Radiation Hazard Analysis
Lake Superior Experiment
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Summary Statement – EMAG Technologies is conducting an experiment to test performance of a radar that is being developed for a spaceborne application supported by a US government customer. The analysis in this report demonstrates that the radiation dosages experienced during radar operation are readily manageable, thus ensuring the safety of controlled and uncontrolled individuals per FCC guidelines.

1.0 Discussion of Experiment and Radar Operating CONOPs to Ensure Safe Radiation Limits

The antenna will be mounted on a tripod as close to the edge of Lake Superior as possible, near the city of Marquette, Michigan. Supporting radar equipment will be set up on a folding table nearby. The radar will send out pulses illuminating a drone carrying a target, located over the surface of the lake. The drone will be offset from the shore at a minimum distance of 600 meters, with drone height ranging from 20 to 200 meters above the lake surface. The radar antenna's boresight will range in elevation from just above 0º to about 20º, and the boresight projected to the ground (lake surface) will be perpendicular to the shoreline. The radar will be operated over 30 minutes continuously, with the time that the radar is actually transmitting energy at no more than 0.2 * 30 minutes = 6 minutes illumination.

It will be seen further on in this report from Tables 2 through 5 that on-axis illumination is the only area of concern, whether that be the near-field region (<0.25 meters), the transition region (0.25 to 0.59 meters), or the far zone region (>0.59 meters). It will be seen from the data further on in this report that we cannot have a civilian (uncontrolled person) on the water continuously over 30 minutes in the line of sight of the radar who is less than the safe far-field uncontrolled threshold of 2.7 meters from the radar. Mitigating factors are that the test will take place in the middle of April, and it is not anticipated that there will be any civilians bathing nor civilians in watercraft in the vicinity due to the frigid nature of the lake at this time. However, in the very unlikely event that civilians are within on the water, near the main beam illumination and within 30 feet of the radar, the radar can simply be switched off by the operator and the radar can be moved to another location without uncontrolled persons on the water.

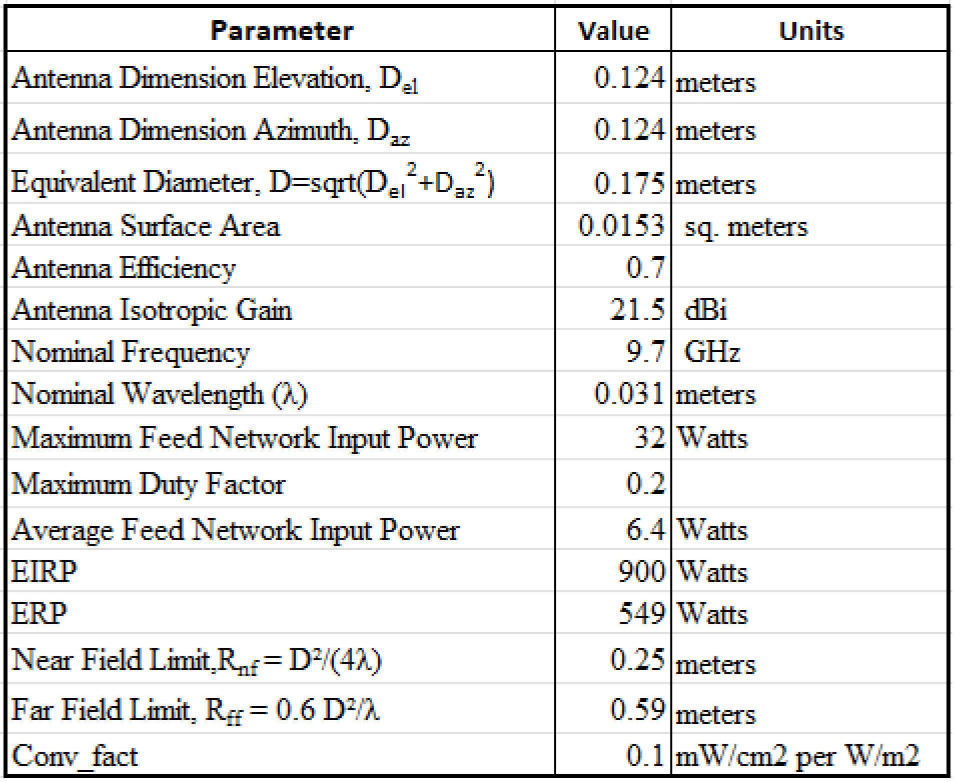
Similarly, no employees will be on the water during the test, so the safe far-field controlled threshold of 1.2 meters (derived further on in this report) is easily met and not of concern.

