ensure that the general public and workers are protected from exposure to harmful radiofrequency radiation when the aircraft is on the ground, a minimum safe distance around the antenna is defined to ensure that the exposure levels are below the maximum safe exposure limits.

2. Radio Frequency Radiation Safety Limits

The FCC RF and microwave exposure standards used in this analysis were derived from the recommendations of two expert organizations, the National Council on Radiation Protection and Measurements ("NCRP") and the Institute of Electrical and Electronic

Engineers ("IEEE"). The relevant safety limits for maximum permissible exposure, are summarized below:

Summary of RF Exposure Guidelines:

Frequency Range (MHz)	Electric Field Strength (E) (V/m)	Magnetic Field Strength (H) (A/m)	Power Density (S) (mW/cm^2)	Averaging Time $\|E\|^2$, $\|H\|^2$ or S (minutes)
(A) Limits for *Occupational/Controlled* Exposure (Note 1)				
1500-100,000	--	--	5	6
(B) Limits for *General Population/Uncontrolled* Exposure (Notes 2, 3)				
1500-100,000	--	--	1.0	30

Note 1: ***Occupational/controlled*** limits apply in situations in which persons are exposed as a consequence of their employment provided those persons are fully aware of the potential for exposure and can exercise control over their exposure. Limits for occupational/controlled exposure also apply in situations when an individual is transient through a location where occupational/controlled limits apply provided he or she is made aware of the potential for exposure.

Note 2: ***General population/uncontrolled*** exposures apply in situations in which the general public may be exposed, or in which persons that are exposed as a consequence of their employment may not be fully aware of the potential for exposure or cannot exercise control over their exposure.

Note 3: A power density of 1.0 mW/cm^2 is mathematically equivalent to 10.0 W/m^2.

The maximum exposure levels used in this analysis are defined in terms of power density (units of Watts per square meter: W/m^2). The maximum exposure level for occupational exposure at 14 – 14.5 GHz is 50 W/m^2, average power density, over a *six* minute period. The maximum exposure level for the general public at this same frequency range is 10 W/m^2, average power density, over a *thirty* minute period. For purposes of this analysis, only the general public exposure limit will be used. It is important to remember that these limits are *exposure* limits, and not *emission* limits, and they are only relevant to locations that are accessible to workers and the general public.

As the following sections will show, the only potential RF radiation hazard from the Connexion system is to workers above the antenna. The general public will not be exposed to harmful levels of microwave energy primarily because the location of the antenna on the top of the airplane limits access to the general public.

3. Summary Results

A summary of the radiation hazard analysis is shown in Table 1. The only potential RF radiation hazard is to airline workers above the antenna when the aircraft is on the ground. Accordingly, the system will be disabled or muted so that microwave energy is not emitted whenever workers are above the horizontal plane of the antenna, for example during de-icing procedures. The following sections will detail this analysis and define the personnel exclusion zone that will protect workers from any RF radiation hazards when the system is enabled.

Table 1 Radiation Hazard Analysis Summary

Par.	Spatial Region	RF Hazard Assessment	Remedy
5.2	Near-by crew and passengers below the horizontal plane of antenna	None	Not necessary
5.4	Above the antenna	RF radiation hazard to personnel	Personnel exclusion zone defined and/or system disabled.
5.5	Facilities in the far-field main-beam	None	Not necessary.

4 Antenna Parameters

4.1 Phased Array and Reflector Antenna Patterns

Because of the highly directional nature of Boeing's AES antennas, for any scan angle only a very small portion of the upper hemisphere contains harmful RF radiation.[1] For example, the narrow beamwidth of the phased array antenna at 14.25 GHz and a scan angle of 0^{o} scan is shown in Figure 3. This pattern shows that in the far field region, outside the approximately 3.5^{0} main-beam, the power is at least 15 dB, or 97% lower than in the main-beam.

