Assessing High-Intensity Radiated Fields (HIRF) from High-Power Antennas for Air Vehicle Safety

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***Abstract*— Advanced Air Mobility (AAM), including Urban Air Mobility (UAM), vehicles may be required to meet stringent High-Intensity Radiated Fields (HIRF) certification requirements. HIRF can cause interference and even damage to vehicle systems. A recently proposed map-based avoidance approach can help reduce HIRF protection costs compared to the standard approach. However, it necessitates knowing the locations, frequencies, and transmit powers of high-power antennas within the operating area. This study aims to provide the necessary transmitter data by utilizing regulatory license databases. Using New York City as a representative urban area, fixed transmitter data are presented for AM, FM, TV, satellite uplink, land-mobile radio, microwave link, weather radars, and others. The maximum effective isotropic radiated powers of the antenna are reported. The associated electric field envelopes at 100 feet (30.48 m) distance are compared against the current rotorcraft HIRF standard. The results show that the current standards for protecting vehicles are inadequate. Maps of regions with high HIRF are illustrated. Data for several other cities are also being considered.**

***Keywords*— HIRF, Map, AAM, UAM, Advanced Air Mobility, Urban Air Mobility, Unmanned Aerial Systems, Certification**

I. INTRODUCTION

Airborne vehicles are susceptible to electromagnetic interference or damage from high-intensity radiated fields (HIRF) sources such as radars, terrestrial and satellite uplink transmitters, TV towers, and microwave links. The HIRF certification environments for rotorcraft, Urban Air Mobility (UAM) [1] and other Advanced Air Mobility (AAM) vehicles can be particularly severe, as these vehicles often operate and hover near powerful ground transmitters. UAM and AAM, including Vertical Take-Off and Landing (VTOL) technologies, refer to the integration of advanced aerial transportation systems into urban environments to enhance mobility, reduce congestion, and provide efficient, on-demand transport services. Enhancing vehicle HIRF protection could lead to undesirable increases in vehicle cost, size, and weight.

A previous study [2] introduced a novel map-based approach to reduce a vehicle's HIRF exposure by maintaining safe distances from transmitters. Fig. 1 illustrates the HIRF avoidance concept, where a vehicle is routed around areas with HIRF fields that exceed its tolerance level. This approach, known as 'HIRF-Map,' allows for a significantly lower tolerance threshold than the standard, potentially reducing vehicle cost and weight. Implementing this approach requires knowledge of transmitter antenna locations, power levels, frequencies, and the vehicle's tolerance level. Fig. 2 demonstrates the implementation of the HIRF-Map approach.

This paper presents the necessary transmitter data from regulatory sources such as the Federal Communications Commission (FCC). Power and electric field strength data are provided for New York City, serving as a representative urban area. The corresponding electric field envelopes are compared with the existing aircraft standards, and the analysis is then extended to include data from eleven additional cities.

Furthermore, a minimum vehicle field tolerance threshold is recommended based on the reported electric field data. This recommendation takes into account the density of avoidance areas identified through the HIRF-Map approach, balancing the trade-off between a lower tolerance level and increased operational airspace for the vehicle.

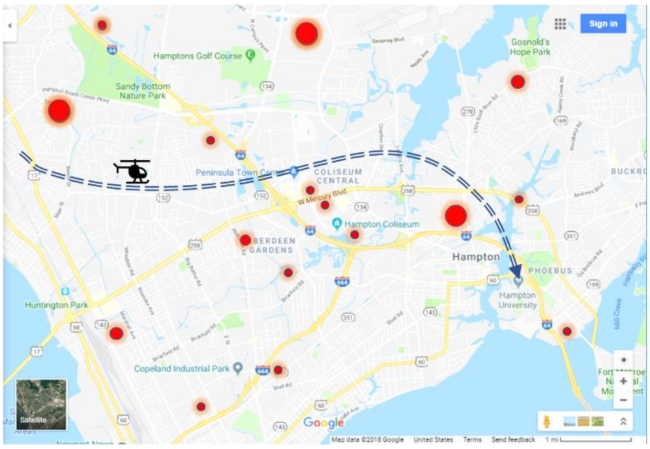


Fig. 1: Illustration of HIRF avoidance.

