High-Intensity Radiated Field (HIRF) Map - An Avoidance Approach for UAM, AAM, and UAS Vehicles

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***Abstract*—Advanced Air Mobility (AAM), Urban Air Mobility (UAM), and Unmanned Aerial Systems (UAS) vehicles will fly in similar airspace to Transport Category Rotorcraft, thereby requiring them to meet the most severe requirements for High-Intensity Radiated Fields (HIRF) certification. The environment is severe for rotorcraft, much more so than for fixed-wing aircraft, due to lower altitude operations, potentially exposing the vehicles to close and direct view of high-power transmitters on the ground. High-level HIRF exposure potentially leads to avionic system upsets, interference, and undesirable effects. Shielding and circuit protection against HIRF will be a significant barrier to size, weight, and cost, especially for emerging electric vertical take-off and landing (eVTOL) and electric short take-off and landing (eSTOL) vehicles. This paper proposes a novel approach to HIRF protection, which reduces costs by testing and certifying vehicles to a "vehicle tolerance level" that is lower than required for Transport Category Rotorcraft. The remaining protection is achieved by maintaining a safe distance from known HIRF sources, calculated based on the vehicle's tolerance level and transmitter characteristics such as transmit power, antenna beamwidth, and direction. Tailored maps are developed, identifying transmitters and avoidance zones within an operating area or along a flight path, allowing for restricted vehicle operations. The HIRF avoidance zones could be smaller for vehicles with higher tolerance levels, enabling them to operate closer to transmitters. Transmitter data can be extracted from regulatory databases like the FCC and NOAA.**

A map tool is developed in Matlab to calculate and plot HIRF avoidance zones from transmitters in FCC and NOAA databases as proof of concept. Illustrations are presented for AM/FM/TV transmitters, communication satellite dishes, and weather radars. Also illustrated are HIRF zones for smaller transmitters, including land-mobile radios, pagers, microwave links, and cellular towers. An example of flight planning around the transmitters is presented.

This method is a substantial deviation from the standard approach and involves slightly higher flight-planning complexity, but the potential cost savings are significant. Future AAM/UAM/UAS aeronautical charts could include these new HIRF avoidance zones.

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

I. Introduction

Airborne vehicles can suffer from electromagnetic interference or even damage due to high-intensity radiated fields (HIRF) from high-power transmitters. The results can lead to the loss of vehicle functions or controls. The need to protect aircraft systems from HIRF has increased in recent years because of many reasons, including greater dependency on digital electronics, reduced shielding in aircraft design, increased databus or processor speed, increased frequency spectrum usage, and the number of transmitters [1].

HIRF sources include radars (weather, airport, ship, aircraft…), terrestrial and satellite uplink transmitters, wireless phone towers, radio/TV towers, microwave links, and others. AM/FM/TV radio antennas can broadcast hundreds of thousands of watts of radiated power. Radars, satellite uplinks, and microwave communication antennas can focus energy into intense narrow beams of significantly increased field intensity. RF threats also include cellular/wireless towers. User equipment such as cellular phones and portable two-way radios close to victim systems could be an interference issue.

Typical airborne vehicles such as aircraft and helicopters are tested to HIRF standards to ensure regulatory conformance [1-4]. HIRF environments in these test standards are mostly dominated by transmitters located near large airports, where aircraft are closest to the ground and are at risk of being illuminated at close distance. Aircraft HIRF environments were computed using typical aircraft flight paths at several US and European representative airports and considerations for military transmitters.

Helicopter's HIRF environment is more severe (higher field levels) than fixed-wing aircraft because helicopters operate closer to the ground in normal operation and can be directly illuminated by ground transmitters inside and outside of airport boundaries. The field strength can reach as high as 7200 V/m peak and 490 V/m average [1-5]. In addition, helicopters may have much less metal shielding surfaces than aircraft. HIRF protection of helicopter systems can be expensive due to high field exposure.