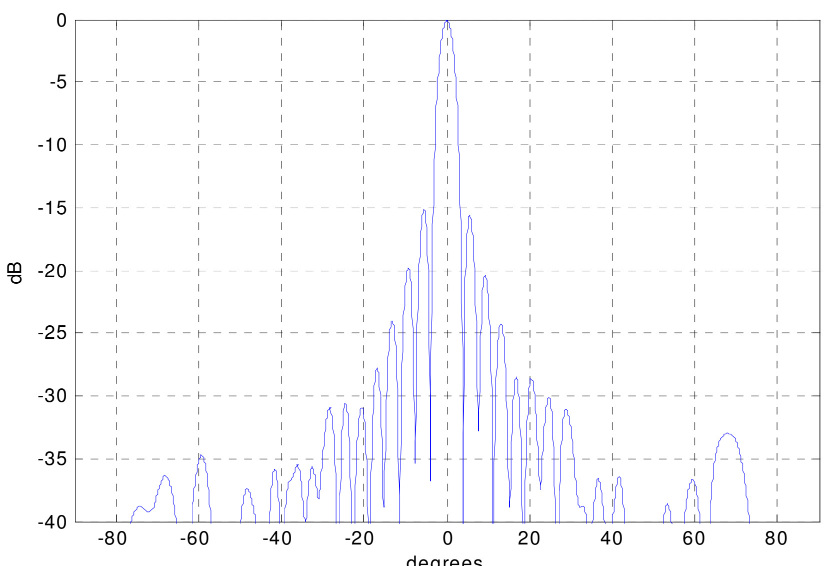

Figure 3. Phased Array Antenna Pattern, 14.25 GHz, On-Axis

The antenna patterns for the reflector antenna are shown in Figures 4 and 5. As shown in Figure 2 and Table 3, the reflector antenna length in the azimuth dimension is significantly larger than its height in the elevation dimension. The wider azimuth

[1] The likelihood of significant human exposure to RF radiation is much less with a high gain antenna than with dipole and omni-directional antennas that have much broader beamwidths.

dimension creates a narrower beamwidth, shown in Figure 4, compared to the slightly larger beamwidth in the elevation dimension shown in Figure 5. The sidelobes of this antenna are also very low.