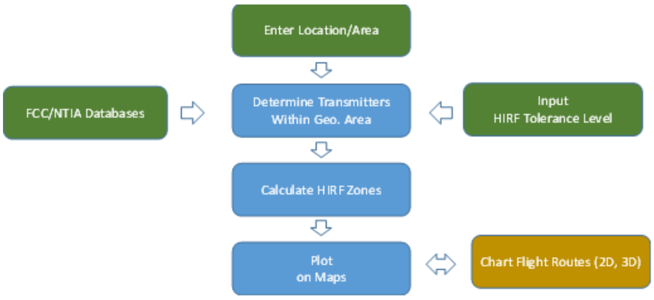


Fig. 2: HIRF-Map implementation.

II. METHODOLOGY

The transmitter data primarily come from the Federal Communications Commission (FCC) [3], which regulates commercial RF spectrum use in the U.S. Additionally, data from the National Oceanic and Atmospheric Administration's (NOAA) weather radar [4] are also considered. Relevant data sources are listed below. Please note that databases for transmitters on federal government land and at airports are not publicly accessible.

- *FCC's Universal Licensing System (ULS):* This database system contains data on microwave links, paging, land-mobile radio, coastal and aviation ground, and many other low-power transmitters. The effective isotropic radiated power (EIRP) can reach up to 75 KW for a 5G transmitter.
- *FCC's Consolidated Database Systems (CDBS):* This system contains data on AM, FM, and TV transmitters, with a maximum EIRP observed at 8.2 MW in New York City. This database recently transitioned to the Licensing and Management System (LMS) and is no longer updated.
- *FCC's International Bureau Filing Systems (IBFS):* This system provides data on satellite uplink transmitters, with observed EIRP reaching up to 1.26 GW in New York City. This system is transitioned to the International Communications Filing System (ICFS).
- *NOAA's Weather Radars:* This dataset contains Terminal Doppler Weather Radars (TDWR) and Next Generation Weather Radar (NEXRAD) locations. EIRP can be as high as 25 GW peak.

EIRP data from the ULS, CDBS, IBFS, and NOAA Weather databases are first plotted against frequency, and power envelopes are calculated for each of the 17 HIRF bands defined in the HIRF standard (see Table I). Field strength envelopes are then derived from the power envelopes and compared to the standard. This comparison is made against the Field Strength Average listed in Table I, except for NOAA weather radar data, which is compared against the Field Strength Peak.

Eq. (1) shows the far-field formula for calculating field strength E at a distance R from an antenna with power P and gain G. The product PG denotes the Effective Isotropic Radiated Power ($EIRP$).

$$E = \frac{1}{R}\sqrt{30PG} \qquad \text{Eq. (1)}$$

Let R_M be the minimum stand-off distance and E_T be the vehicle's field tolerance level. Eq. (2) calculates the required avoidance radius to be displayed on a map. This approximation assumes far-field conditions and does not account for higher-order effects such as reflection, diffraction, etc. In addition, cumulative effects from multiple carriers or antennas are not considered.

$$R_M = \frac{1}{E_T}\sqrt{30PG} \qquad \text{Eq. (2)}$$

TABLE I: ROTORCRAFT SEVERE HIRF ENVIRONMENT

FREQUENCY	FIELD STRENGTH (V/m)	
	PEAK	AVERAGE
10 kHz - 100 kHz(1)	150	150
100 kHz - 500 kHz	200	200
500 kHz - 2 MHz	200	200
2 MHz - 30 MHz	200	200
30 MHz - 70 MHz	200	200
70 MHz - 100 MHz	200	200
100 MHz - 200 MHz	200	200
200 MHz - 400 MHz	200	200
400 MHz - 700 MHz	730	200
700 MHz - 1 GHz	1400	240
1 GHz - 2 GHz	5000	250
2 GHz - 4 GHz	6000	490
4 GHz - 6 GHz	7200	400
6 GHz - 8 GHz	1100	170
8 GHz - 12 GHz	5000	330
12 GHz - 18 GHz	2000	330
18 GHz - 40 GHz	1000	420

Table I shows the HIRF bands' frequencies and the required field strength tolerance level per SAE 5583A standard [5].

III. HIRF FIELD RESULTS

This section calculates the field strength envelopes for the three FCC database systems (ULS, CDBS, and IBFS) specific to New York City. Additionally, it reports field strength data for NOAA weather radars.

a) ULS

Fig. 3a displays the EIRP (in kW) of ULS transmitters for frequencies up to 2.5 GHz. This includes various transmitter types such as cellular, coastal & aviation ground, land-mobile radios (broadcast, commercial, and private), microwave, and paging. Transmitters with EIRP below 1.5 kW are not shown. The figure also includes the maximum power envelope segmented by the HIRF bands in Table I.