Advanced Air Mobility (AAM), Urban Air Mobility (UAM), and Unmanned Aircraft Systems (UAS) vehicles operate in similar HIRF environments as helicopters, as they fly close to the ground and can be illuminated directly by ground transmitters. It is expected that AAM vehicles may be required to meet the same HIRF requirements for helicopters. Protection against severe HIRF environment could result in undesirable increased vehicle cost, size, and weight. Low-cost constructions with less shielding and filtering may make passing the standard certification approach difficult. In this paper, AAM refers to AAM/UAM/UAS for simplicity.

The goal of this effort is to explore a new approach to lower the costs of vehicle HIRF protection while maintaining a similar level of safety. This paper proposes developing a HIRF map as an alternate approach. Rather than designing the vehicles to the worst-case HIRF environments associated with aircraft and helicopter standards, this approach restricts vehicles from being exposed to more severe environments than they can safely tolerate. By staying away from HIRF transmitters at safe distances, HIRF tolerance could be achieved with much less protection than normally required, leading to lower design and manufacturing costs. This approach requires the knowledge of transmitters' locations, radiation characteristics, and the vehicle tolerance level that is far less than required for a helicopter. The safe standoff distances and avoidance zones are computed and plotted onto maps to set operational boundaries so that the vehicle's field tolerance level is not exceeded. This concept is generalized and termed as HIRF Map in this paper. An illustration of the concept is shown in Fig. 1 which shows the vehicle's flight path around HIRF zones marked in red color.

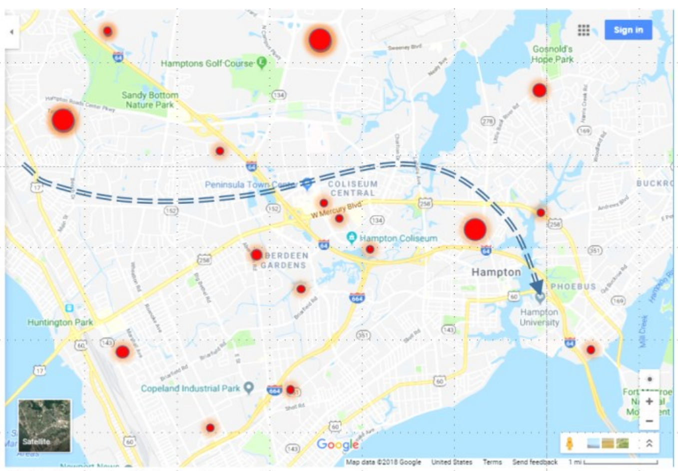


Illustration only. Not actual transmitters

Fig. 1. Planning flights around HIRF transmitters.

II. RF Protection Concept/Approach

The key point to this approach is that the vehicle should stay far from a transmitter sufficiently so that its signal strength falls below the vehicle tolerance level. Let E_T (V/m) be the vehicle tolerance level (determined through testing). This tolerance level can be arbitrary and is supposed to be much lower than the regulatory environments. [6] is an example of laboratory testing to determine the tolerance level. P_T is the HIRF transmitter's effective isotropic radiated power (EIRP), in watts. Setting the vehicle tolerance's equivalent power density, computed from E_T, to be greater than the power density from the HIRF source at distance R (in meters), then solve for R,

$$E_T^2/377 \; > \; P_T/(4\pi R^2) \quad ,$$

$$R \; > \; (30 * P_T)^{1/2} / E_T \qquad (1)$$

This operation results in R, the minimum safe distance from the transmitter. A map is then developed to highlight the region inside the radius R from the transmitter. This region is at higher risk of interference and is highlighted for avoidance. Map regions outside of radius R are considered lower interference risk for vehicle operation.