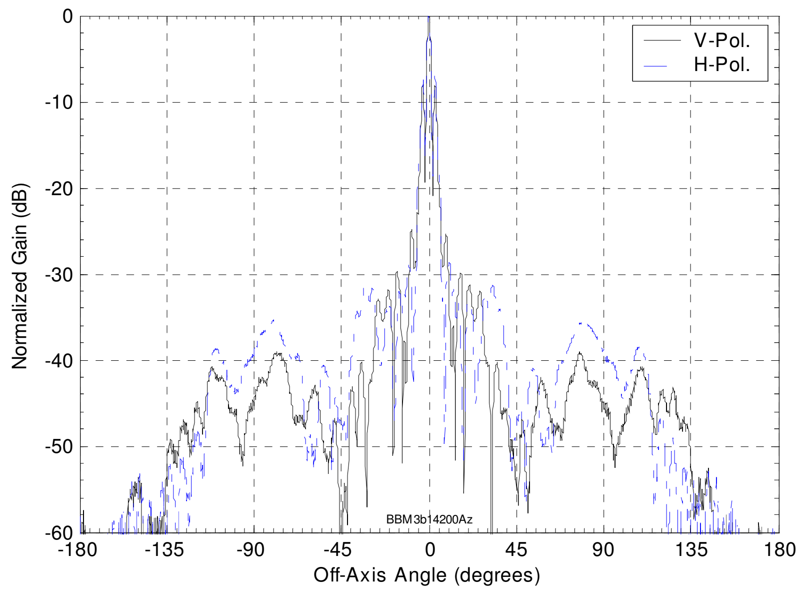

Figure 4. Reflector Antenna Azimuth Plane Transmit Pattern, 14.2 GHz

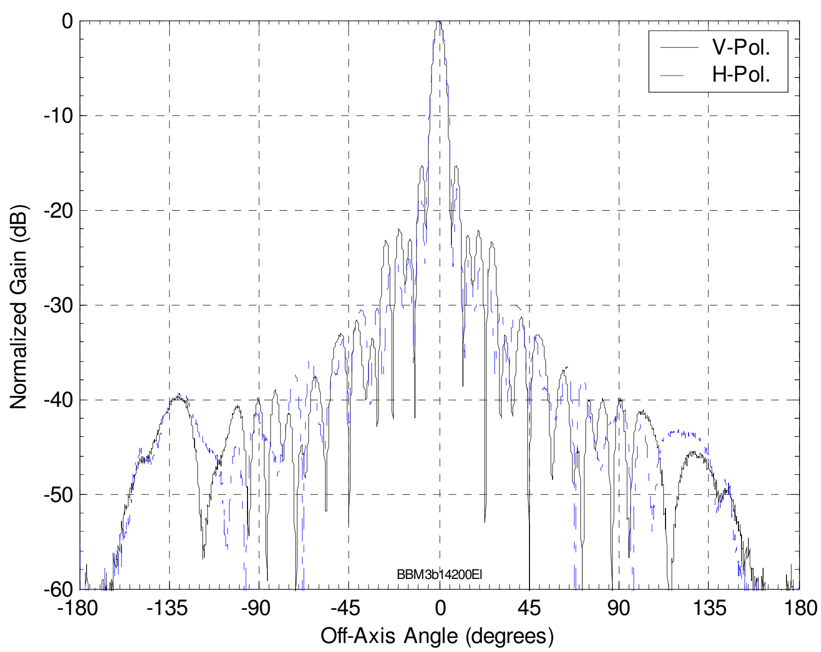

Figure 5. Reflector Antenna Elevation Plane Transmit Pattern @ 14.2 GHz

4.2 AES Antenna Specifications

The phased array antenna AES specifications are given in Table 2. The nominal EIRP needed for the highest data rate is 46.5 dBW. As indicated in Item 7, the maximum measured EIRP is 49.5 dBW, which is the highest expected transmit power on the ground.[2] Since this analysis assumes operation on the ground, the maximum measured EIRP of 49.5 dBW was used for all calculations.

Table 2 – Phased Array Antenna Parameters

1	Antenna diameter in longest dimension, D,	0.3704 m
2	Antenna surface area, $A = \pi * D^2/4$	0.1077 m^2
3	Wavelength at 14.25 GHz, λ,	0.0210 m
4	Antenna Beamwidths at zenith	3.3° x 3.5°
5	Bore-sight gain, $\mathbf{G_b} = 10*LOG(4*\pi*A/\lambda^2)$	34.86 dBi
6	Nominal EIRP at max data rate	46.50 dBWi
7	Maximum EIRP (typical, measured)	49.50 dBWi
8	Max power P = EIRP – G dBW	14.64 dBW = 29.1 W

Table 3 summarizes relevant antenna characteristics of the reflector antenna AES. The maximum EIRP of this antenna is 46.7 dBW, compared to 49.5 dBW (on the ground) for the phased array antenna on boresight, but because the reflector antenna does not suffer

[2] This differs from both the 42.2 dBW maximum EIRP value for on-ground operations and the 51.2 dBW maximum EIRP value for in-flight operations authorized by the FCC. As discussed in the narrative application, Boeing seeks elimination of the 42.2 dBW restriction while operating on the ground. However, Boeing would not object to a special condition limiting the maximum transmit power for the phased array antenna to 49.5 dBW while operating on the ground. The 51.2 dBW value is the predicted highest transmitter output at cruise altitude in very cold conditions, and thus should be maintained for in-flight operations.

the scan loss that is inherent to electronically scanned phased array antennas, the reflector antenna transmitted power is approximately equal to the transmitted power of the reflector antenna at lower scan angles. The reflector antenna AES can operate down to an elevation angle of 5° above the horizon without any loss in directive gain, although on the ground the elevation angle will be limited to 10º or greater (*i.e.*, a scan angle of 80º or less) to keep the RF radiation below the plane of the antenna within a safe level.