Fig. 3b extends this data to frequencies up to 30 GHz. EIRP values as high as 75 kW are observed around 3.5 GHz from 5G wireless transmitters. Above 6 GHz, EIRP from microwave link transmitters dominates, reaching up to 57 kW.

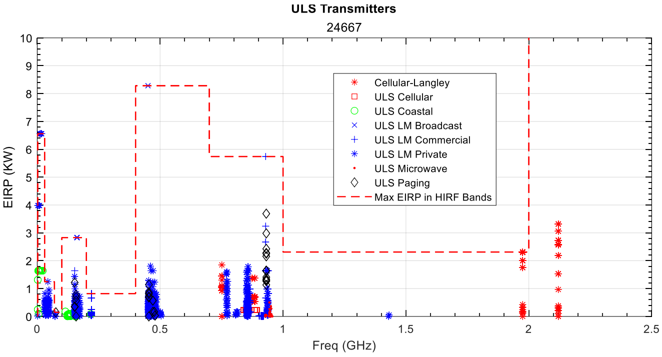


Fig 3a: ULS Transmitters' EIRP to 2.5 GHz

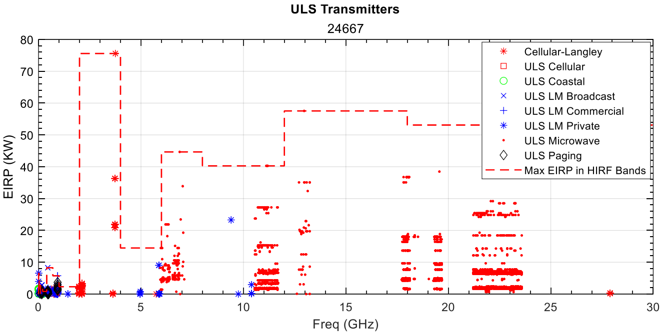


Fig 3b: ULS Transmitters' EIRP to 30 GHz.

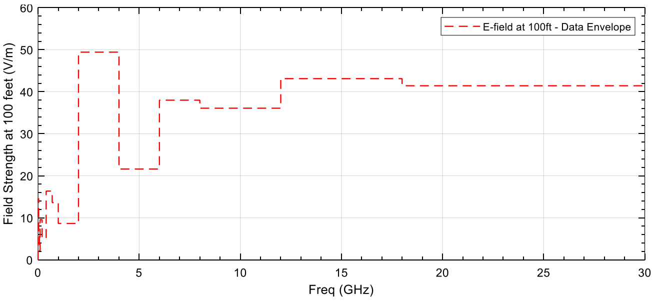


Fig 3c: ULS transmitters' field strength envelopes.

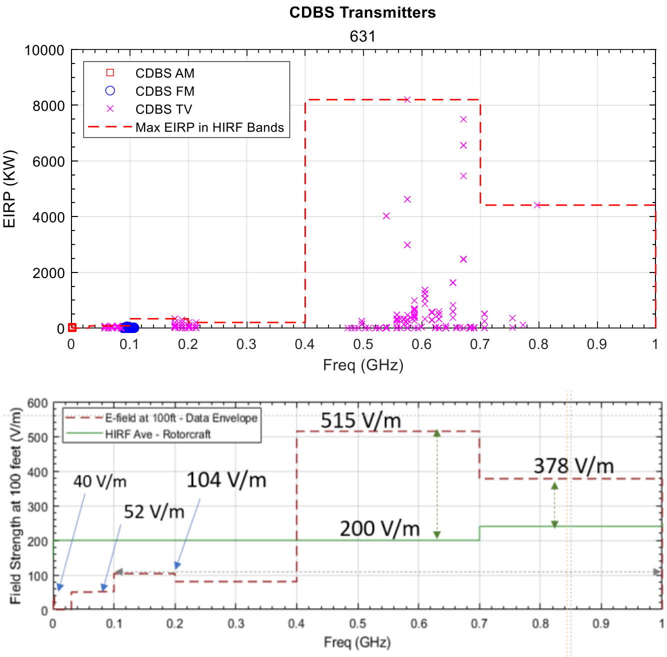
Fig. 3c shows the field strength envelope calculated from the power envelope in Fig. 3b. Field strength is calculated using Eq. (1) and at 100' (30.48 m) distance per standard [5]. The field strength envelope is approximately lower than 25 V/m under 2 GHz and 50 V/m above 2 GHz. These levels are significantly lower than the HIRF-Average standard level in Table I. Vehicles with these tolerance thresholds may not need to avoid ULS transmitters in the New York City region.

b) CDBS

Transmit powers (EIRPs) and their envelope are shown in Fig. 4a for CDBS transmitters. The maximum EIRPs are 50 kW for AM, 65.6 kW for FM, and 8.2 MW for TV transmitters.