It is noted that a vehicle's tolerance level can vary with frequency and modulation. The appropriate level should be chosen to match the transmitter's characteristics. The implementation to demonstrate the concept is described below

A. HIRF Map Implementation

This implementation aims to illustrate the concept, demonstrate the feasibility and identify potential issues. The steps of generating a HIRF map include:

1. Import transmitter databases from regulatory sources. Identify transmitters within the area of interest.
2. Determine AAM vehicle tolerance level through testing.
3. Compute the HIRF map from the transmitters' powers and the vehicle's HIRF tolerance level.
4. Overlay HIRF map calculations onto commercial maps.
5. Mark HIRF regions for flight planning.

Map regions outside of radius R from the transmitter are considered lower interference risk. The worst-case antenna direction, gain, and power data are used for conservative calculations.

Matlab [7] was used in the implementation. Key elements in the process are illustrated below in Fig 2. Green boxes denote input data. Blue boxes denote calculations. The gold box denotes two-way interaction with flight planning tools, which is not implemented in this paper.

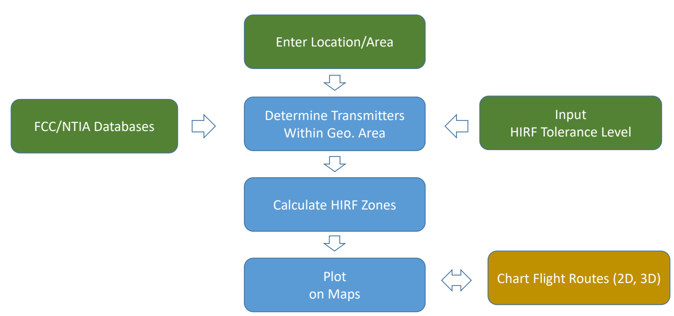


Fig. 2. HIRF Map process.

B. Transmitter Databases

The most important component of this approach is having access to accurate and up-to-date databases of transmitters. This can be challenging since many sources are not available to the public for security or proprietary concerns. However, it is believed that some of the issues can be mitigated by having proper access authorization. For this demonstration, the paper focuses mainly on publicly available data. Additional databases can be added if access is provided. The main source of transmitter data is the Federal Communications Commission (FCC). Weather radars are also included. Further discussions are below.

1) FCC

In the US, the largest publicly available transmitter databases are maintained by the FCC [8]. FCC's databases are grouped into three systems: Consolidated Database System (CDBS), International Bureau Filing System (IBFS), and Universal Licensing System (ULS). Public files are downloadable and are updated regularly, often daily. Instructions on database structures are well documented. It is noted that the FCC databases only report the spectrum licenses, not whether a transmitter is currently active. Therefore, the use of the FCC license databases to create HIRF maps results in more conservative results.

a) CDBS:

CDBS contains data on AM, FM, and TV broadcast services. Data used for plotting HIRF maps include frequency, power, antenna gain, GPS location, station call sign, and more. It is noted that GPS data for many transmitters are rounded to the nearest second, thus antenna locations can be off as much as 30 meters. This should be accounted for in flight planning.

For map purposes, power data given in Effective Radiated Power (FM and TV) or field strength (at a given distance) (AM) are first converted to Equivalent Isotropic Radiated Power (EIRP) before calculating safe distance R in Eq. 1. Data for the highest field direction is used to ensure a conservative calculation.

b) IBFS

IBFS contains international and satellite applications and licenses. Relevant to this work are satellite earth-stations transmitters. While the actual radiated power is not nearly as high as for TV transmitters, antennas can have high gains and narrow beam widths (2 degrees or less typically), resulting in EIRP that can exceed 1 billion watts. Like the CDBS database, GPS location data for many locations are truncated to the nearest second so location uncertainty needs to be accounted for in flight planning.

Conservative calculations in this study assume the worst case if data are not provided. If elevation data are specified, the HIRF zone radius is scaled down by multiplying with the cosine of the elevation angle. If angular data are provided, the HIRF zones become smaller fan-shaped regions representing possible scanning ranges of the transmitters. Otherwise, zero-deg antenna elevation angle and 360-deg azimuth steering range are assumed.

c) ULS

ULS database contains consolidated databases for many services. The below services are used in the calculations of HIRF maps. Other services may not be suitable for HIRF map calculations as they do not contain the necessary data.