Table 3 – Reflector Antenna Parameters

Aperture Dimensions	65.0 cm x 19.6 cm elliptical
Antenna Beamwidth	2.0º × 6.2º
Transmit Gain	33.1 dBi 14.2 GHz
Maximum EIRP	46.7 dBW
Receive Gain	31.6 dBi at 12.0 GHz
G/T	10.5 dB/K
Minimum Elevation Angle	5º (10º on the ground)
Antenna Polarization	Linear

5. Calculation of Radiated Power Levels

The following regions characterize the RF field in front of the antenna:

Near-Field Region: A region in general proximity to an antenna in which the electric and magnetic fields do not necessarily decrease with distance away from the antenna, and do not approximate a plane-wave character, but vary considerably at equidistant points from the antenna. In this region the energy is essentially confined to a cylindrical pattern having the same diameter as the antenna.

Far-Field Region: The region of the field of an antenna where the angular field distribution is essentially independent of the distance from the antenna. In this region the field has a predominantly plane-wave nature; *i.e.*, locally uniform distribution of electric field strength and magnetic field strength in planes transverse to the direction of propagation.

In the literature of antenna theory, the distance from the antenna to the far-field zone is generally taken to be on the order of $2D^2/\lambda$, where D is the greatest dimension of the antenna and λ is the wavelength. This distance can be greater or smaller depending on the parameter of interest, for example, minimizing the phase difference from equidistant points from the antenna so that the electromagnetic waves approximate a plane wave. In the case of radiation hazard assessment, however, a shorter distance defining the beginning of the far-field zone is acceptable because it is the magnitude of the power levels that are of interest rather than the angle of the vector at each point.

From references [1] and [2], a realistic, practical distance from a large antenna where the far-field zone begins is:

$$R_f = 0.5\, D^2/\lambda \qquad (1)$$

where R_f = distance to the far-field region, in meters (m)
D = diameter of antenna in longest dimension, in meters (m)
= 0.37 meters for phased array antenna
= 0.65 meters for reflector antenna
λ = transmitter wavelength, 0.0210 meters for both antennas

Therefore,

$R_f = 0.5\, D^2/\lambda$
$= 0.5\,(0.3704)^2/0.0210 =$ **3.27 meters** (phased array antenna)
$= 0.5\,(0.650)^2/0.0210 =$ **10.0 meters** (reflector antenna)

5.1 Power Density Levels in the Near Field

The electromagnetic field in the near field is extremely complex and calculation of field strength at each point in the near field requires numerical integration methods. The energy in the near-field region is largely confined to a cylinder of diameter equal to the antenna diameter in the direction of the antenna scan angle. Figure 6 shows an example with the antenna pointed directly vertical at a 0^o scan angle. Computer analysis of the electrical fields in the area immediately above the phased array antenna and the reflector antenna has shown the maximum power density is approximately 1200 W/m^2. This is considerably greater than the general public exposure limits of 10 W/m², therefore the entire cylindrical near-field area for all scan angles is considered a hazardous area. Section 5.3 will define the minimum distance from the antenna in the far field to reduce the RF radiation to a safe level.