2.0 Description of Radar

This analysis predicts the radiation levels for an experimental X-band radar using an array of microstrip patches as the radiator. This report is developed in accordance with the prediction methods contained in OET Bulletin No. 65, Evaluating Compliance with FCC Guidelines for Human Exposure to Radio Frequency Electromagnetic Fields, Edition 97-01, pp 26-30. The maximum level of non-ionizing radiation to which employees may be exposed is limited to a power density level of 5 milliwatts per square centimeter (5 mW/cm^2) averaged over any 6 minute period in a controlled environment and the maximum level of non-ionizing radiation to which the general public is exposed is limited to a power density level of 1 milliwatt per square centimeter (1 mW/cm^2) averaged over any 30 minute period in a uncontrolled environment. Note that the worse-case radiation hazards exist along the beam axis perpendicular to the face of the patch array antenna.

The relevant parameters for assessing antenna performance are provided in Table 1 below.

Table 1. Radar and Antenna Parameters



Parameter	Value	Units
Antenna Dimension Elevation, D_{el}	0.124	meters
Antenna Dimension Azimuth, D_{az}	0.124	meters
Equivalent Diameter, $D=\text{sqrt}(D_{el}^2+D_{az}^2)$	0.175	meters
Antenna Surface Area	0.0153	sq. meters
Antenna Efficiency	0.7	
Antenna Isotropic Gain	21.5	dBi
Nominal Frequency	9.7	GHz
Nominal Wavelength (λ)	0.031	meters
Maximum Feed Network Input Power	32	Watts
Maximum Duty Factor	0.2	
Average Feed Network Input Power	6.4	Watts
EIRP	900	Watts
ERP	549	Watts
Near Field Limit, $R_{nf} = D^2/(4\lambda)$	0.25	meters
Far Field Limit, $R_{ff} = 0.6\ D^2/\lambda$	0.59	meters
Conv_fact	0.1	mW/cm2 per W/m2

In the following sections, the time averaging power density in the above regions, as well as other critically important areas will be calculated and evaluated. The calculations are done in the order discussed in OET Bulletin 65, and we use aperture antenna approximations for the field values for the patch antenna array.

3.0 Time Averaging Factor

For testing on the Lake Superior shore, the radar is operated continuously for 30 minutes while illuminating a drone carrying a target over the lake. The transmit duty factor will be 0.2. Therefore, the time averaging factors for ground testing are computed as follows:

Time_averaging_factor = 0.2

4.0 Near Field Region (0 to 0.25 meters from antenna surface)

The geometrical limits of the radiated power in the near field approximate a cylindrical volume with a diameter equal to that of the antenna. In the near field, the power density is neither uniform nor does its value vary uniformly with distance from the antenna. For considering radiation hazard exposure, it is assumed that the on-axis flux density is at its maximum value throughout the length of this region. The length of this region, i.e., the distance from the antenna to the end of the near field, is computed as R_{nf} in Table 1 above.

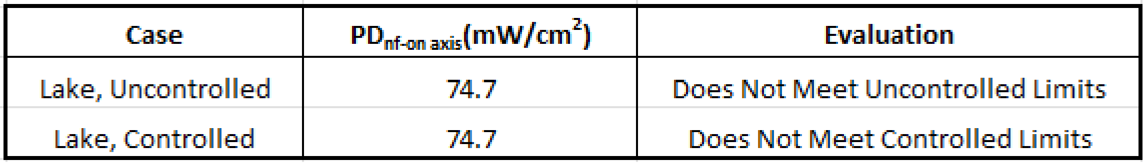
The on-axis maximum time-averaged power density in the near field is given by:

$PD_{\text{nf-on axis}} = (16\varepsilon P)/(\pi D^2)$ (Time_avg_factor) Conv_fact, $0<R<0.25$ meters (Eq 1)

Where ε = antenna efficiency = 0.7,
D^2 = antenna_dim_el^2 + antenna_dim_az^2, meters = 0.031 square meters
P = peak power at feed network input, Watts
Time_avg_factor = 0.2 as discussed above.
Conv_fact =0.1 W/m^2 to mW/cm^2

We now evaluate (1) with the time averaging factor computed above.