- Land Mobile (Broadcast Auxiliary, Commercial, and Private)
- Maritime Coast & Aviation Ground
- Microwave
- Paging
- Broadband Radio Service (BRS) & Education Broadband Service (EBS)
- Market-Based Services
- Cellular

Characteristics such as antenna beamwidth, direction, and height may be incorporated in creating HIRF zones if the data are provided, such as in microwave transmitters. It is noted that cellular transmitter data are not up to date and do not reflect the abundance of wireless transmitters today. The data are maintained internally by spectrum licensees and may not be available to the public. As a result, mapping is not accurate regarding cellular and wireless transmitters. Also, it is noted that there is no rounding in the GPS data so the mapped locations should be precise.

2) NOAA Weather Radars

National Oceanic and Atmospheric Administration (NOAA) weather radars are also included in the transmitters list. They include Terminal Doppler Weather Radar (TDWR) and Next-Generation Weather Radar (NEXRAD) [9]. They are assumed to have 360-degree azimuth rotation and zero-degree elevation angle. A quick calculation shows radiated power of approximately 25-27 billion watts EIRP. Table 1 contains a few technical data.

TABLE 1: NOAA's TDWR AND NEXRAD WEATHER RADARS

	TDWR	**NEXRAD (WSR-88D)**
Frequency	5600-5650 MHz	2700-3000 MHz
Peak Power	250 kW	750 kW
Power Gain	50 dB	45.5 dB
Beam Width	0.55 degrees	0.95 degrees
Pulse Width-max	1.1 msec	4.7 msec

3) Other Transmitters

Other databases of interest but not included in the current version are those managed by The National Telecommunications and Information Administration (NTIA) and the Federal Aviation Administration (FAA). The NTIA manages the spectrum used by the US federal government, including the military. The FAA maintains databases of transmitters at and near airports for supporting safe airspace operation. Access to these databases is restricted from the public so they are not currently included in the HIRF Map features. They can be included in future updates if access is given.

4) Other Features

Airport and helipad locations and military installation boundaries are also included in the HIRF Map tool since they could be relevant for flight planning. Also included are the FAA's UAS facility maps that show the maximum altitudes around airports where FAA may authorize some drone operations without additional safety analysis.

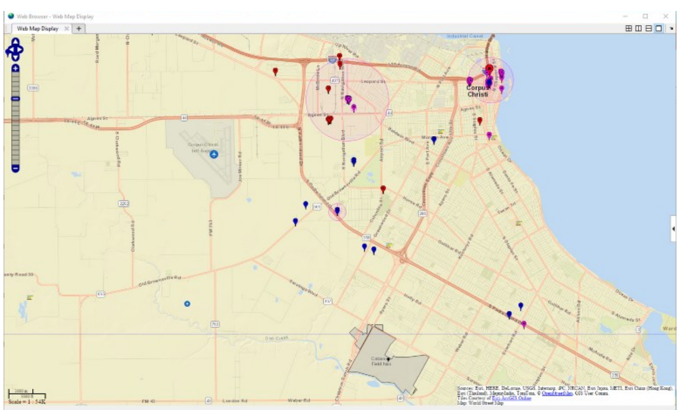
III. MAP EXAMPLES

Examples of HIRF zones for CDBS, IBFS, and ULS transmitters are shown. Also included are examples of NOAA weather radars and others. Each database and subset can be turned on or off and zoomed in if desired.

Also displayed on maps are markers and boundaries for airports, helipads, and military bases whose areas are shaded in black. These are avoidance zones for reasons other than HIRF (e.g. security or aircraft collision risks). Helipads, marked as yellow helicopter icons, are of interest as they could play a role in launching and landing AAM vehicles.