Fig. 4b compares the field strength envelope against the rotorcraft HIRF-Average standard. The peak field strength of 515 V/m observed between 0.4 and 0.7 GHz exceeds the 200 V/m standard level. This indicates that the existing standard is inadequate for vehicles operating near the highest-power TV transmitters.

To protect against CDBS transmitters, the recommended vehicle tolerance levels are 40 V/m for frequencies from 500 kHz to 2 MHz, 55 V/m from 30 MHz to 70 MHz, and approximately 100 V/m from 0.1 GHz to 1 GHz. While these tolerance levels may be insufficient for handling a 515 V/m field strength above 400 MHz, Fig. 4c shows that the avoidance zones are small enough to ensure ample space for vehicle operation. Additionally, the low HIRF-zone density depicted in Fig. 4c suggests that the recommended 100 V/m tolerance level could be further reduced. Matlab^{T} was used to generate Fig. 4c and similar maps.



Figs. 4a, 4b: AM, FM, and TV transmitters' EIRPs (upper) and field strength envelopes (lower).

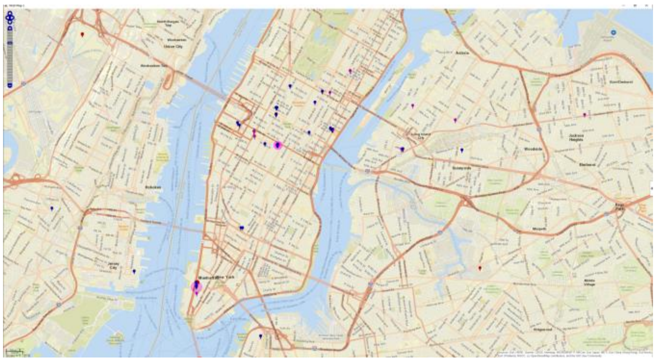


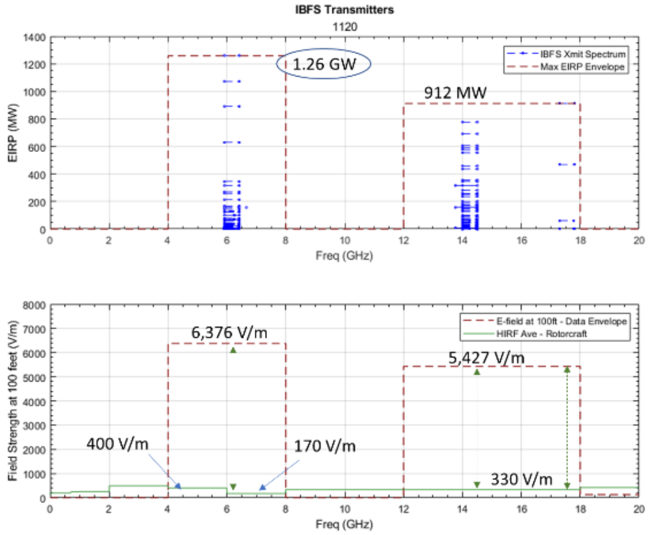
Fig. 4c: CDBS HIRF avoidance zones for 100 V/m tolerance level.

c) IBFS

Figs. 5a and 5b display the EIRPs, EIRP envelopes, and corresponding field strength envelopes at a 100-foot distance from satellite uplink antennas in New York City. The maximum EIRP reaches up to 1.26 GW. The field strength envelope indicates values of 6,376 V/m between 4-8 GHz and 5,427 V/m between 12-18 GHz.

Field levels from the current rotorcraft HIRF-Average standard are shown in green, with corresponding standard levels of 400 V/m for 4-6 GHz, 170 V/m for 6-8 GHz, and 330 V/m for 12-18 GHz. These standards are significantly lower than the observed field strengths, making them inadequate for protecting rotorcraft and AAM vehicles.

Fig. 5c illustrates the HIRF-avoidance zones for a 500 V/m tolerance level, which provides ample operational space for vehicles, demonstrating the effectiveness of this approach in high HIRF environments in urban areas. Reducing the tolerance level to 250 V/m effectively doubles the radius of the HIRF zones, reducing the available operational space but still maintaining usability. Consequently, the recommended tolerance level ranges from 250 to 500 V/m.



Figs. 5a, 5b: EIRP and electric field envelope from satellite uplink transmitters.