Table 2. On-Axis Worst Case Near Field Power Densities



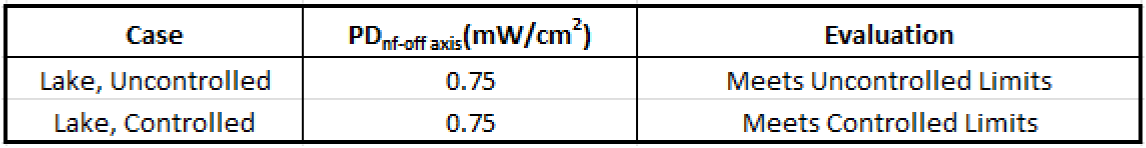
Case	$PD_{\text{nf-on axis}}$(mW/cm^2)	Evaluation
Lake, Uncontrolled	74.7	Does Not Meet Uncontrolled Limits
Lake, Controlled	74.7	Does Not Meet Controlled Limits

According to Bulletin 65, off-axis power density calculations in the near field may be performed as follows: assuming that the point of interest is at least one antenna diameter removed from the center of the main beam, the power density at that point is at least a factor of 100 (20 dB) less than the value calculated for the equivalent on-axis power density in the main beam. Therefore, for regions at least D meters away from the center line of the dish, whether behind, below, or in front under of the antenna's main beam, the power density exposure is at least 20 dB below the main beam level as follows:

$PD_{\text{nf-off axis}} = PD_{\text{nf-on axis}}/100$, $0<R<0.25$ meters (Eq 2)

Using this equation, the off-axis near field power densities are computed as follows:

Table 3. Off-Axis Worst Case Near Field Power Densities



Case	$PD_{\text{nf-off axis}}$(mW/cm^2)	Evaluation
Lake, Uncontrolled	0.75	Meets Uncontrolled Limits
Lake, Controlled	0.75	Meets Controlled Limits

5.0 Transition Region (0.25 meters < R < 0.59 meters)

The transition region is located between the near and far field regions. As stated in Bulletin 65, the power density begins to vary inversely with distance in the transition region. The maximum power density in the transition region will not exceed that calculated for the near field region, and the transition region begins at that value. The maximum value for a given distance within the transition region may be computed for the point of interest according to:

$PD_t =$ $(PD_{nf})(R_{nf})/R$, for $0.25 < R < 0.59$ meters (Eq 3)

where: PD_{nf} = near field power density from either Table 2 or 3 as appropriate
R_{nf} = near field distance = 0.25 meters
R = distance to point of interest

The beginning value is the maximum near field density, and the value at the end of the transition region is therefore computed from (Eq 3) to be:

Table 4. On-Axis Worst Case Power Densities at Edge of Transition Region

Case	$PD_{trans\_edge\_on\ axis}$ (mW/cm^2)	Evaluation
Lake, Uncontrolled	31.6	Does Not Uncontrolled Limits
Lake, Controlled	31.6	Does Not Controlled Limits

for on axis illumination and for off-axis illumination

Table 5. Off-Axis Worst Case Power Densities at Edge of Transition Region

Case	$PD_{trans\_edge\_off\ axis}$ (mW/cm^2)	Evaluation
Lake, Uncontrolled	0.32	Meets Uncontrolled Limits
Lake, Controlled	0.32	Meets Controlled Limits

6.0 Far-Field Region

The on- axis power density in the far field region (PD_{ff}) varies inversely with the square of the distance as follows:

$PD_{ff} = PG/(4\pi R^2)$ (Time_avg_factor) (Conv_fact), $R > 0.59$ meters (Eq 4)

where: P = total peak power delivered patch array antenna feed network = 32 Watts
G = Numeric Antenna gain = 10^(21.5/10)=140.7
R = distance to the point of interest
Time_avg_factor =0.2
Conv_fact =0.1 W/m^2 to mW/cm^2

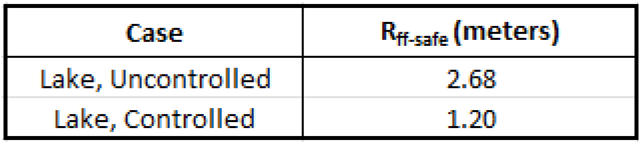
We may invert Eq (4) to determine the minimum safe distance as follows:

$R_{ff\text{-}safe}$ = sqrt[PG/(4π $PD_{ff\text{-}allowed}$) (Time_avg_factor) (Conv_fact)] (Eq 5)

where: P = total power delivered patch array antenna feed network = 32 Watts
G = Numeric Antenna gain = 10^(21.5/10)=140.7
R = distance to the point of interest
Time_avg_factor = 0.2
Conv_fact = 0.1 W/m^2 to mW/cm^2
$PD_{ff\text{-}allowed}$ = 1 mW/cm^2 uncontrolled, 5 mW/cm^2 controlled

Using (eq 5), the safe on-axis distances required are as follows:

Table 6. Computed Minimum Safe Distances for Worst Case On-Axis Illumination



Case	$R_{ff\text{-}safe}$ (meters)
Lake, Uncontrolled	2.68
Lake, Controlled	1.20

7.0 Summary

EMAG Technologies has built an X-band prototype radar and plans to operate it to do drone target testing over Lake Superior. We have demonstrated in this report that a very simple experiment control CONOPs suffices to ensure that both controlled and uncontrolled individuals will not receive radiation dosages above the required levels.