A. CDBS Database

Examples of CDBS transmitters HIRF zones are shown in Fig. 3a-b for a small area in Corpus Christi, Texas. The vehicle tolerance level is set at 10 V/m across the entire frequency band. The small red, blue, and magenta markers and the surrounding shaded circles represent AM, FM, and TV transmitter locations, respectively, and their HIRF zones. HIRF zones for AM and FM transmitters tend to be much smaller than for TV transmitters so the map size may need to be increased to be visible, as shown in Fig. 3b. An individual circle on a map represents the HIRF zone associated with a frequency channel or station. More than one station may share a transmitter location, as indicated by concentric circles resulting in a darker shade. Selecting a marker in the center of the circles pops up additional information about the transmitter. In the example only the station identification KWDT-LP is shown; however, much more detailed data can be displayed.



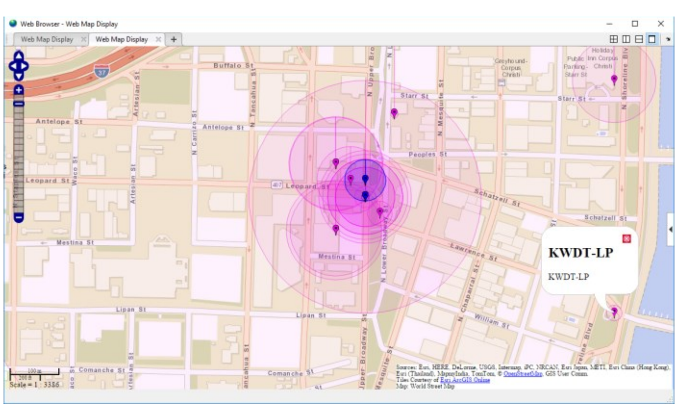


Fig. 3a & 3b: HIRF maps using CDBS database. 10V/m vehicle field tolerance level. Location: Corpus Christi, TX.

B. IBFS Database

Figs. 4a to 4c show examples of IBFS transmitter locations and the associated HIRF zones. Fig. 4a shows the HIRF zones of transmitters for which frequency coordination data are provided in the FCC's database. The frequency coordination data include information on angular range, antenna elevation angle, etc. These data help narrow the HIRF zones to only the possible angular range rather than the entire 360 degrees assumed in the worst-case scenario. Antenna elevation information also helps reduce the HIRF range by multiplying the calculated HIRF circle radius with the cosine of the elevation angle. The results are fan-shaped HIRF zones as illustrated. Fig. 4b overlays a satellite view with a HIRF map. 5 V/m tolerance level are assumed for all frequencies in 4a-b.

Fig. 4c also includes transmitters that do not have frequency coordination data. Without the data, the worst-case assumptions are made that the antennas have zero-degree elevation angles and can rotate 360 degrees. These assumptions result in circular HIRF regions as shown. In IBFS databases, frequency coordination data are included for far less than half of transmitters. Like CDBS, IBFS's GPS data are also truncated to the nearest second. The tolerant field level is set at 10 V/m. Military base boundaries, airports, and helicopter pads are displayed.

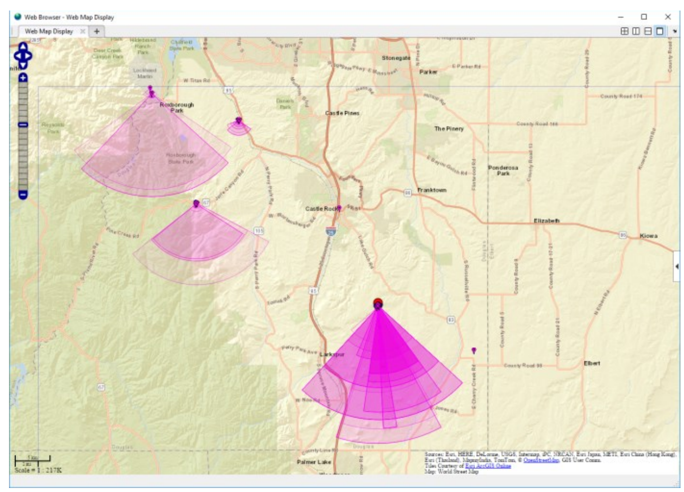


Fig. 4a: Examples of IBFS transmitters' HIRF zones. 5 V/m tolerance level.