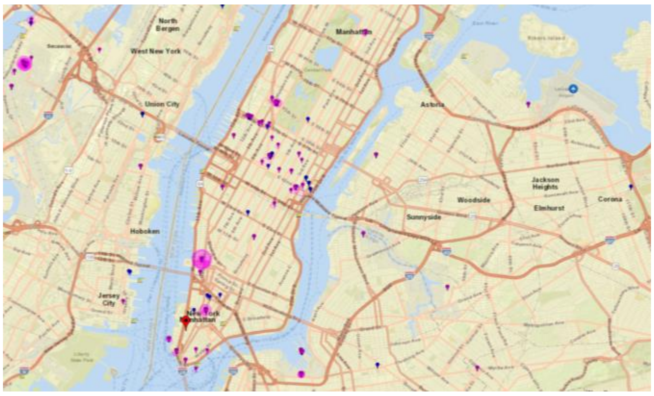
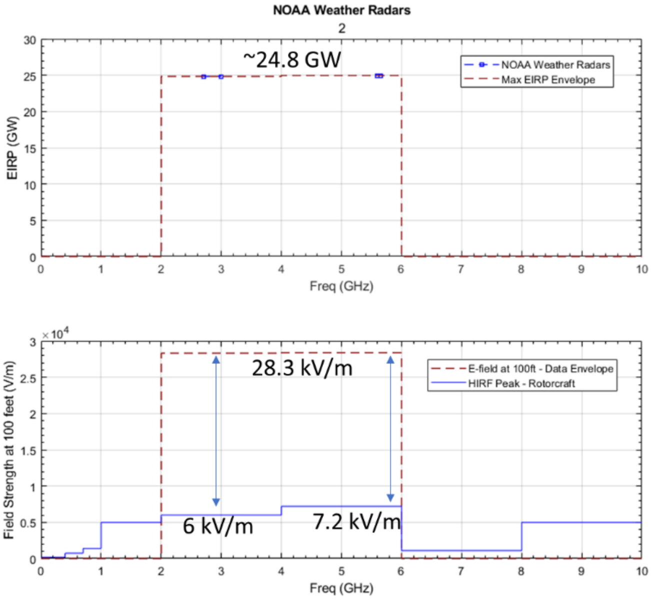


Fig. 5c: IBFS HIRF avoidance zones for 500 V/m tolerance level.

d) NOAA Weather Radars

Figs. 6a and 6b display the peak power (EIRP) for NOAA weather radars, the corresponding field strength, and a comparison with the HIRF-Peak standard. At a 100-foot distance, the peak field strength reaches 28.3 kV/m, significantly higher than the standard levels of 6 kV/m and 7.2 kV/m for the 2-6 GHz range. This indicates that the existing standards are inadequate for protecting against weather radar at this distance.

The recommended field tolerance level is approximately 1000 V/m, corresponding to a stand-off distance of around 866 meters. This tolerance level is significantly lower than the standard, which is advantageous. The large stand-off distance is acceptable, as these radars are typically not installed in urban areas, providing ample space for avoidance. There are approximately 200 such radars in the U.S. Fig. 6c illustrates the two avoidance zones for the 1000 V/m peak tolerance level (represented by blue circles at the bottom of the graph).



Figs. 6a, 6b: EIRP and field strength envelopes for NOAA weather radars

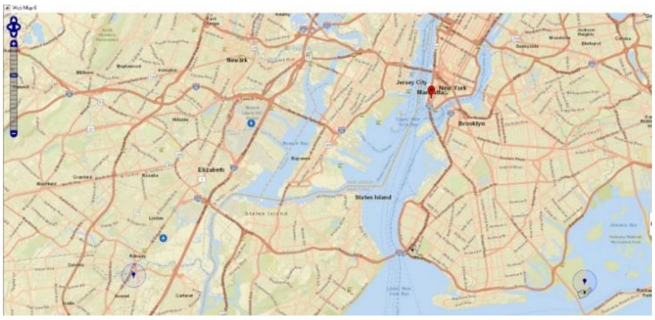


Fig. 6c: NOAA weather radar HIRF zones (blue circles in low left and right of the image). HIRF zone radius = 866 m for 1000 V/m peak field tolerance level. The city center is in red.