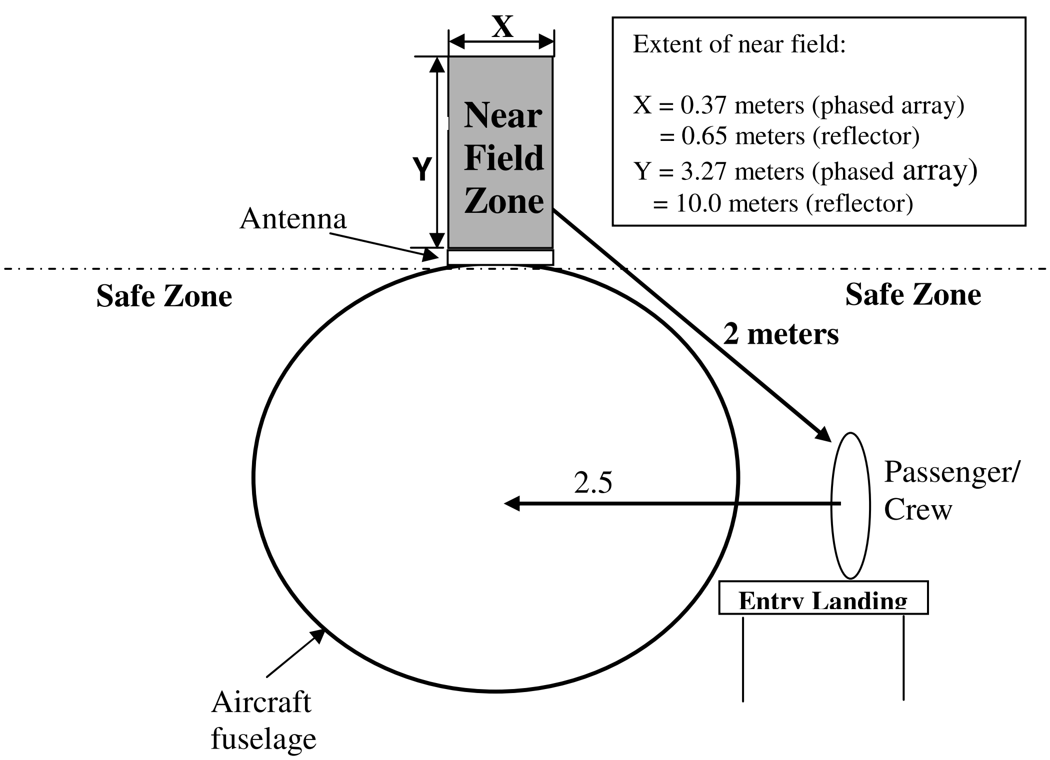

Figure 6. Uncontrolled Area vs. Near-Field Region

5.2 Power Density Levels in Passenger and Crew Areas Near the Antenna

Figure 6 shows an example of a passenger entering the plane from a staircase that is moved next to the airplane, rather then from an enclosed jetway. Measurements have been made on the antenna range with the phased array antenna to ensure that passengers entering an airplane immediately below the antenna as shown in Figure 6 are safe from harmful levels of RF radiation. To model the antenna mounted directly above the passenger door on a Boeing 737 fuselage,[3] measurements were made on a phased array antenna that was placed on a 72-inch radius cylinder. At the phased array antenna maximum scan angle of 63^o, the measured power density at the horizon 72 inches from the antenna was approximately 2 W/m^2, which is within safe limits. The microwave energy continues to decay very rapidly from that point towards the entry area below the antenna, therefore it is concluded that the phased array antenna produces no harmful RF radiation to people entering the airplane as shown in Figure 6.

Computer calculations were also made of power density levels at different scan angles from the reflector antenna in a vertical plane 2.1 meters from the fuselage center. At the maximum elevation angle of 10 degrees above the horizon, the power density on the horizon is at a safe level of 1 W/m^2 and decreases rapidly to below 0.1 W/m^2 at distances greater than a meter below the antenna.

It is therefore concluded that both Connexion transmit antennas present no RF radiation hazard in the near field to the general public and airline crews even if the antenna is installed immediately above the entry area of the aircraft.

5.3 Power Density Levels in the Far Field

Power density levels in the far field of the antenna are more predictable than in the near field, and are easily calculated from the standard range equation:

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[3] Both the phased array antenna and reflector antenna typically will be mounted farther back along the aircraft fuselage (rather than directly above the passenger door), and the Boeing 737 example analyzed here represents the smallest commercial aircraft on which AESs will be installed. Thus, the distances provided in Figure 6 are extremely conservative, and the actual distance between a transmitting AES and passengers/crews will be greater.

$$\text{Power Density} = \text{EIRP}/\ 4\pi r^2 \qquad \textbf{(2)}$$

Where EIRP (dBWi) = total power radiated from the antenna
r (meters) = distance from the antenna