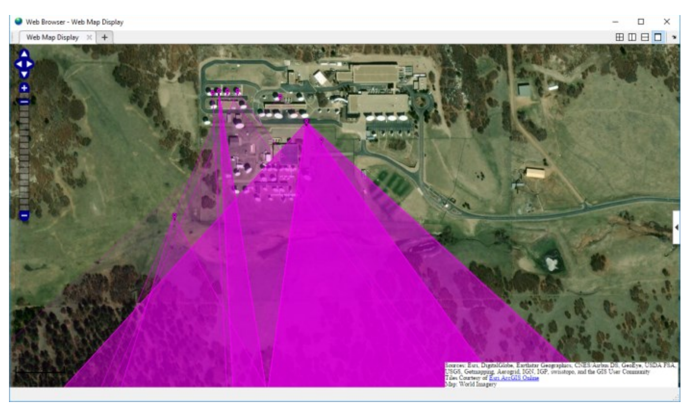


Fig. 4b: Examples of IBFS transmitters' HIRF zones. 5 V/m tolerance level. Satellite view.

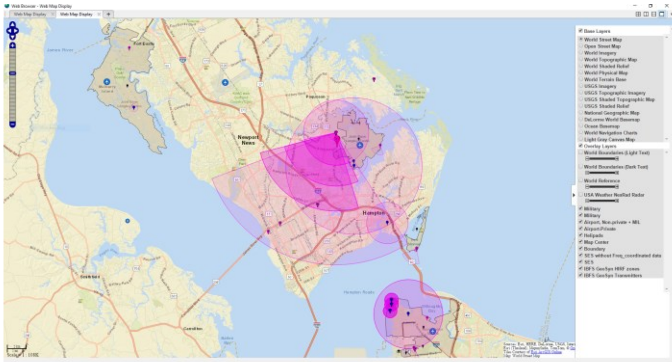


Fig. 4c: Example of transmitters without angular information. 360-degree antenna rotation is assumed. 10 V/m tolerance level.

C. ULS Databases

Fig. 5a shows an example of ULS transmitters near Hampton, Virginia. Data came from databases for Cellular, Microwave Link, Land Mobile (Commercial, Broadcast, and Private), Maritime Coast & Aviation Ground, and Paging. The colored markers show the transmitter locations and HIRF zones, with different colors associated with corresponding databases. The HIRF zones shown are very small and are barely visible in the current view.

The right side of the figure show options that can be ticked to select the base map or to turn on-or-off maps features. These options are available to all HIRF maps in this report. Street maps, imagery maps, or terrain maps can be chosen. In addition, colored markers represent different types of transmitters, and they can be turned on or off interactively. The same is also true for HIRF zones.

In this figure, only 16 cellular and similar wireless transmitters are seen in an area that is approximately 40 km by 100 km. This density is far lower than can be confirmed on the ground, indicating that the cellular and wireless databases are far from complete. Past efforts to gain access to privately owned wireless base station databases were challenging. This difficulty indicates that the vehicles may need to be immune to cellular/wireless transmitters by default, so database access is not necessary.

Figs. 5b and 5c show a zoomed view of one of the HIRF zones along with a satellite view. Data associated with land mobile (green), paging (black), and microwave link (blue) transmitters are seen. Microwave links can be seen as pencil beams.

Fig. 5d illustrates an example of an urban area (Corpus Christi, Texas). The flight path (in red) can intercept microwave links' HIRF zones so the vehicle will need to be rerouted.

D. NOAA Weather Radars

Locations and HIRF zones of NOAA weather radars can be displayed along with CDBS, IBFS, or ULS maps. An example of NEXRAD and TDWR transmitters in the continental US is shown in Fig. 6. The figure inset illustrates the HIRF zone of a TDWR radar near Corpus Christi, Texas for a 10 V/m UAS tolerant level.