IV. MAXIMUM HIRF FIELDS FOR 12 URBAN AREAS

In addition to New York City, data are reported for the urban areas in eleven other major cities in the U.S. The cities include San Francisco, Chicago, Dallas, Los Angeles, Atlanta, Houston, Miami, Boston, Seattle, Phoenix, and Denver. The areas are 40 x 40 km minimum in size. The data presented in Tables II, III, and IV, corresponding to the ULS, CDBS, and IBFS databases, respectively, offer insights into the similarities and differences among the cities. In each table, the last row indicates the number of FCC data records available.

a) ULS

Table II displays the maximum 100-foot field strengths of ULS transmitters, as recorded in the ULS databases. The last column shows the composite maximum field strength for each frequency band. An analysis of various urban areas, including New York City, reveals that most ULS data fall below 25 V/m for frequencies under 2 GHz and below 50 V/m for frequencies above 2 GHz. However, a few outliers, crossed out in the table, exhibit significantly higher field strengths. These anomalies are believed to be incorrectly recorded data, recognized by the incorrect frequencies, or having substantially higher power levels than others within the same service category. Additionally, some data points show unusually high field strengths compared to their peers yet cannot be easily dismissed as invalid; these are highlighted in boxes. Such transmitters are rare and can be avoided using the HIRF-Map approach.

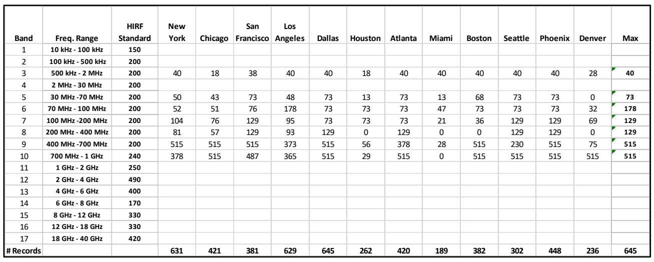
TABLE II: ULS TRANSMITTERS MAXIMUM FIELD STRENGTHS (V/M)

Band	Freq. Range	HIRF Standard	New York	Chicago	San Francisco	Los Angeles	Dallas	Houston	Atlanta	Miami	Boston	Seattle	Phoenix	Denver	Max
1	10 kHz - 100 kHz	150													0
2	100 kHz - 500 kHz	200					1				13	1			13
3	500 kHz - 2 MHz	200	1	2	1	1	2	1	1	1	13	1	1	1	13
4	2 MHz - 30 MHz	200	15		18	7	13	7	7	7	7	18	1	10	18
5	30 MHz -70 MHz	200	6	4	4	5	5	4	4	4	5	4	5	4	6
6	70 MHz - 100 MHz	200	2	2	2	4	4	4	3	1	2	2	2	3	4
7	100 MHz -200 MHz	200	10	7	6	9	10	10	8	10	8	7	6	7	10
8	200 MHz - 400 MHz	200	5	5	5	4	4	5	4	5	3	5	2	1	5
9	400 MHz -700 MHz	200	16	7	14	14	10	36	7	8	8	17	8	10	36
10	700 MHz - 1 GHz	240	14	14	11	14	13	17	48	13	14	14	14	17	48
11	1 GHz - 2 GHz	250	9	9	9	9	9	9	9	9	9	9	9	9	9
12	2 GHz - 4 GHz	490	49	49	49	49	49	49	49	49	49	49	49	49	49
13	4 GHz - 6 GHz	400	22	20	16	27	115	~~788~~	16	17	0	16	38	32	115
14	6 GHz - 8 GHz	170	38	25	33	34	40	51	27	46	24	555	45	44	555
15	8 GHz - 12 GHz	330	36	38	~~161~~	52	30	~~738~~	30	~~1598~~	36	~~2278~~	75	48	75
16	12 GHz - 18 GHz	330	43	34	41	51	36	34	36	34	160	34	37	40	160
17	18 GHz - 40 GHz	420	41	40	44	46	29	24	24	24	35	35	41	36	46
# Records			24,667	8,834	7,651	97,640	12,227	12,311	7,603	5,662	9,227	17,151	34,316	9,196	

b) CDBS

Table III shows the field maximum for CDBS transmitters for the twelve cities. The overall maximum is shown in the last column. The highest field level is 512 V/m between 400 MHz and 1 GHz. This level exceeds the HIRF-Average standard of 200 V/m and 240 V/m.