The distance to the near field/far field boundary given by equation (1) is 3.27 meters and 10.0 meters for the phased array and reflector antenna, respectively. The maximum transmit power on the ground is 49.5 dBWi and 46.7 dBWi for the phased array and reflector antennas, respectively. Inserting these values for the EIRP in equation (2) gives the power densities at the beginning of the far field region for each antenna:

$$PD = 10^{4.95} / 4\pi(3.3)^2 = 663.28\ W/m^2 \qquad \text{(phased array)}$$
$$PD = 10^{4.67} / 4\pi(10.0)^2 = 37.2\ W/m^2 \qquad \text{(reflector)}$$

These values exceed the 10 W/m^2 maximum exposure level for the general public. The minimum distance, r_{min} , from the antenna where the exposure level does not exceed this safe level can be calculated by rearranging equation (2) and inserting 10 W/m^2 for the power density:

$$r_{min} = [\text{EIRP}/4\pi * \text{Power density}]^{0.5} \qquad \textbf{(3)}$$
$$= [10^{4.95} / 4\pi*10]^{0.5}$$
$$= \textbf{26.6 meters} \qquad \text{(phased array)}$$
$$r_{min} = [10^{4.67} / 4\pi*10]^{0.5}$$
$$= \textbf{19.3 meters} \qquad \text{(reflector)}$$

These distances are in the far-field zone of the antennas as calculated above using equation (1), and therefore the use of equation (2) to calculate power density levels is valid and will be used to define an exclusion zone for personnel located above the antenna when the transmitter is enabled.

5.4 Personnel Exclusion Zone Defined

In its earlier applications, Boeing showed that for its phased array antenna, the area below the horizontal plane is well below maximum RF exposure levels at the relevant power levels when the aircraft is in flight and on the ground.[4] Similarly, measurements of the reflector antenna on a cylindrical ground plane of the same size of a Boeing 737 fuselage have shown that at a 10^o elevation angle above the horizon the sidelobes are at least 16 dB below the main beam. The maximum EIRP of the reflector antenna is 46.7 dBW, 16 dB below this results in an EIRP of 30.7 dBW on the plane of the antenna. At the 10 meter distance to the far field of the reflector antenna where equation (2) is applicable, the power density is:

$$\text{Power Density} = \text{EIRP} / 4\pi r^2 \qquad \textbf{(4)}$$

$$\text{Power Density} = 10^{3.07} / 4\pi(10\text{ m})^2$$

$$\text{Power Density} = 9.4\ \text{W/m}^2$$

This level is within the 10 W/m^2 maximum exposure level for the general public.

To ensure personnel safety an exclusion zone was calculated above the horizontal plane of the antenna, which is defined as the locus of all points of the main-beam at all scan angles in the hemisphere above the antenna where the far-field PD equals 10 W/m^2. The transmit antenna is conservatively assumed to be mounted 8.5 m from the nose of a 737-800, which is the most forward antenna position on this airplane. The exclusion zone for both antennas is shown in Figure 7.

As shown in equation (3), the minimum safe distance from the reflector antenna, r_{min}, is a constant 19.3 m at all scan angles. Due to the nature of the electronically scanned

[4] *See* Radiation Hazard Study (dated Nov. 30, 2000), as supplemented Aug. 13, 2002, File Nos. SES-LIC-20001204-02300 and SES-MOD-20020308-00429, Call Sign E000723.

phased array antenna, the minimum safe distance near the phased array antenna varies as a function of scan angle. Measurements have shown the radiated power decreases approximately as $\cos^{1.2}(\theta)$, where θ is the antenna scan angle from zenith. Equation (3) with the $\cos^{1.2}(\theta)$ factor to account for the reduced power output with scan angle and 10 W/m^2 for the maximum exposure limit can be used to calculate the exclusion zone for the phased array antenna as a function of scan angle:

$$
\begin{aligned}
R\text{, meters} &= \mathrm{SQRT}[\ (\text{Max EIRP})*\cos^{1.2}(\theta)\ /\ (4\ \pi*\mathrm{MPE}_{\mathrm{Limit}})\ ] \qquad \textbf{(5)} \\
&= \mathrm{SQRT}[\ 10^{4.95}\ *\cos^{1.2}(\theta)\ /\ (\ 4\ \pi*10\mathrm{W}/)\ ] \\
&= 26.6 \text{ meters, } \theta = 0^{o} \text{ scan angle} \\
&= 19.9 \text{ meters, } \theta = 52^{o} \text{ scan angle} \\
&= 16.6 \text{ meters, } \theta = 63^{o} \text{ scan angle}
\end{aligned}
$$