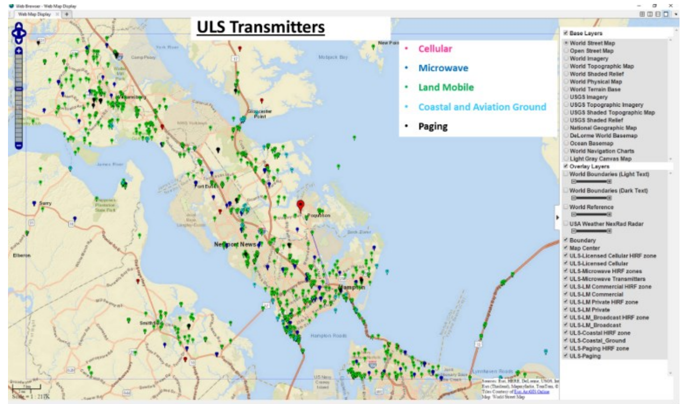


Fig. 5a: ULS transmitters near Hampton, VA region.

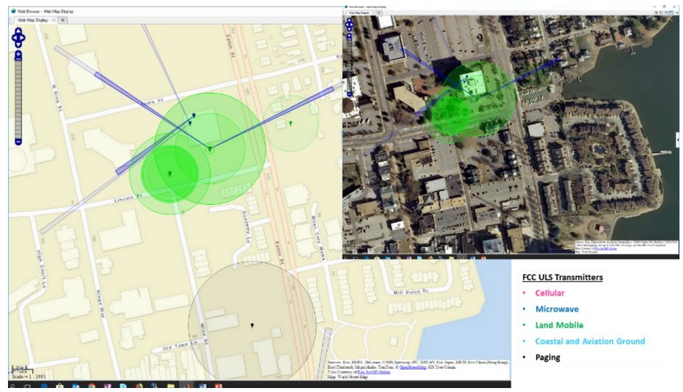


Fig. 5b: ULS transmitters HIRF zones example. Microwave links, land mobile, and paging transmitters are seen. 5V/m vehicle tolerance level.

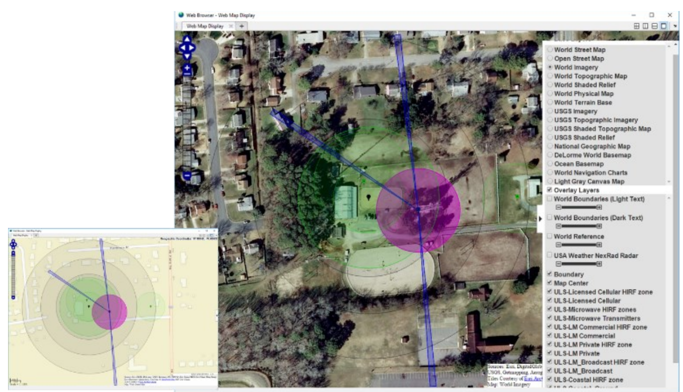


Fig. 5c: ULS transmitters HIRF zones example. Satellite view.

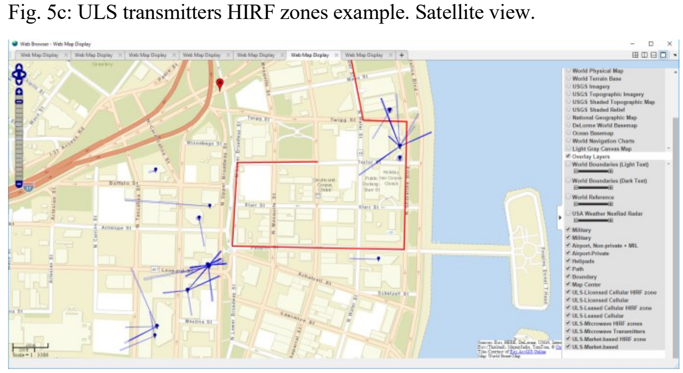


Fig. 5d: ULS's microwave links can intersect with the potential flight path (in red). Location: Corpus Christi, Texas; 5 V/m vehicle tolerance.