TABLE III: CDBS TRANSMITTERS MAXIMUM FIELD STRENGTH (V/M)

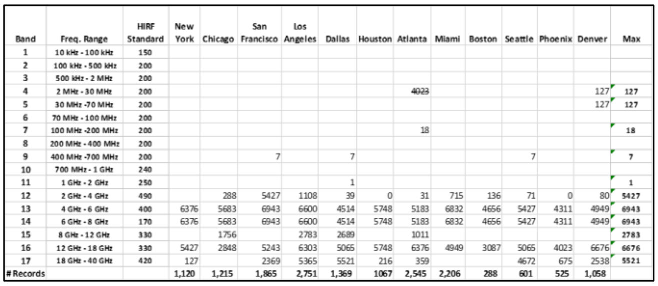


Band	Freq. Range	HIRF Standard	New York	Chicago	San Francisco	Los Angeles	Dallas	Houston	Atlanta	Miami	Boston	Seattle	Phoenix	Denver	Max
1	10 kHz - 100 kHz	150													
2	100 kHz - 500 kHz	200													
3	500 kHz - 2 MHz	200	40	18	38	40	40	18	40	40	40	40	40	28	40
4	2 MHz - 30 MHz	200													
5	30 MHz -70 MHz	200	50	43	73	48	73	13	73	13	68	73	73	0	73
6	70 MHz - 100 MHz	200	52	51	76	178	73	73	73	47	73	73	73	32	178
7	100 MHz -200 MHz	200	104	76	129	95	73	73	73	21	36	129	129	69	129
8	200 MHz - 400 MHz	200	81	57	129	93	129	0	129	0	0	129	129	0	129
9	400 MHz -700 MHz	200	515	515	515	373	515	56	378	28	515	230	515	75	515
10	700 MHz - 1 GHz	240	378	515	487	365	515	29	515	0	515	515	515	515	515
11	1 GHz - 2 GHz	250													
12	2 GHz - 4 GHz	490													
13	4 GHz - 6 GHz	400													
14	6 GHz - 8 GHz	170													
15	8 GHz - 12 GHz	330													
16	12 GHz - 18 GHz	330													
17	18 GHz - 40 GHz	420													
# Records			631	421	381	629	645	262	420	189	382	302	448	236	645

c) IBFS

Table IV shows the results for IBFS transmitters. Generally, their field levels are comparable to that of New York City, but with the addition of high-power transmitters in the bands 2-4 GHz, 8-12 GHz, and 18-40 GHz. The peak field can be as high as 6,943 V/m between 4 - 8 GHz. Again, these field levels far exceed the average standard levels between 170 – 400 V/m for rotorcraft.

TABLE IV: IBFS TRANSMITTERS MAXIMUM FIELD STRENGTH (V/M)

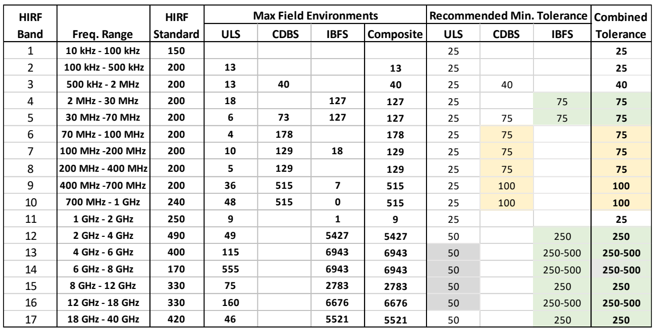


Band	Freq. Range	HIRF Standard	New York	Chicago	San Francisco	Los Angeles	Dallas	Houston	Atlanta	Miami	Boston	Seattle	Phoenix	Denver	Max
1	10 kHz - 100 kHz	150													
2	100 kHz - 500 kHz	200													
3	500 kHz - 2 MHz	200													
4	2 MHz - 30 MHz	200							~~4023~~					127	127
5	30 MHz -70 MHz	200												127	127
6	70 MHz - 100 MHz	200													
7	100 MHz -200 MHz	200							18						18
8	200 MHz - 400 MHz	200													
9	400 MHz -700 MHz	200			7		7					7			7
10	700 MHz - 1 GHz	240													
11	1 GHz - 2 GHz	250					1								1
12	2 GHz - 4 GHz	490		288	5427	1108	39	0	31	715	136	71	0	80	5427
13	4 GHz - 6 GHz	400	6376	5683	6943	6600	4514	5748	5183	6832	4656	5427	4311	4949	6943
14	6 GHz - 8 GHz	170	6376	5683	6943	6600	4514	5748	5183	6832	4656	5427	4311	4949	6943
15	8 GHz - 12 GHz	330		1756		2783	2689		1011						2783
16	12 GHz - 18 GHz	330	5427	2848	5243	6303	5065	5748	6376	4949	3087	5065	4023	6676	6676
17	18 GHz - 40 GHz	420	127		2369	5365	5521	216	359			4672	675	2538	5521
# Records			1,120	1,215	1,865	2,751	1,369	1067	2,545	2,206	288	601	525	1,058	

d) Combined Field Environment

Table V summarizes the maximum field environments in Tables II, III, and IV. The composite field maximum is listed in column 7. Column 3 also displays the HIRF-Average standard. The standard does not provide sufficient vehicle HIRF protection for frequencies above 400 MHz.