At the maximum phased array scan angle of 63^{o}, the minimum distance is reduced from a maximum distance of 26.6 m to 16.6 meters. The 52^{o} scan angle is shown in this example because it corresponds to the maximum horizontal distance from the antenna of 15.7 meters. This equation can be used at all scan angles to obtain a “controlled” boundary for airline workers that is entirely above the plane of the phased array antenna, extending 26.6 meters directly above the antenna, and decreasing with scan angle from the vertical to 16.6 meters horizontally from the antenna at a 63 degree scan angle, as shown in Figure 7. Because of the size of this potential hazardous area, *customer airline procedures will ensure the transmitter power is turned off during any maintenance procedures above the antenna*, such as de-icing operations.

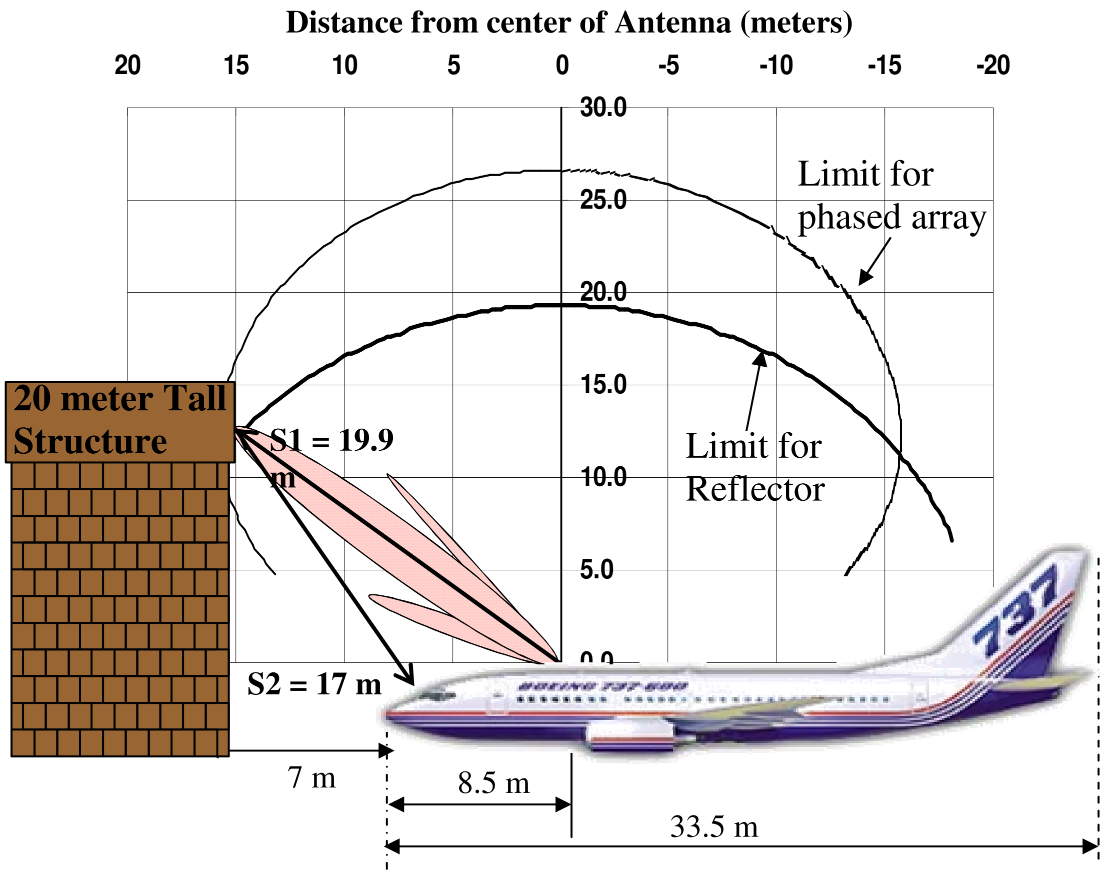

Figure 7. Potential Hazardous Volume Above the Aircraft on the Ground

5.5 Calculation of Far-Field Power Impinging Upon Adjacent Structures

Figure 7 also illustrates the possibility of an aircraft parked near an airport structure while the transmit antenna is active and scanned towards the structure. Normally, if either the transmit or the receive signal path from the airplane to the satellite is blocked the transmitter is shut down automatically. However, for consideration of the worst-case scenario it is assumed that the transmitter remains active at full power even when blocked by a building.

From equation (5), the phased array antenna potential hazardous area extends 26.6 meters vertically. At a 52^{o} scan angle this distance is reduced to 19.9 meters. This corresponds to the maximum lateral distance of 15.7 meters from antenna center (or 7.2 meters in front of the airplane) and is at a point 12.3 meters (about 4 stories) above the top of the airplane, as shown in Figure 7.

The reflector antenna gain is constant at all scan angles, which will result in a slightly longer lateral safe distance from the antenna at the 10^o elevation angle shown in the example of Figure 7. From equation (3) the minimum safe distance, r_{min}, is a constant 19.3 meters and the maximum lateral distance at a 10^o elevation will be cos(10)* 19.3 meters or 19.0 meters from the antenna center (10.5 meters in front of the plane).

This is the extent of the hazardous area in free space, without any obstructions blocking the transmit beam. As previously indicated, the transmitter will be turned off during maintenance operations when personnel may be near the antenna. Inside a building a person can be considered safe for a number of reasons.