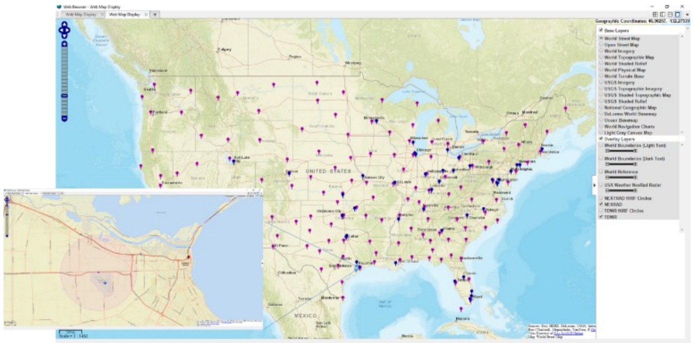


Fig. 6: Example of HIRF map using NOAA weather radars database.

IV. Summary Findings and Discussions

Preliminary findings are discussed below; many were not discussed in the earlier sections.

Databases:

- The HIRF Map concept is technically feasible, using FCC fixed transmitters databases and other public sources.

- Need to seek limited access to NTIA's database and FAA's transmitter database for airports. Without them, AAM/UAS vehicles should avoid military/government sites and airports. An approved liaison could help address security concerns.

- Data for cellular and wireless services are inadequate in the FCC databases. Although seeking access to commercial cellular/wireless transmitter databases could be useful, as a mitigation strategy, AAM/UAS vehicles should be built to inherently tolerate cellular/wireless signals due to the ubiquity of their transmitters. The environment proposed in [10] for cellular/wireless bands may also be considered.

- More accurate and precise GPS locations of CDBS (AM, FM, TV) and IBFS (Satellite Earth Stations) transmitters are desirable to minimize location uncertainties. Often, GPS locations are reported for the facility instead of the antenna.

- The HIRF Map concept and tools can easily be tailored to individual regions or countries.

Vehicle:

- This approach allows for arbitrarily low HIRF tolerance levels; however, some default generic minimum tolerance level is recommended. This is to overcome uncertainties associated with the lack of transmitter databases for cellular/wireless base stations, unlicensed/unregulated devices, and handheld/portable transmitters. Choosing a level to match one of the RTCA/DO-160 [4] categories would be appropriate. Or generic levels similar to EN 62000-6-2 immunity standard for industrial environments could be a good start [11]. As an illustration, for a vehicle with generic tolerance levels of 10 V/m and 30 V/m, the stand-off distances R (using Eq. 1) from a 120-watt wireless base station transmitter would be 6 m and 2 m, respectively.

Map:

- The current HIRF Map tool displays HIRF zones associated with a single frequency channel/carrier. The tool can be configured to use the cumulative power of all carriers.

- Web Map function in Matlab was used for the demonstration. Additional capabilities may be available in other commercial maps.

- HIRF maps are not restricted to two-dimensional. Three-dimensional HIRF maps could allow flying above or under the transmitters' HIRF zones. Examples include flying over/under the microwave beams, or over weather radars, satellite dishes, and TV transmitters. This would be an easy addition to the existing capabilities.

Architecture:

- This capability should be added to UAM, AAM, and UAS architecture as a Supplemental Data Service, similar to services for terrain, micro weather, obstacles, and others. An example of UAM architecture can be found in [12].

V. Conclusion

The HIRF Map concept is technically feasible for flight planning. The proposed approach may allow AAM/UAM/UAS vehicles to satisfy airworthiness requirements without designing and certifying to the worse case HIRF environment. Some restrictions may apply, including vehicles should be immune to cellular and wireless signals by default. It is also recommended to avoid operating near airports and government/military facilities without additional access to NTIA and FAA transmitter data. The tool can easily be tailored for countries other than the U.S.

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