TABLE V: COMBINED FIELD THRESHOLD RECOMMENDATION (V/M)



HIRF Band	Freq. Range	HIRF Standard	Max Field Environments				Recommended Min. Tolerance			Combined Tolerance
			ULS	CDBS	IBFS	Composite	ULS	CDBS	IBFS	
1	10 kHz - 100 kHz	150					25			25
2	100 kHz - 500 kHz	200	13			13	25			25
3	500 kHz - 2 MHz	200	13	40		40	25	40		40
4	2 MHz - 30 MHz	200	18		127	127	25		75	75
5	30 MHz -70 MHz	200	6	73	127	127	25	75	75	75
6	70 MHz - 100 MHz	200	4	178		178	25	75		75
7	100 MHz -200 MHz	200	10	129	18	129	25	75		75
8	200 MHz - 400 MHz	200	5	129		129	25	75		75
9	400 MHz -700 MHz	200	36	515	7	515	25	100		100
10	700 MHz - 1 GHz	240	48	515	0	515	25	100		100
11	1 GHz - 2 GHz	250	9		1	9	25			25
12	2 GHz - 4 GHz	490	49		5427	5427	50		250	250
13	4 GHz - 6 GHz	400	115		6943	6943	50		250-500	250-500
14	6 GHz - 8 GHz	170	555		6943	6943	50		250-500	250-500
15	8 GHz - 12 GHz	330	75		2783	2783	50		250	250
16	12 GHz - 18 GHz	330	160		6676	6676	50		250-500	250-500
17	18 GHz - 40 GHz	420	46		5521	5521	50		250	250

Columns 8, 9, and 10 present the recommended minimum vehicle field tolerance levels for ULS, CDBS, and IBFS transmitters. These tolerance levels are primarily based on data from New York City, with adjustments made to account for data from other cities. The selected tolerance levels are designed to ensure acceptable HIRF avoidance zone sizes and densities across all 12 urban areas.

The final column displays the Combined Tolerance, calculated as the maximum value from the previous three columns. Shaded boxes indicate that vehicles with these tolerance levels should rely on the HIRF-Map to avoid certain transmitters, as the required stand-off distance exceeds the standard 100 feet. Green boxes denote that IBFS transmitters are the source of the exceedance, yellow boxes point to CDBS transmitters, and gray boxes highlight ULS transmitters. In HIRF Band 14, the combined threshold is shaded in both gray and green, signaling that both ULS and IBFS sources should be considered for map-based avoidance.

The table shows that the recommended Combined Tolerance (column 11) is significantly lower than the HIRF-Average Standard (column 3) for frequencies up to 4 GHz. This reduction could lead to lower vehicle costs, as previously discussed. However, for frequencies above 4 GHz, the Combined Tolerance levels are comparable to the standard, or even slightly higher. This is due to the elevated field environments generated by IBFS transmitters. While these high-field environments were not adequately addressed in the original HIRF standard, the HIRF-Map approach outlined in this study offers effective vehicle protection by maintaining safe distances from these sources.

V. CONCLUSIONS

The data demonstrate that RF field environments can significantly exceed the existing HIRF standards designed to protect rotorcraft. The proposed HIRF-avoidance approach offers enhanced protection for AAM vehicles against these severe RF environments. Additionally, this new method could allow for lower vehicle tolerance levels below 4 GHz, potentially reducing the costs associated with HIRF protection.

ACKNOWLEDGMENTS

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Matlab Web Map and Google Maps were used in the figures. More information can be found in [6,7,8].

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[7] Sources for Matlab’s Web Map: Esri ArcGIS Online (Tiles), Esri, HERE, DeLorme, Garmin, TomTom, USGS, Intermap, iPC, INCREMENT, NRCan, Esri Japan, METI, Esri China (Hong Kong), Esri Korea, Esri (Thailand), NGCC, OpenStreetMap, the GIS User Community, MapmyIndia, GEBCO, FAO, NPS, GeoBase, IGN, KadasterNL, DigitalGlobe, Earthstar Geographic, CNES/Airbus DS, GeoEye, USA FSA, Getmapping, Aerogrid, IGP, swisstopo, and others. The OpenStreetMap license is available at: *https://www.openstreetmap.org/copyright*

[8] Google Maps: http://map.google.com