First, microwave energy at 5.2 GHz is attenuated an average 12 dB when passing horizontally through a building wall [3].[5] Microwave energy at 14 GHz is attenuated more than energy at 5 GHz, and additional attenuation will occur at the higher incidence angles from the antenna to the building shown in Figure 7.

Second, to raise an RF exposure concern, a person must be located near the antenna (*i.e.*, within 7.2 meters in front of the plane for the phased array antenna and 10.5 meters in front of the plane for the reflector antenna), have an unobstructed line-of-sight to the antenna, experience no attenuation of the signal through a building, and remain stationary within the narrow mainbeam of the antenna for longer than the thirty-minute averaging

[5] Glass that is not reflective or tinted may have less attenuation than walls.

time of the FCC exposure guidelines.[6] The likelihood that a person with an unobstructed view of the antenna would remain stationary within the narrow mainbeam of the antenna for such an extended period is extremely remote.

Finally, the transmit antenna will automatically shut off if a building obstructs the antenna's view of the GSO satellite. Thus, if a person inside a building is within the mainbeam of the antenna, transmissions would cease automatically and the potential exposure to RF radiation would be eliminated.

For these reasons, it is concluded there is no RF radiation hazard to people located inside a building next to the airplane.

References

1. *Evaluating Compliance with FCC Guidelines for Human Exposure to Radiofrequency Electromagnetic Fields,* OET Bulletin 65, August 1997.
2. *IEEE Recommended Practice For The Measurement of Potentially Hazardous Electromagnetic Fields – RF and Microwave, Annex B,* IEEE Standard C95.3, 1991
3. ITU-R Recommendation P.1411-1*, Propagation Data and Prediction Methods for the Planning of Short-Range Outdoor Radiocommunication Systems and Radio Local Area Networks in the Frequency Range 300 MHz to 100 GHz.*

[6] The beam-width of the phased array antenna is less than 1.7 meters wide at this point. Figure 3 shows that outside the main-beam the power levels are reduced by at least 15 dB. This is also true for the reflector antenna. At the 80^o scan angle shown in Figure 7, and at the 19.3 meter distance from Equation (3), the beamwidth of the reflector antenna will only be about 2 meters. As with the phased array antenna, the reflector antenna patterns of Figures 4 and 5 show that anywhere outside this narrow beamwidth the power is at least 15 dB below the maximum EIRP, thereby reducing the RF exposure to safe a level.